SOCIO-ECONOMIC RESEARCH ON FUSION

SERF 3 (2001-2002)

External Costs of Fusion.

List of Authors:

Euratom/CIEMAT Fusion Association, Spain:

- Y. Lechón
- R. Sáez
- H. Cabal

CEPN, Euratom-CEA Fusion Association, France

- T. Schneider
- S. Lepicard
- L. Vaillant

Euratom/IPP Fusion Association, Germany

- T. Hamacher

Studsvik Eco & Safety AB, Euratom/VR Fusion Association, Sweden

- B. Hallberg
- K. Aquilonius

Euratom/UKAEA Fusion Association, United Kingdom

- D. Ward

VTT, Euratom/Tekes Fusion Association, Finland

- R. Korhonen

Acknowledgements

This work has been partially founded by the European Commission DG XII Fusion Programme.
Authors would like to acknowledge Dr. Tosato for his helpful comments which significantly helped to improve this final report. The sole responsibility for the content remains with the authors

EXECUTIVE SUMMARY

Introduction

Based on SEAFP project (Raeder et al, 1995) findings a preliminary assessment of environmental external costs associated to fusion power was performed under the framework of the first phase of the SERF (Socioeconomic Research on Fusion) project (Sáez et al, 1999). This study showed very low external costs of fusion power compared with other traditional and new energy generating technologies. In order to update the assessment of externalities of fusion power, SERF2 project a new power plant was included and an analysis of the key variables influencing the external cost was carried out. In the new phase of the SERF project, SERF3, three new additional plant models have been introduced with the aim of assessing the possibilities of silicon carbide to be used as structural material for fusion power plants. Furthermore, comparison of fusion external costs with those of other generation technologies in the state of technology development expected for 2050 has been also performed.

Task objectives

The objective of the task of External Costs of Fusion is to improve the work already done in previous SERF projects and to make more in depth comparisons with other alternative energy technologies.

The task has been structured in three main topics:

- Inclusion of further plant models into the analysis
- Comparison of fusion with other technologies taking into account their expected technological change
- Reevaluation of C-14 externalities based on safety and environmental studies.

Conclusions

External costs of new concepts of fusion power plants using silicon carbide as structural material have been evaluated and the results obtained compared to the external costs of other advanced energy generation technologies.

Fusion power plants with using silicon carbide have external costs of around 0.6-0.7 mEuro/kWh, which are lower than external costs previously obtained in SERF1 and 2 for fusion power plants using steel as structural material. The use of silicon carbide allows a higher thermal efficiency and this fact has a great impact in the external costs figure expressed in terms of external costs per unit of electricity produced.

C-14 impacts, considered as the most important contributor to the external costs figure in previous models, have been reduced considerably, having only a major role in waste disposal impacts. Other nuclide having an impact on global doses is Tritium whose impacts dominate the power plant operation stage of the fuel cycle.

Since radiological impacts are very reduced, other aspects such as occupational aspects become important. Especially noticeable are the external costs related to accidents in the construction and decommissioning of the power plant. It is important to stress that these external costs have been calculated on the basis of accident statistics in the several sectors involved in the construction of the power plant for the year 1995. Accident rates could decrease considerably by the year 2050 when the construction of the power plant would start, reducing accordingly the external costs produced.

Differences in external costs between different waste handling scenarios are very reduced.

Waste disposal external costs are conditioned by the retention and release period considered. External costs can vary in 2 and a half order of magnitude depending on the assumption made.

External costs for a hypothetical accident of the fusion power plant have been evaluated and the results were in the range of 10^{-7} to 10^{-6} mEuro/kWh which are very reduced compared to total costs calculated for the fusion fuel cycle.

External costs of other advanced technologies have been calculated. The technologies have been selected taking into account the expected share they will have in future energy scenarios. Only technologies expected to play a major role in future energy system have been assessed. The technologies selected are the following:

- Fossil technologies:
  - Advanced coal technologies with carbon capture and disposal: Pressurised Fluidized Bed Combustion (PFBC) and Integrated Gasification Combined Cycle (IGCC)
  - Natural gas combined cycle with carbon capture and disposal (IGCC)
- Fuel cells powered by natural gas
- Renewable technologies:
  - Biomass gasification
  - Wind power
  - Solar photovoltaics
  - Geothermal energy
- Advanced Nuclear fission:
  - The Energy Amplifier (EA)
  - The High Temperature Reactor (HTR).
  - The AMSTER concept

Technological advances have explicitly considered whenever possible. However, in the case of renewable technologies such as PV or wind energy, the technologies considered are current commercial technologies and not advanced concepts.

Other limitation in the comparison of external costs is the consideration or not of secondary emissions in the different technologies and the inclusion or not of important fuel cycle stages and impacts.

Fusion is the energy generation technology of lowest external costs with the only exception of wind energy. Geothermal energy and PV energy follow in external costs. Biomass gasification is the renewable technology of highest costs. Among fossil technologies, NGCC has the lowest external costs and, if CO_2 sequestration is implemented this technology situates very close to renewable technologies as PV. Fuel cells technologies show high external costs mainly due to the fossil origin of H_2.

External costs using the abatement costs of CO_2 of 19 Euro/t are rather different in some technologies, especially fossil technologies, fuel cells and geothermal energy. These technologies show much higher external costs. Renewable technologies and fusion are almost not affected due to the very reduced CO_2 emissions of these cycles, especially in the case of biomass gasification. Consequently the comparison of fossil and renewable technologies changes dramatically when CO_2 abatement costs are considered. Fusion technology is not affected either and becomes the technology with lowest external costs.

A significant part of the external costs produced in the renewable fuel cycles and fusion are related to the effect of the life cycle emissions in the production of the wind turbines, PV modules, or fusion materials. These life cycle data is characteristic of the current energy system. Future energy systems composed of cleaner technologies could have lower emissions associated, and therefore the external costs associated to renewable technologies decrease accordingly.

Sensible and uncertain points in the estimation of the external costs of the different fuel cycles have been highlighted along the document but they are summarised here:

- Global warming damages factors considered specially in the case of fossil fuels.
- Period of release of radionuclides from waste repositories and occupational accidents rates in the fusion fuel cycle.
- Monetary valuation of mortality.
- Inclusion of global impacts.
- Integration time of impacts.

Externalities related to the emissions of C-14 in several stages of the fusion fuel cycle have been identified as the main contributor to the total external cost figure in previous SERF projects. Due to the importance of these impacts, they have been analysed using other approaches than the external costs calculation approach in order to overcome the criticisms that the concept of external costs have. This has been done using the indicator “Life expectancy”. The results showed that the impacts of fusion on the life-expectancy are only marginal, even in the worst case. This is not the case for other technologies.

The behaviour of C-14 in a future environment with increasing concentrations of CO_2 in the atmosphere has been evaluated in order to assess the influence of this increased concentration in the C-14 impacts calculated. The results show that the increased collective dose commitments of releases are relatively little dependent on the CO_2 concentration level.

SUMMARY

Introduction

Based on SEAFP project (Raeder et al, 1995) findings a preliminary assessment of environmental external costs associated to fusion power was performed under the framework of the first phase of the SERF (Socioeconomic Research on Fusion) project (Sáez et al, 1999). This study showed very low external costs of fusion power compared with other traditional and new energy generating technologies. In order to update the assessment of externalities of fusion power, SERF2 project a new power plant was included and an analysis of the key variables influencing the external cost was carried out. In the new phase of the SERF project, SERF3, three new additional plant models have been introduced with the aim of assessing the possibilities of silicon carbide to be used as structural material for fusion power plants. Furthermore, comparison of fusion external costs with those of other generation technologies in the state of technology development expected for 2050 has been also performed.

Task objectives

The objective of the task of External Costs of Fusion is to improve the work already done in previous SERF projects and to make more in depth comparisons with other alternative energy technologies.

The task has been structured in three main topics:

- Inclusion of further plant models into the analysis
- Comparison of fusion with other technologies taking into account their expected technological change
- Reevaluation of C-14 externalities based on safety and environmental studies.

Methodology for externalities assessment

The ExternE methodology

The methodology that has been 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. This is a series of logical steps, which trace the impact from the activity that creates it to the damage it produces, independently for each impact and activity considered.

The ExternE methodology for externalities assessment was applied to the assessment of the external costs of a fusion power plant in the previous phases of the SERF project. Results of the assessment were presented to the ExternE community in the framework of the Concerted Action “Concerted Action for an External Costs Discussion Group”.

More details on the methodology in general, and on the specific methods for the valuation of each impact, may be found in the reports issued by the ExternE Project (European Commission, 1995, 1999a,b,c and Friedrich and Bickel, 2001).

Some methodological remarks

The use of the methodology involves making some important assumptions regarding key aspects of the assessment that could affect significantly the final results. These key aspects are mainly the use of a discount rate in order to account for future costs and benefits, the selection of the time horizon used to integrate long term impacts, the monetary valuation of mortality impacts and the damage costs considered for climate change impacts.

In the present evaluation of externalities two values for the discount rate, 0 and 3%, were applied to compute the external costs of the fusion fuel cycle; a time horizon of 10,000 years in the reported value and a 100,000 years time horizon for informative purposes have been used; regarding the valuation of mortality the value of a life year lost (VLYL) has been used.

Regarding global warming damage costs, the ExternE methodology gives a central estimate of 2.4 Euro/t CO_2 with a minimum value of 0.1 Euro/t CO_2 and a maximum value of 16.4 Euro/t CO_2. As a result of the intrinsic difficulties on the estimation of damage costs of climate change, the current phase of the ExternE project recommends as a second best option the use of the abatement costs to reach the objectives of the Kyoto protocol (Friedrich, 2002). A median estimate for these abatement costs is 19 Euro per t of CO_2.

Then, in our estimation of external costs from global warming in the different fuel cycles that will be analysed, both the central estimate of 2.4 Euro/t of CO_2 recommended by ExternE and also the value of 19 Euro/t of CO_2 have been used. A limitation of the use of these abatement costs is that they could not be relevant to the assessment of technologies for 2050. However, the introduction of this value serves as a illustration of the sensitivity of the externalities estimation to the global warming damage costs value.

Several estimates of marginal global warming damages costs exist in the literature (Nordhaus, 1994; Cline, 1992; Fankhauser, 1995; Peck and Teisberg, 1993; Maddison, 1994). Overall, marginal damages range from US$10 to $221 per ton of carbon. The values selected in this study are then within the range of the published values.

External costs of advanced technologies

External costs of fusion.

Technical aspects of fusion models

The new power plant models introduce silicon carbide composite as structural material. The main technical information relevant to the assessment of externalities during the upstream and power generation stages is summarised here:

- Safety: the introduction of SiC serves to improve the safety further from the previous models.
- Activation of materials: The use of SiC/SiC reduces the C-14 generation in structural materials substantially.
- Material issues: Due to the low density of SiC/SiC the mass of material used is lower than in a steel plant. On the other hand recycling of silicon carbide is less easy.
- Efficiency: The use of silicon carbide is expected to allow a higher coolant temperature, higher thermodynamic efficiency and therefore higher electrical output. An electrical power of 1.5GW is considered in the three cases.
- Occupational radiation exposure: this exposure is not expected to be significant.
- Releases during normal operation. No new work has been performed in the area and therefore the routine emissions available for the base plant model will be used for the new plant models (Ward, 2002).

Externalities of 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. These stages have external costs associated of around 0.196 mEURO/kWh. From this figure, the materials manufacturing stage is responsible for approximately 18% of these externalities and the construction of the power plant is responsible for the 82%. In the construction of the power plant most of the external costs are related to occupational accidents produced in the building activities.

External costs of the power generation stage are dominated by the global dispersion of H-3, followed by those produced by occupational accidents in the power plant and the occupational exposure of the work force. Radiological effects of routine releases other than tritium have a negligible influence in the external costs produced

Externalities of decommissioning and site restoration

Decommissioning phase includes radiological decontamination of the plant and demolition of the buildings, interim storage during 100 years and transport of waste to final repositories and recycling. External costs due to routine replacement of materials during normal operation were also considered in this stage.

Non-contaminated and decontaminated materials may be recycled immediately after decommissioning. Radioactive material must be stored, and radioactive decay will with time reduce the activity of the components. Radioactive components will be kept in an intermediate storage at the site up to 100 years, although material might be recycled continuously, as the radioactivity of different parts become lower than the safety limit set by authorities. After that, some parts have to be taken to final repositories.

Decommissioning, i.e. decontamination, removal of components and material, demolition of buildings, preparation for recycling and transport to storage, is the phase with the highest external cost, mainly due to the high costs for occupational accidents and diseases.

Externalities of waste disposal

Radioactive waste not suitable for recycling is assumed to be disposed in geologic repositories. From the previous SERF studies it was clear that the most important radionuclide in the fusion waste was C-14 since it produces global collective doses as it is introduced in the global carbon cycle. Due to high solubility C-14 will reach biosphere rather rapidly when released from waste. The conclusion of the performed studies is that if C-14 impacts are integrated over long time spans (100000 years), the waste containing C-14 has to be isolated for rather long time spans, more than 20000 years from the environment to have low external costs.

Different disposal options have been considered and three release cases have been constructed. An additional case in which water comes into contact with the disposed material immediately and starts to dissolve material has also been considered simulating a case in which wastes are nor disposed in geological repositories. External costs of this scenario are very high, up to 39.5mEuro/kWh.

It is not easy to find any best estimate value for external costs of fusion waste disposal. Any best estimate case has not been chosen but the range for external cost has been given on the basis of three release cases. The range has release periods 20000 – 30000 years, 50000 – 60000 years and 50000 – 75000 years. This gives cost range 0.02...1.1 mEuro/kWh for Model 4, range 0.03...2.0 mEuro/kWh for Model 5 and range 0.03…2.3 mEuro/kWh for Model 6 when 10000 years integration time is used. If integrated 100000 years range

0.02…1.7 mEuro/kWh for Model 4, range 0.04...3.1 mEuro/kWh) for Model 5 and range 0.05...3.4 mEuro/kWh for Model 6 are estimated.

Externalities of fusion accident

The selected accident scenario was the same as in SERF2. Complementary calculations were performed by considering, for each studied site, a larger panel of dispersion conditions and two distinct regulatory limits sets for tritium contents in major foodstuffs. These calculations served as a basis for re-evaluating direct external costs of fusion and allowed a sensitivity analysis of the major parameters mostly influencing the results, especially regarding to potential local food restrictions.

The accident scenario adopted in this study is a complete loss of all cooling for a prolonged time period (up to three months) with no operation of any safety system or operator intervention. The external costs of fusion accident have been derived from the radiological impacts of tritium solely. Due to the technical capabilities of the fusion power plant from the safety point of view, as evaluated in the SEAFP study, the occurrence of such an accident is considered to be well below 10^{-7} per year. As a conservative approach, this value has been retained for the calculations of external costs.

The external costs (direct costs) estimated for the selected fusion accident scenario in new plant models (PM 4, 5 & 6) are in the range of 10^{-7} – 10^{-6} mEuro.kWh^{-1}, which remains rather low as compared with the total external costs of fusion.It must be noted that this evaluation does not take into account risk aversion.

Summary of the external costs of fusion

External costs of silicon carbide fusion models have been estimated and the results obtained cycle are summarised in Table i.

Table i. External costs of the fusion fuel cycle (silicon carbide models) considering a 10000 years integration time, 0% discount rate, the present practice recycling scenario, a release period for waste disposal of 50000-60000 years and limits set1 for fusion accident scenario.

	External cost (mEuro/kWh)		
	Model 4	Model 5	Model 6
Upstream and power generation stages	0.27 (0.07-1.06) [0.33(0.09-1.37)]	0.27 (0.07-1.07) [0.33(0.09-1.37)]	0.27 (0.07-1.06) [0.33(0.09-1.37)]
Decommissioning, recycling and site restoration	0.31 (0.12-0.93)	0.31 (0.12-0.93)	0.31 (0.12-0.93)
Waste disposal	0.03 (0.02-1.1)	0.05 (0.03-2)	0.06 (0.03-2.3)
Accidents	6.1e-07 (2-13e-07)	6.1e-07 (2-13e-07)	6.1e-07 (2-13e-07)
Subtotal	***0.62 (0.21-3.10)*** ***[0.68(0.22-3.40)]***	***0.64 (0.22-4.00)*** ***[0.70(0.23-4.30)]***	***0.65 (0.22-4.29)*** ***[0.71(0.23-4.60)]***

Expressed between square brackets are the external costs calculated considering the CO_2 abatement costs of 19 Euro/t of CO_2.

Since radiological effects of the emissions of the power plant on the general public have been reduced considerably in the new models, occupational aspects become important. Especially noticeable are those related to accidents in the construction and decommissioning of the power plant. It is important to stress that these external costs have been calculated on the basis of accident statistics in the several sectors involved in the construction of the power plant for the year 1995. Accident rates could decrease considerably by the year 2050 when the construction of the power plant would start, reducing accordingly the external costs produced.

External costs of non nuclear advanced technologies

Selection of non nuclear advanced technologies

Several studies on energy scenarios for the 21st century have been consulted in order to assess what are the predictions for the contribution of different technologies in the energy generation of 2050 (Nakicenovik and Riahi, 2002; Interlaboratory working group, 2000; Cabinet Office, 2002). Following these studies we have selected some advanced technologies to be compared with fusion with regards to their external costs. These technologies are the following:

- Fossil technologies:
  - Advanced coal technologies with carbon capture and disposal
  - Natural gas combined cycle with carbon capture and disposal (NGCC)
- Fuel cells powered by natural gas
- Renewable technologies:
  - Biomass gasification
  - Wind power
  - Solar photovoltaics
  - Geothermal energy

Long-term advances in the different technologies are not known but some trends have been identified.

Advanced coal technologies considered are Integrated Gasification Combined Cycle, a technology in the demonstration stage, and Pressurized Fluidised Bed Combustion, a technology expected to be available in the year 2005. Due to the rigidities of the electricity system, these technologies together with NGCC are expected to be still in use in 2050.

The use of CO_2 sequestration however is a technology in its development stage. The first commercial-scale storage in a deep saline reservoir commenced operation in 1996, offshore Norway. It is still necessary more research and development before practical application.

Fuel cell technologies are at different stages of development. The larger-scale stationary fuel cell systems, the ones considered here, are the furthest from commercialization. They are expected to be available on the market around 2010.

Biomass gasification combined cycle is an advanced technology still in its development stage. Other renewable are rather established technologies in a commercial stage. Specially in PV energy some other more advanced concepts could have been selected but the total lack of data has prevented us from including them in the analysis of externalities which is very intensive in the requirements of data.

External costs of advanced fossil and renewable technologies

External cost calculated for advanced fossil and renewable technologies are summarised in Table ii. The considered state of technology development in the cases studied has been included in the table, as well as the main points of the impact pathway that generate the largest share of the values.

Table ii. External costs of advanced fossil and renewable technologies (0% discount rate, 1-3% discount rate for global warming impacts, 100 years time horizon for global warming impacts)

Technology	Stage of technology development	External costs (mEuro/kWh)	Main causes of impacts
IGCC	Demonstration	4.97 (1.96-14.77) [17.58(15.33-26.09)]	Atmospheric emissions in operation (46%) Global warming (39%)
PFBC	Development	9.35 (3.05-32.22) [19.89(14.23-41.68)]	Atmospheric emissions in operation (60%) Global warming (20%)
NGCC	Commercial	2.73 (1.00-8.72) [8.74(7.37-14.11)]	Atmospheric emissions in operation (45%) Global warming (35%)
IGCC with CO_2 seq.	Development	3.90 (1.25-13.47) [6.97(4.49-16.23)]	Atmospheric emissions in operation (63%) Global warming (15%)
PFBC with CO_2 seq.	Development	6.51 (1.99-23.23) [8.43(3.4-24.894)]	Atmospheric emissions in operation (55%) Global warming (11%)
NGCC with CO_2 seq.	Development	2.01 (0.60-7.37) [3.33(2.00-8.56)]	Atmospheric emissions in operation (55%) Global warming (14%)
Biomass gasification	Development	4.24 (1.14-16.30) [4.91(1.85-16.9)]	Atmospheric emissions in operation (58%) Upstream emissions (32%) Global warming (25%)
Fuel cells PAFC	Development	5.31(1.71-18.60) [12.7(9.57-25.2)]	Secondary and upstream emissions (76%) Global warming (21%)
Fuel cells MCFC	Development	3.58 (1.18-12.40) [9.09(7.03-17.3)]	Secondary and upstream emissions (73%) Global warming (24%)
Geothermal	Demonstration	1.33 (0.14-3.98) [8.11(0.37-16.0)]	Global warming (74%) Water quality (24%)
PV with batteries	Commercial	2.03 (0.54-8.06) [3.45(2.04-9.34)]	Secondary emissions (87%) Global warming secondary (13%)
PV without batteries	Commercial	0.72 (0.18-3.00) [1.60(1.12-3.79)]	Secondary emissions (91%) Global warming secondary (9%)
Wind with flywheels	Commercial	0.43 (0.12-1.53) [1.32(1.06-2.33)]	Secondary emissions (42%) Global warming secondary (30%) Noise (14%) Visual intrusion (14%)

Expressed between brackets are the external costs calculated considering the CO_2 abatement costs of 19 Euro/t of CO_2.

External costs of the radiological impact of advanced nuclear fission

Selected advanced reactors

Three selected innovative reactors were identified:

- The Energy Amplifier (EA), which is a hybrid reactor (developed by Carlo Rubbia
- The High Temperature Reactor (HTR).
- The AMSTER concept (developed by EDF and CEA), which is a molten salt reactor. The externalities of such a concept could not be evaluated due to lack of data.

Calculations of the external costs

External costs of the Energy Amplifier. ^{14}C gaseous release at the reprocessing step could have a very important radiological impact. There is more than one order of magnitude between external costs calculated with or without taking them into account.

Table iii. Economic valuation of radiological impacts for the Energy amplifier (100000 year integration time)

	DR 0%	DR 3%	DR 10%
Cost in Euro/ year	$1.04\ 10^{8}$	$9.22\ 10^{6}$	$5.37\ 10^{6}$
Cost in Euro/ kWh	$5.94\ 10^{-3}$	$5.27\ 10^{-4}$	$3.07\ 10^{-4}$

Including ^{14}C gaseous release at the reprocessing step

External costs of the HTR. HTR shows rather low external costs from 0.0583 to 0.033 mEuro / kWh .As a matter of fact, gaseous releases, which are usually associated with the most important part of the radiological impacts, are quite low for the electricity generation step. Furthermore, as there is no reprocessing stage, gaseous release over the fuel cycle should be quite low.

Table iv. Economic valuation associated with the HTR fuel cycle (100000 year integration time)

	DR 0%	DR 3%	DR 10%
Cost in Euro / year	$1.38\ 10^{5}$	$9.64\ 10^{4}$	$7.82\ 10^{4}$
Cost in Euro / kWh	$5.83\ 10^{-5}$	$4.07\ 10^{-5}$	$3.30\ 10^{-5}$

The values presented cannot be taken as accurate values, as many steps (fuel fabrication, transportation of radiological material, storage of spent fuel…) were not taken into account within the field of this study.

Occupational exposure at the electricity generation stage is the most penalizing step and a growing contribution of mining with the discount rate is observed.

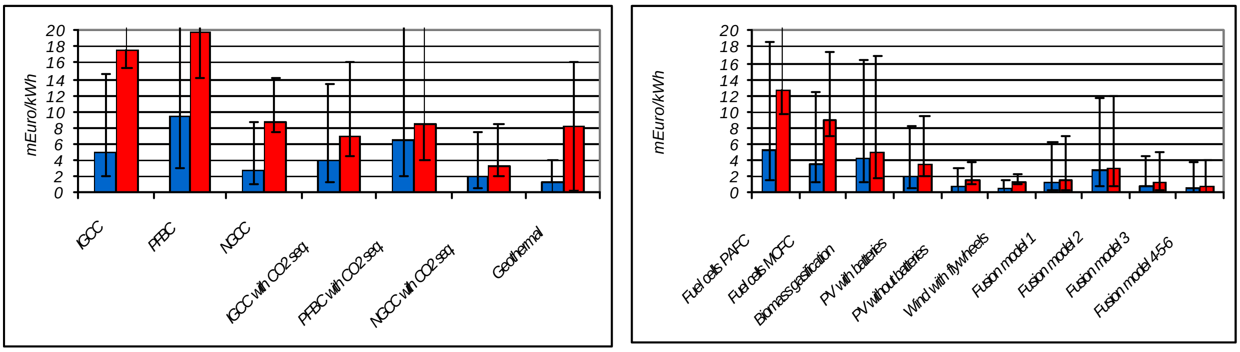
The most penalizing radionuclide in both fuel cycles, as far as routine releases are concerned, is ^{14}C. We carried out our calculations in the local, regional and European areas. If we had considered the global dispersion of ^{14}C over the world, radiological impacts would have been increased by a factor 10, and, as a consequence, external costs. The radiological impact associated with the disposal of waste was not considered here. Other stages of the fuel cycles such as manufacturing of the necessary materials and construction and decommissioning of the power plant have not been considered in this study and this fact should be taken into account when comparing the results with those of other technologies.

Comparison of external costs

External costs of the different technologies calculated are compared in this section. External costs of previous fusion plant concepts calculated in SERF3 are also included in the comparison.

When comparing the external costs of different technologies several considerations have to be taken into account. Firstly is should be noted that in the analysis of the externalities of the fusion fuel cycle most stages of the fuel cycle and most impacts have been considered. In contrast, in other cycles several impacts or stages are missing. For instance, the estimation of external costs of nuclear advanced concepts include only the damage of radiological impacts of the operation and reprocessing stages, other important stages and impacts being excluded from the analysis. External costs calculated for HTR cannot be used for comparison since much of the stages of the fuel cycle have not been taken into account.

Fossil and nuclear fission power plants do not include secondary emissions (emissions from the manufacturing of the construction materials) which are taken into account in renewable technologies and fusion. Secondary emissions have been considered to be trivial in fossil fuel plants compared to the operational emissions, and therefore have been excluded from the analysis (EC, 1995a). However this is not true for renewable energies and fusion in which it has been demonstrated that secondary emissions are capable of causing significant externalities compared to the final externality figure (EC, 1995a; CIEMAT, 1998). Comparison of external costs of technologies that consider secondary emissions and those that do not, are depicted separately in figure i.

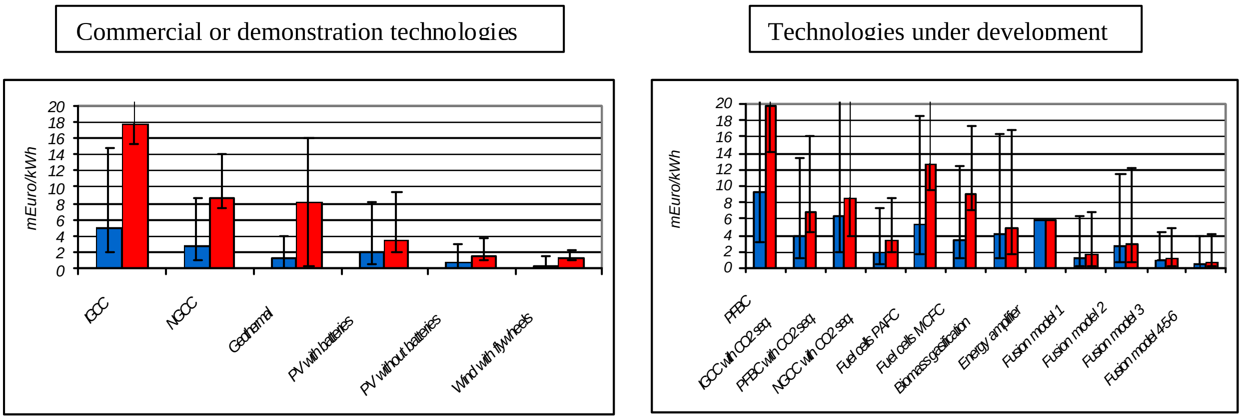


No consideration of secondary emissions

Consideration of secondary emissions

Figure i. Comparison of external costs of advanced technologies taking into account or not secondary emissions

Renewable technologies considered in this study are current commercial technologies and not advanced concepts. In contrast in other technologies such as fusion, advanced fission and advanced fossil technologies future technological improvement have been explicitly considered. External costs of renewable technologies could experience significant decrements if improvements in efficiency would have been considered. Comparison of external costs of commercial or demonstration technologies and those technologies in development stage are depicted separately in figure ii.


Commercial or demonstration technologies

Technologies under development

Figure ii. Comparison of external costs of technologies taking into account or not technological advances.

A significant part of the external costs produced in the renewable fuel cycles and fusion are related to the effect of the life cycle emissions in the production of the wind turbines, PV modules or fusion materials, the so call secondary emissions. These life cycle data is characteristic of the current energy system. Future energy systems composed of cleaner technologies could have lower emissions associated, and therefore the external costs associated to renewable technologies could decrease accordingly.

Bearing all these comparison limitations in mind and in order to provide a complete picture of the whole range of technologies considered, a figure showing all the technologies has been also included, figure iii. In this figure it can be seen that fusion, specially the new silicon carbide models, is the energy generation technology of lowest external costs with the only exception of wind energy. Geothermal energy and PV energy follow in external costs. Biomass gasification is the renewable technology of highest costs. Among fossil technologies, NGCC has the lowest external costs and, if CO_2 sequestration is implemented this technology situates very close to renewable technologies as PV. Fuel cells technologies show high external costs mainly due to the fossil origin of H_2.

External costs of the different technologies using the abatement costs of CO_2 of 19 Euro/t are also depicted in red in figure iii. Some technologies are highly affected by this modification, especially fossil technologies, fuel cells and geothermal energy. These technologies show much higher external costs. Renewable technologies are almost not affected due to the very reduced CO_2 emissions of these cycles, especially biomass gasification. Fusion technology is not affected either and becomes the technology with lowest external costs.

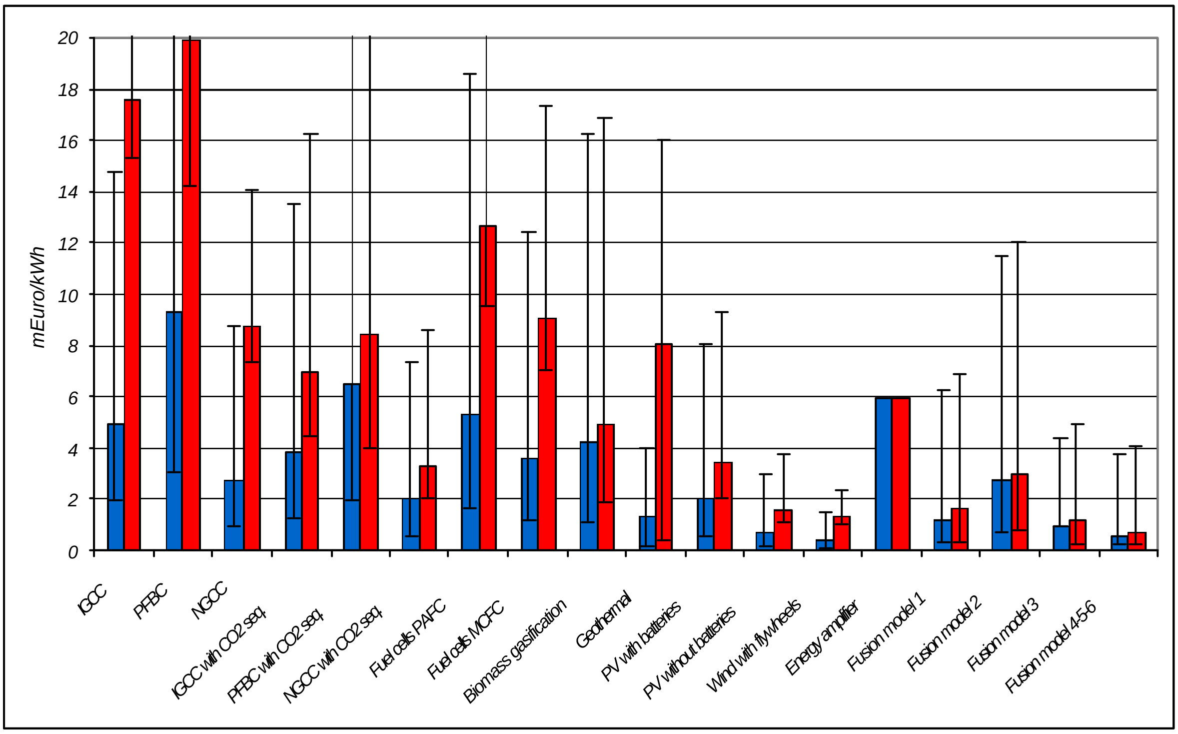


Figure iii. External costs of advanced fossil and renewable technologies in comparison with fusion (in blue colour global warming damage costs of 2.4 Euro/t and in red colour global warming damage costs of 19 Euro/t). (0% discount rate, 10000 years integration time for radiological impacts, 100 years for global warming impacts).

Sensible and uncertain points in the estimation of the external costs of the different fuel cycles have been highlighted along the document but they are summarised here:

- Global warming damages factors considered specially in the case of fossil fuels.
- Period of release of radionuclides from waste repositories and occupational accidents rates in the fusion fuel cycle.
- Monetary valuation of mortality.
- Inclusion of global impacts.
- Integration time of impacts.

Reevaluation of C-14 externalities based on safety and environmental studies

Externalities related to the emissions of C-14 in several stages of the fusion fuel cycle have been identified as the main contributor to the total external cost figure. Due to the importance of these impacts, they have been analysed using other approaches than the external costs calculation approach in order to overcome the criticisms that the concept of external costs have.

The behaviour of C-14 in a future environment with increasing concentrations of CO_2 in the atmosphere has been evaluated in order to assess the influence of this increased concentration in the C-14 impacts calculated.

External costs versus environmental standards or other sustainability indices

The Socio-Economic Studies on Fusion (SERF) (Borelli, 2001) evaluated the external costs of fusion with help of the ExternE methodology (EU-Methodology,1995). As a matter of fact some items were identified which let to severe problems in the evaluation procedure. The most pronounced was the evaluation of the external costs of ^{14}C releases from possible final repositories. The different values of the external costs varied considerable between the different discount rates. Another major problem is to define a retention time for the final repository (Hamacher,2001) . Another major problem is the valuation of greenhouse gas emissions.

Impacts on human life and health dominate the composition of external costs. Most of the external costs are contributed by health effects mainly mortality. Therefor it seems wise to look for an indicator which is strongly coupled to human health. An indicator summing up all the effects on human life and health is the life-expectancy.

The advantage of the life-expectancy is that it does not only “measure” environmental impacts, it depends also on social issues, like violence and education. Another advantage is that an analysis of the life-expectancy values “positive” externalities.

The impacts of fusion on the life-expectancy are only marginal, even in the worst case. This is not the case for other technologies.

Impacts and transfer of C-14 releases in the future environment

Global impacts of radionuclide C-14 releases due to operation and waste repositories were found to dominate the radiological impact in SERF1 and SERF2 studies. Factors that contribute to radiation doses caused by C-14 in the atmosphere and accumulation into vegetation are therefore among the key variables. In these studies, circulation of C-14 has been assessed as a part of the natural carbon cycle without considering the impact of carbon flows caused by increased amounts of carbon dioxide in the atmosphere. In the future environment the carbon dioxide levels in the atmosphere will increase. This has impact on the transfer of C-14. Besides dilution impact (so called Suess effect) anthropogenic carbon dioxide has impact on the flows of carbon in the environment. Some basic evaluations of the impact of the future increase of the atmospheric carbon dioxide concentration levels on the estimation of the global impacts of C-14 emissions have been performed. It has been concluded that increased collective dose commitments of releases are relatively little dependent on the CO_2 concentration level in the range about 450 – 900 ppm.

Conclusions

External costs of new concepts of fusion power plants using silicon carbide as structural material have been evaluated and the results obtained compared to the external costs of other advanced energy generation technologies.

Fusion power plants with using silicon carbide have external costs of around 0.6-0.7 mEuro/kWh, which are lower than external costs previously obtained in SERF1 and 2 for fusion power plants using steel as structural material. The use of silicon carbide allows a higher thermal efficiency and this fact has a great impact in the external costs figure expressed in terms of external costs per unit of electricity produced.

C-14 impacts, considered as the most important contributor to the external costs figure in previous models, have been reduced considerably, having only a major role in waste disposal impacts. Other nuclide having an impact on global doses is Tritium whose impacts dominate the power plant operation stage of the fuel cycle.

Since radiological impacts are very reduced, other aspects such as occupational aspects become important. Especially noticeable are the external costs related to accidents in the construction and decommissioning of the power plant. It is important to stress that these external costs have been calculated on the basis of accident statistics in the several sectors involved in the construction of the power plant for the year 1995. Accident rates could decrease considerably by the year 2050 when the construction of the power plant would start, reducing accordingly the external costs produced.

Differences in external costs between different waste handling scenarios are very reduced.

Waste disposal external costs are conditioned by the retention and release period considered. External costs can vary in 2 and a half order of magnitude depending on the assumption made.

External costs for a hypothetical accident of the fusion power plant have been evaluated and the results were in the range of 10^{-7} to 10^{-6} mEuro/kWh which are very reduced compared to total costs calculated for the fusion fuel cycle.

External costs of other advanced technologies have been calculated. The technologies have been selected taking into account the expected share they will have in future energy scenarios. Only technologies expected to play a major role in future energy system have been assessed. The technologies selected are the following:

- Fossil technologies:
  - Advanced coal technologies with carbon capture and disposal: Pressurised Fluidized Bed Combustion (PFBC) and Integrated Gasification Combined Cycle (IGCC)
  - Natural gas combined cycle with carbon capture and disposal (IGCC)
- Fuel cells powered by natural gas
- Renewable technologies:
  - Biomass gasification
  - Wind power
  - Solar photovoltaics
  - Geothermal energy
- Advanced Nuclear fission:
  - The Energy Amplifier (EA)
  - The High Temperature Reactor (HTR).
  - The AMSTER concept

Technological advances have explicitly considered whenever possible. However, in the case of renewable technologies such as PV or wind energy, the technologies considered are current commercial technologies and not advanced concepts.

Other limitation in the comparison of external costs is the consideration or not of secondary emissions in the different technologies and the inclusion or not of important fuel cycle stages and impacts.

Fusion is the energy generation technology of lowest external costs with the only exception of wind energy. Geothermal energy and PV energy follow in external costs. Biomass gasification is the renewable technology of highest costs. Among fossil technologies, NGCC has the lowest external costs and, if CO_2 sequestration is implemented this technology situates very close to renewable technologies as PV. Fuel cells technologies show high external costs mainly due to the fossil origin of H_2.

External costs using the abatement costs of CO_2 of 19 Euro/t are rather different in some technologies, especially fossil technologies, fuel cells and geothermal energy. These technologies show much higher external costs. Renewable technologies and fusion are almost not affected due to the very reduced CO_2 emissions of these cycles, especially in the case of biomass gasification. Consequently the comparison of fossil and renewable technologies changes dramatically when CO_2 abatement costs are considered. Fusion technology is not affected either and becomes the technology with lowest external costs.

A significant part of the external costs produced in the renewable fuel cycles and fusion are related to the effect of the life cycle emissions in the production of the wind turbines, PV modules or fusion materials. These life cycle data is characteristic of the current energy system. Future energy systems composed of cleaner technologies could have lower emissions associated, and therefore the external costs associated to renewable technologies decrease accordingly.

Sensible and uncertain points in the estimation of the external costs of the different fuel cycles have been highlighted along the document but they are summarised here:

- Global warming damages factors considered specially in the case of fossil fuels.
- Period of release of radionuclides from waste repositories and occupational accidents rates in the fusion fuel cycle.
- Monetary valuation of mortality.
- Inclusion of global impacts.
- Integration time of impacts.

Externalities related to the emissions of C-14 in several stages of the fusion fuel cycle have been identified as the main contributor to the total external cost figure in previous SERF projects. Due to the importance of these impacts, they have been analysed using other approaches than the external costs calculation approach in order to overcome the criticisms that the concept of external costs have. This has been done using the indicator “Life expectancy”. The results showed that the impacts of fusion on the life-expectancy are only marginal, even in the worst case. This is not the case for other technologies.

The behaviour of C-14 in a future environment with increasing concentrations of CO_2 in the atmosphere has been evaluated in order to assess the influence of this increased concentration in the C-14 impacts calculated. The results show that the increased collective dose commitments of releases are relatively little dependent on the CO_2 concentration level.

TABLE OF CONTENTS

1. INTRODUCTION

An extensive assessment of fusion environmental and safety aspects was performed under the SEAFP (Safety and Environmental Assessment of Fusion Power) project (Raeder et al, 1995) of the European Fusion Programme. Based on SEAFP findings a preliminary assessment of environmental external costs associated to fusion power was performed under the framework of the first phase of the SERF (Socioeconomic Research on Fusion) project (Sáez et al, 1999). This study showed very low external costs of fusion power compared with other traditional and new energy generating technologies. Some aspects of the external costs could no be assessed in detail, though. Since then some technological changes, that could have incidence in the external costs, were introduced in the design of the power plant, especially changes related to reactor materials. This was done in the projects SEAFP-2 and SEAL (Cook et al, 1999). In order to introduce all these changes and update the assessment of externalities of fusion power, SERF2 project included a task devoted to the improvement of the work performed under SERF1. In the SERF2 project, a new power plant was included and an analysis of the key variables influencing the external cost aiming to set some recommendations for the design of fusion power plants with minimum external costs was also carried out. In the new phase of the SERF project, SERF3, three new additional plant models have been introduced with the aim of assessing the possibilities of silicon carbide to be used as structural material for fusion power plants. Furthermore, comparison of fusion external costs with those of other generation technologies in the state of technology development expected for 2050 has been also performed.

2. TASK OBJECTIVES

The objective of the task of External Costs of Fusion is to improve the work already done in previous SERF projects and to make more in depth comparisons with other alternative energy technologies.

The task has been structured in three main topics:

- Inclusion of further plant models into the analysis
- Comparison of fusion with other technologies taking into account their expected technological change
- Reevaluation of C-14 externalities based on safety and environmental studies.

The work has been performed by six work teams whose specific contributions are summarised in this document.

3. METHODOLOGY FOR EXTERNALITIES ASSESSMENT

3.1 The ExternE methodology

The methodology that has been 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. This is a series of logical steps, which trace the impact from the activity that creates it to the damage it produces, independently for each impact and activity considered.

The underlying principles on which the methodology has been developed are:

Transparency, to show precisely how results are calculated, the uncertainty associated with the results and the extent to which the external costs of any fuel chain have been fully quantified.

Consistency, of methodology, models and assumptions (e.g. system boundaries, exposure-response functions and valuation of risks to life) to allow valid comparisons to be made between different fuel chains and different types of impact within a fuel chain.

That analysis should be comprehensive, we should seek to at least identify all of the effects that may give rise to significant externalities, even if some of these cannot be quantified in either physical or monetary terms.

These characteristics should be present along the stages of the assessment of externalities, which are the following: site and technology characterisation; identification of fuel chain burdens; identification of impacts; prioritisation of impacts; quantification of impacts and economic valuation

Uncertainty arises in each stage of the assessment. An estimation of uncertainty ranges was performed following the approach proposed within the ExternE methodology (EC, 1999a, Rabl, A; J.V. Spadaro, 1999). 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 have been used. The labels are:

A = high confidence, roughly corresponding to $\sigma_G = 2.5$ to 4;

B = medium confidence, roughly corresponding to $\sigma_G = 4$ to 6;

C = low confidence, roughly corresponding to $\sigma_G = 6$ to 12.

These labels can be interpreted in terms of multiplicative confidence intervals: if the cost has been estimated to be μ_g, the probability is approximately 68% that the true value is in the interval $[\mu_g/\sigma_G, \mu_g.\sigma_G]$ and 95% that is in $[\mu_g/\sigma_G^2, \mu_g.\sigma_G^2]$.

Labels have been assigned to the different categories of impacts following the results obtained in the ExternE National Implementation Project (EC, 1999c) and the more precise indications made in Rabl and Spadaro (1999) regarding the incidence of cancers from exposure to radionuclides.

Specific uncertainty analysis in some stages of the assessment of the fusion fuel cycle has been performed using a statistical error propagation method (Bergstrom and Hallberg, 2000). The median of the results variables were used as mid estimates, while the 5%-percentil and 95%-percentil were taken as minimum and maximum estimates, respectively.

The ExternE methodology for externalities assessment was applied to the assessment of the external costs of a fusion power plant in the previous phases of the SERF project. Results of the assessment were presented to the ExternE community in the framework of the Concerted Action "Concerted Action for an External Costs Discussion Group".

More details on the methodology in general, and on the specific methods for the valuation of each impact, may be found in the reports issued by the ExternE Project (European Commission, 1995, 1999a,b,c and Friedrich and Bickel, 2001).

3.2 Some methodological remarks

The use of the methodology involves making some important assumptions regarding key aspects of the assessment that could affect significantly the final results. These key aspects are mainly the use of a discount rate in order to account for future costs and benefits, the selection of the time horizon used to integrate long term impacts, the monetary valuation of mortality impacts and the damage costs considered for climate change impacts. The assumptions made in the present evaluation of externalities regarding these topics are summarised in the following paragraphs.

3.2.1 Discounting

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 methodology considers the use of two values for the discount rate: 0 and 3. In the case of the global warming estimates the values considered are 2,4 – 3,2. The rationale for the selection of this range and best estimate, and a broader description of issues relating to discounting can be found in Freidrich and Bickel (2001).

In order to be in line with the general recommendations of the methodology two values for the discount rate, 0 and 3%, were applied to compute the external costs of the fusion fuel cycle. In the comparison of external costs section reported values are calculated using a 0 % discount rate.

3.2.2 Time horizon

The ExternE methodology states that impacts should be assessed over their full time course. This clearly introduces a good deal of uncertainty specially when we use time scales running far beyond recorded history which could be the case in the fusion waste disposal impacts. However the methodology concludes "it is informative to conduct analysis of impacts that take effect over periods of many years in spite of the large uncertainties involved".

The time course of different impacts is of course different and therefore it is not necessary to analyse all the impacts with the same time scale.

Regarding the time scale for long-term impacts of radionuclides, the ExternE methodology used in the nuclear fuel cycle a time horizon of 10,000 years. Results of the externalities of these fuel cycles would have been much higher if a 100,000 years time horizon were considered. The objective of selecting a time horizon of 100,000 years in these estimations was to capture all the possible impacts in spite of the uncertainties. However, in order to compare with existing results in ExternE for the nuclear fuel cycle it would be important to perform the analysis also with a shorter time horizon. In consequence both values for the time horizon: 10,000 and 100,000 years have been used. A time horizon of 10,000 years in the reported value and a 100,000 years time horizon for informative purposes.

3.2.3 Spatial limits of the impact analysis

The site-specific approach of the methodology involves the location of the power plants analysed in an specific place. The site selected for the implementation of the fusion power plant has been Lauffen in the South-western part of Germany. It is situated on the river Neckar about 35 km north of Stuttgart. Whenever possible other fuel cycles have been considered located also in Lauffen, with the exception of the IGCC fuel cycle located in Puertollano (Spain), the geothermal fuel cycle located in the Azores archipelago, the wind fuel cycle locate din a coastal area of Germany and the fission advanced reactors located in Marcoule (France).

The spatial scope of the assessment of externalities of the fuel cycles is divided into three scales:

- local scale: which covers the effects on a local area of 100 km x 100 km with the power plant in the centre.
- regional scale, which covers the effects on Europe
- global scale, which covers the effects on the whole Earth

Consideration of regional and global impacts has major implications in the size of the total impact, since some pollutants, radioactive and conventional, may become widely dispersed through the regional and global ranges and in many cases regional and global effects are far greater than effects on the local scale.

3.2.4 Monetary valuation

The rationale and procedures underlying the economic valuation are those used within the ExternE Project. The approach followed 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 mortality is a very controversial issue. The current ExternE approach assumes a strong relationship between the individual’s WTP for risk reduction and the change in life expectancy. Several empirical valuation studies are on-going and until the final results come the recommendation of the ExternE methodology is to use the concept of the value of a life year lost (VLYL) for the valuation of mortality arising from illnesses linked to exposure to air pollution. For fatal accidents, mortality impacts in climate change and similar cases where the impact is sudden the Value of Statistical Life (VSL) estimates are recommended. The best estimate of VSL used in ExternE is 3,313,900 EURO. Values of VLYL used in the methodology are summarized in tables Table 1 and Table **2**.

Table 1. Estimated VLYL for acute and chronic effects of air pollution (EURO 2000). Source: Friedrich and Bickel, 2001

	Discount rate	VLYL
Acute mortality	0%	104,760
	3%	165,700
Chronic mortality	0%	104,760
	3%	90,700

Table 2. Summary of the monetary values of radiological effects for different discount rates (EURO 2000)

	DR 0%	DR 3%
Non fatal cancer	481,050	481,050
Hereditary effect	3,313,900	377,785
Fatal cancer	2,333,983	1,863,623
Values per man.Sv		
Public	207,564	154,685
Workers	170,969	134,538

3.2.5 Climate change

Climate change impacts are extremely complex and the understanding of the mechanisms of action is still very poor. Marginal costs for greenhouse gases emissions have been estimated in ExternE using two models: the Open Framework Model and the Fund model. The final recommendation is a central estimate of 2.4 Euro/t CO_2 with a minimum value of 0.1 Euro/t CO_2 and a maximum value of 16.4 Euro/t CO_2. (Friedrich and Bickel, 2001). This recommendation has received many criticisms (Krewitt, 2002). The first reason argued to doubt of the results is that quantification of damage costs from global warming only covers a time horizon of 100 years in spite of the very long term nature of the expected impacts. Other important criticisms is that the utilisation of different discount rates might lead to a change in the sign of the costs since short term benefits might dominate the global estimate.

As a result of these intrinsic difficulties on the estimation of damage costs of climate change, the final recommendation is under continuous revision. The current phase of the ExternE project recommends as a second best option the use of the abatement costs to reach the objectives of the Kyoto protocol (Friedrich, 2002). A median estimate for these abatement costs is 19 Euro per t of CO_2. Then, in our estimation of external costs from global warming in the different fuel cycles that will be analysed, both the central estimate of 2.4 Euro/t of CO_2 recommended by ExternE and also the value of 19 Euro/t of CO_2 have been used. A limitation of the use of these abatement costs is that they could not be relevant to the assessment of technologies for 2050. However, the introduction of this value serves as a illustration of the sensitivity of the externalities estimation to the global warming damage costs value.

Several estimates of marginal global warming damages costs exist in the literature (Nordhaus, 1994; Cline, 1992; Fankhauser, 1995; Peck and Teisberg, 1993; Maddison, 1994). Overall, marginal damages range from US$10 to $221 per ton of carbon. The values selected in this study are then within the range of the published values.

4. EXTERNAL COSTS OF ADVANCED TECHNOLOGIES

4.1 External costs of fusion.

4.1.1 Technical aspects of fusion models

Technical input related to the characteristics of the new models, models 4, 5 and 6, have been provided by UKAEA (Ward, 2001). These models are the models studied in the most recent safety and environmental study in the fusion programme SEAFP-99 (Taylor and Sublet, 1999).

The characteristics of these new models together with the other models considered previously in SERF are summarised in Table 3.

Table 3. Characteristics of fusion power plant models

Plant Model	FW/blanket structure	Tritium-generating material	Neutron multiplier	FW/blanket coolant
1	vanadium alloy	Li_2O ceramic pebble bed	None	Helium
2	low activation martensitic steel	Liquid $Li_{17}Pb_{83}$	$Li_{17}Pb_{83}$	Water
3	low activation martensitic steel	Li_4SiO_4 ceramic pebble bed	Beryllium	Helium
4	SiC/SiC	Liquid $Li_{17}Pb_{83}$	$Li_{17}Pb_{83}$	liquid $Li_{17}Pb_{83}$
5	LA martensitic steel with SiC/SiC insulators	Liquid $Li_{17}Pb_{83}$	$Li_{17}Pb_{83}$	Helium and liquid $Li_{17}Pb_{83}$
6	SiC/SiC	Li_4SiO_4 ceramic pebble bed	Beryllium	Helium

The new power plant models introduce silicon carbide composite as structural material. The in-vessel shield is assumed to be stainless steel 316 in the three new models.

Model 4 is a fully silicon carbide model with liquid metal coolant.

Model 5 is similar to the earlier model 2 but with helium and liquid metal coolants instead of water and with SiC inserts in the blanket. It is based in the Dual Coolant concept of the Power Plant Availability study. These two facts have the effect of removing the costs due to C-14 produced from water coolant in plant model 2 and increasing the efficiency of the plant up to 45% with an electrical output of 1.5GW.

Model 6 is very similar to model 3 but with SiC replacing steel. It is based in the Advanced Ceramic Breeder concept of the Power plant Availability Study that was also the basis of power plant model 3.

Armour materials are only present in plant model 5 since plant models 4 and 6 have SiC first walls that do not need armour coating.

All the aspects of the plant outside the in-vessel shield are assumed to be invariant between the three models. The new models 4,5 and 6 are speculative to a greater extent than plant model 1, 2 and 3 since they are based in blanket designs that are not developed in detail (Taylor and Sublet, 1999).

Removable blanket modules lifetimes are assumed to be 5 full power years. Divertor replacements are assumed to occur at 20 full power month intervals and fixed components have a useful lifetime of 25 full power years.

The main technical information relevant to the assessment of externalities during the upstream and power generation stages is summarised here:

- Safety: The main impact of SiC on safety is its very low decay heat. Then the introduction of SiC serves to improve the safety further from the previous models.
- Activation of materials: The use of SiC/SiC reduces the C-14 generation in structural materials substantially. This can be half the level of production of a steel plant. Introducing a martensitic steel shield would allow further reduction in C-14 generation. Plant model 6 with tritium generating material that does not contain oxygen has the lowest production rate of C-14.
- Material issues: Due to the low density of SiC/SiC (3 times lower than steel) the mass of material used is lower than in a steel plant. On the other hand recycling of silicon carbide is less easy.
- Efficiency: The use of silicon carbide is expected to allow a higher coolant temperature, higher thermodynamic efficiency and therefore higher electrical output. An electrical power of 1.5GW is considered in the three cases.
- Occupational radiation exposure: Since none of the new models incorporate water coolant this exposure is not expected to be significant.
- Releases during normal operation. No new work has been performed in the area and therefore the routine emissions available for plant model 1 will be used for the new plant models (Ward, 2002).

4.1.2 Externalities of upstream and power generation stages

Externalities of upstream and power generation stages of the fusion fuel cycle have been assessed by CIEMAT. The main findings are summarised in this section, and further details can be found in Lechón and Sáez, 2002.

Upstream stages considered in this study are the manufacturing of the necessary materials and the construction of the power plant.

Materials manufacturing

Silicon carbide (SiC) fibres reinforced SiC matrix (SiC/SiC) composites have been developed for fusion application. The attractiveness for fusion comes from its high temperature strength, pseudo-ductile fracture behaviour and low induced radioactivity under fusion environment (Kohyama et al,).

The manufacturing process of silicon carbide has been investigated in order to estimate the external costs associated to this material.

SiC fibres are available form different companies: Nycalon S from Nippon Carbon and Tyranno SA from Ube industries. In order to make composites of high density several techniques are used: Forced chemical vapour deposition (FCVD), polymer impregnation and pyrolysis PIP and reaction sintering (RS).

Silicon carbide does not occur naturally and must be synthesised by high temperature chemical reaction. High quality silica, carbon source (usually petroleum coke) and electricity (23,8MJ/kg) are the major ingredients in the production of silicon carbide. The manufacture is carried out in an Acheson furnace. The reaction requires about 2-3 days. When it is complete the result is silicon carbide and a quantity of unreacted material. The silicon carbide is selected for purity and is crushed and classified (Mineral Resources, 1997).

In order to achieve SiC fibre capable to be used at temperatures as high as 1700 degrees, a new technique has been developed at JAERI (Japan Atomic Energy Research Institute): polycarbosilane fibre is irradiated in a helium atmosphere with electron beams. The irradiation produces cross-linkings between carbosilane polymers and makes them suitable to fabricate SiC fibres (Seguchi et al, 1993).

The fabrication of SiC fibre reinforced SiC composite by polymer impregnation and pyrolisis has been changed at JAERI to introduce EB irradiation. Also polyvinilsylane (PVS) has been incorporated into the precursor polymer. Polycarbosilano (PCS) and PVS are dissolved as slurry and impregnated into SiC fabric. After impregnation the composite is irradiated by electron beam for curing of polymers. The cured polymer in the composite is converted into ceramics by pyrolysis through firing process.

Information regarding emissions and energy use in the process of fabrication of SiC/SiC composite is scarce. Information on emissions and energy use of the production of SiC powder has been gathered from AP-42 and IPCC (Houghton et al, 1996). Emissions in other stages of the fabrication process of SiC/SiC could not be found.

Assessment of external impacts related to the energy use and emissions in the production and manufacture of materials for the fusion power plant was performed by RIS∅ National Laboratory of Denmark in the first phase of the SERF project using current energy system data of Denmark. Results of this assessment have been used here. Complete calculation procedures and details on the methodology followed can be found in appendix C of Sáez et al, 1999.

Once the emissions associated to this stage of the fuel cycle have been estimated, the external costs are calculated using the values recommended in the ExternE transport project for the assessment of LCA impacts (Friedrich and Bickel, 2001) expressed in EURO/t of pollutant emitted for SO_2 and NO_x, and for CO_2 the values recommended for these impacts by the ExternE methodology (Krewitt, 1999).

The effect of the introduction of SiC/SiC composite replacing steel has been evaluated taking into account the amount of steel replaced by SiC/SiC in each of the models. Taking into account the difference in the emission factors of steel production and SiC/SiC production, the differences in external costs calculated are:

Model s 4 and 6: 1,35e-04 mEuro/kWh less

Model 5: 6,65e-05 mEuro/kWh less

These differences are, as expected, not significant.

SiC/SiC composite is much less amenable for recycling than steel. However, no consideration of the possibility of recycling is taken into account in this assessment of external costs of manufacturing of materials. Therefore, the effect of using SiC/SiC composite instead of steel in the reduction of the possibilities of recycling is not considered.

External costs obtained for the manufacturing of materials of the new models are:

- Model 4: 3.33E-02 [9,38e-02]
- Model 5: 3.34E-02 [9,38e-02]
- Model 6: 3.33E-02 [9,38e-02]

Expressed between square brackets are the external costs calculated considering the CO_2 abatement costs of 19 Euro/t of CO_2.

Construction of the power plant

It has been estimated that the construction of the fusion power plant considered will last approximately 12 years. Along these years there are no radioactive materials present, and so no radiological risks will be included in this section.

The population that is mainly at risk are the workers involved in the construction, so the occupational impacts should be taken into account. Other risks are expected due to the transportation of the necessary materials.

Transport of construction materials

The amount of replacement materials is included within the construction materials, and their impacts are evaluated together. The amount of construction materials is shown in the following table:

Table 4. Amount of construction materials

	Steel (t)	Concrete (t)	Earth (t)	Others
Model 4	3.24E+05	6.82E+05	1.22E+06	4.14E+04
Model 5	3.31E+05	6.82E+05	1.22E+06	3.95E+04
Model 6	3.24E+05	6.82E+05	1.22E+06	1.88E+04

The assumptions regarding transport modes and distances are the same as in previous SERF2.

Damages produced by the atmospheric emissions of transport vehicles

In order to estimate the damages produced by the emissions of this transport stage, results from the ExternE Transport project have been used (Friedrich and Bickel, 2001).

The marginal damages used for the estimation of external costs of transport activities are the following:

- 0.70 EURO/100t.km for a diesel HDV type EUROII
- 0.05 EURO/100 t.km for a electric goods train

The resulting damages considering our transport necessities are shown in Table 5

The effect of considering abatement costs for global warming emissions instead of damage factors could not be assessed in this stage since the considered marginal damages for the different modes of transport include the global warming effect in a non desegregated way.

Damages produced by traffic accidents

In fact, the transport of construction material implies an increase in the traffic intensity that may lead to an increase in the number of deaths and injuries due to road accidents. Accident rates for Germany were taken from the ExternE study of Coal and Lignite (EC, 1995b) in the same manner as it was made in previous SERF1 and 2. Results are shown in Table 5.

Occupational accidents

The potential impacts in the occupational domain fall into two general categories, accidents and diseases. As there are not available statistics concerning power plant construction, the impact should be estimated with indirect methods. National economic data and the total cost of construction could be used to estimate the workforce involved. Accident statistics of the compensation societies can be used to estimate the expected risks per person-year. Details on the methodology used to estimate occupational impacts can be found in Sáez et al, 1999. Results obtained updated with the new efficiencies of new models are shown in Table 5.

Summary of upstream stages

Upstream stages of the fusion fuel cycle analysed in this study are the manufacturing of materials and the construction of the power plant. These stages have external costs associated of around 0.196 mEURO/kWh. From this figure, the materials manufacturing stage is responsible for approximately 18% of these externalities and the construction of the power plant is responsible for the 82%. In the construction of the power plant most of the external costs are related to occupational accidents produced in the building activities.

Table 5. Summary of external costs of upstream stages

		Model 4 (mEURO/kWh)	Model 5 (mEURO/kWh)	Model 6 (mEURO/kWh)
Manufacturing of materials		3.33E-02 [9.38E-02]	3.34E-02 [9.38E-02]	3.33E-02 [9.38E-02]
Transport of construction materials	Damages from atmospheric emissions	3.07E-03	3.08E-03	3.00E-03
	Traffic accidents	2.78E-03	2.79E-03	2.75E-03
Building activities	Occupational accidents	1.57e-01	1.57e-01	1.57e-01
Sub Total		***0.196 [0.256]***	***0.196[0.256]***	***0.196[0.256]***

Expressed between square brackets are the external costs calculated considering the CO_2 abatement costs of 19 Euro/t of CO_2.

Power plant operation

Atmospheric and aquatic routine releases

No new work has been performed in the area and therefore the routine emissions available for earlier models are applied to the new ones. There are emissions for plant models 1 and 2. It is considered that plant model 1 emissions are applicable to plant models 4, 5 and 6. Although plant model 5 is fairly similar to plant model 2, it is considered that the emissions of the later model are in the major part due to the use of water as coolant. Plant model 6 is refrigerated with helium and liquid metal, so it is considered that its releases will be more similar to those of plant model 1 (Ward, 2002).

Therefore the calculation of doses and associated external costs performed for plant model 1 are relevant to the new plant models adjusting them for the new efficiencies of the power plants. Details on the calculations of this doses and external costs can be found in Sáez et al, 1999 and CIEMAT, 2001.

External costs due to local dispersion of radioactive releases from the power plants are summarized in Table 7.

The external costs calculated produced by the global dispersion of H-3 and C-14 releases to atmosphere from the fusion power plants are shown in Table 6. Results have been calculated taking into account two integration periods, 10000 years and 100000 years, and two discount rates 0% and 3%. Results corresponding to 10000 years and 0% discount rate will be the ones comparable to the results of the ExternE project for the nuclear fuel cycles.

Table 6. Damages and costs of the global dispersion of C-14 and H-3 (mEuro/kWh).

Discount rate	0%		3%	
Integration period	10000 years	100000 years	10000 years	100000years
C-14	2.06E-05	3.11E-05	9.01E-07	9.01E-07
H-3	6.43E-02	6.43E-02	2.44E-02	2.44E-02
Sub-Total	**6.43E-02**	**6.43E-02**	**2.44E-02**	**2.44E-02**

In these models, the reduction attained in the emissions of C-14 from the use of different materials and cooling media has produced as a consequence that the global effect of the releases of C-14 are negligible and the effect of tritium releases are much more important.

The consideration of two different integration times does not have a noticeable influence in the result since H-3 does not produce any additional dose after 10000 years and C-14 effect is negligible.

Occupational health

The impact pathways considered in the occupational domain are direct exposure to radiation during working hours and the statistical probability of occurrence of occupational accidents.

Occupational doses

The occupational doses considered from the normal operation of the new plant models are those calculated for plant model 1 in the SEAFP-2 project (Cook et al, 1999) and equal to 0.18 man.Sv/year. The expected external costs resulting from the total occupational exposure are reported in Table 7.

Occupational accidents

Non radiological impacts of the normal operation of the fusion power plant are due to occupational accidents leading to deaths or injuries in the workforce of the power plant not related to the radiological exposure. In order to estimate this kind of impacts, statistical observations of the number of accidents occurring at power plants are currently used by the methodology. In the case of fusion power plant, these data are of course not available since we are considering a hypothetical power plant operating in the next century. An approach could be the consideration of the same accident rate as nuclear fission plants.

Using accident statistics of nuclear power plants in Germany obtained from the ExternE National Implementation Project (EC, 1999d) expressed in number of cases per TWh the external costs can be calculated. Results obtained are summarised in Table 7.

Summary of the normal operation stage

In Table 7 external costs estimated for the operation stage of the fusion power plant are shown. External costs of the power generation stage are dominated by the global dispersion of H-3, followed by those produced by occupational accidents in the power plant and the occupational exposure of the work force. Radiological effects of routine releases other than tritium have a negligible influence in the external costs produced.

Table 7 Summary of external costs of the power generation stage of the fusion fuel cycle expressed in mEuro/kwh.

				0%	3%
Power plant operation	Radioactive emissions	Local	Inhalation	2.69E-04	2.01E-04
			External exposure from the cloud	6.83E-08	5.09E-08
			External exposure from the ground	1.47E-10	1.10E-10
			Ingestion	1.52E-09	1.14E-09
		Global		6.43E-02	2.44E-02
	Occupational exposure			3,12E-03	2.46E-03
	Other occupational accidents			9.85E-03	9.85E-03
Sub-Total				**0.08**	**0.04**

Summary of external costs of upstream stages and power operation stage

In Table 8 all the components of the external costs produced in the upstream stages and power generation stage of the fusion fuel cycle are summarised. Total costs amount for 0.28mEURO/kWh for the three plant models since differences among them are negligible.

Upstream stages are the dominant cause of external costs as it can be seen in Figure 1.

Within upstream stages, occupational accidents in the construction of the power plant are the prevalent causes of external impacts. Energy use and emissions in the manufacturing of materials produces also noticeable external costs. It is important to note that these impacts have been estimated on the basis of the current energy mix. Future energy systems composed of cleaner technologies could have lower emissions associated, and therefore the external costs associated to this stage could decrease accordingly.

Radiological effects in the local range due to the routine emissions from the power plant have a little effect in the subtotal external costs figure in the stages analysed.

Collective doses from the global dispersion of H-3 produce also high external costs.

Since radiological effects of the emissions of the power plant on the general public are very reduced, occupational aspects become important. Especially noticeable are those not related to the radiological exposure such as accidents in the construction and operation of the power plant. It is important to stress that these external costs have been calculated on the basis of accident statistics in the several sectors involved in the construction of the power plant for the year 1995. Accident rates could decrease considerably by the year 2050 when the construction of the power plant would start, reducing accordingly the external costs produced.

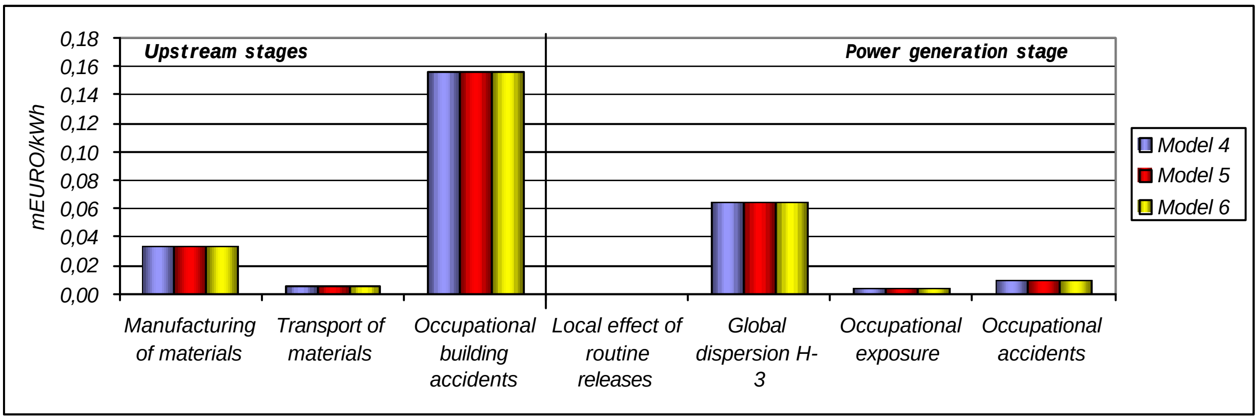


Figure 1. External costs of upstream and power generation stages.

Table 8. Summary table of external costs of the upstream and power generation stages of the fusion fuel cycle in mEuro/kWh (0% discount rate and 10000 years integration time).

Stage	**Burden**			**Model 4**	**Model 5**	**Model 6**
Materials manufacturing				3,55E-02 [9.38E-02]	3,55E-02 [9.38E-02]	3,55E-02 [9.38E-02]
Transport of construction materials	Damages from atmospheric emissions			3,07E-03	3,08E-03	3,00E-03
	Road accidents			2,78E-03	2,79E-03	2,75E-03
Building activities	Occupational accidents			1,57E-01	1,57E-01	1,57E-01
Power plant operation	Routine emissions	Local	Inhalation	2,69E-04	2,69E-04	2,69E-04
			External exposure cloud	6,83E-08	6,83E-08	6,83E-08
			External exposure ground	1,47E-10	1,47E-10	1,47E-10
			Ingestion	1,52E-09	1,52E-09	1,52E-09
		Global		6,43E-02	6,43E-02	6,43E-02
	Occupational exposure			3,12E-03	3,12E-03	3,12E-03
	Other occupational accidents			9,85E-03	9,85E-03	9,85E-03
Sub-Total				***0.27 (0.07-1.06) [0.33 (0.09-1.37)]***	***0.27 (0.07-1.07) [0.33 (0.09-1.37)]***	***0.27 (0.07-1.06) [0.33 (0.09-1.37)]***

68% confidence intervals are shown in brackets. Expressed between square brackets are the external costs calculated considering the CO_2 abatement costs of 19 Euro/t of CO_2.

Consideration of a discount rate of 3% reduces the external costs to 0.23 mEuro/kWh.

4.1.3 Externalities of decommissioning and site restoration

Externalities of the decommissioning and site restoration phase of the fusion fuel cycle have been assessed by Studsvick Eco&Safety AB. The main findings are summarised in this section, and further details can be found in Aquilonius and Hallberg (2002).

Decommissioning phase includes radiological decontamination of the plant and demolition of the buildings, interim storage during 100 years and transport of waste to final repositories and recycling. External costs due to routine replacement of materials during normal operation were also considered in this stage.

Radioactive components will be kept in an intermediate storage at the site up to 100 years, although material might be recycled continuously, as the radioactivity of different parts become lower than the safety limit set by authorities.

Description of activities

Decommissioning

The activities of decommissioning consist of:

- decontamination, i.e. cleaning of radioactive contaminated material,
- removal of components and material,
- demolition of buildings,
- preparations for recycling,
- transport to intermediate and final storage.

Two main types of radioactive material are present, firstly neutron activated components in the reactor and, secondly, the main group of material contaminated by tritium. The plant will contain buildings and equipment for handling and decontamination of those active components during operation.

Decommissioning of a nuclear facility will start with chemical and physical decontamination as regards radionuclides. The purpose is to rinse contamination from the surface of components and buildings. This is done in order to be able to recycle material, and to reduce the amount of radioactive waste. Two main principles can be identified: mechanical and chemical. Mechanical decontamination is for example blasting, while with chemical methods the contaminated material is dissolved in chemical solutions. The decontamination activities include management of radioactive waste.

Radioactive waste management

Two scenarios have been considered. In the first, waste is treated according to present practice, and only the non 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, up to 100 years [Brodén and Olsson, 2001].

In the second future prospective scenario, the calculations were based on criteria reported in Rocco and Zucchetti, 1998. According to these criteria, 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, 4, 7 and 14 % (PM5, PM6 and PM4, respectively) of the total waste volume was considered as waste for final disposal [Rocco *et al*, 2001].

An overview of the assumed handling of high-level tritiated and neutron-activated radioactive waste is given in Figure 2.

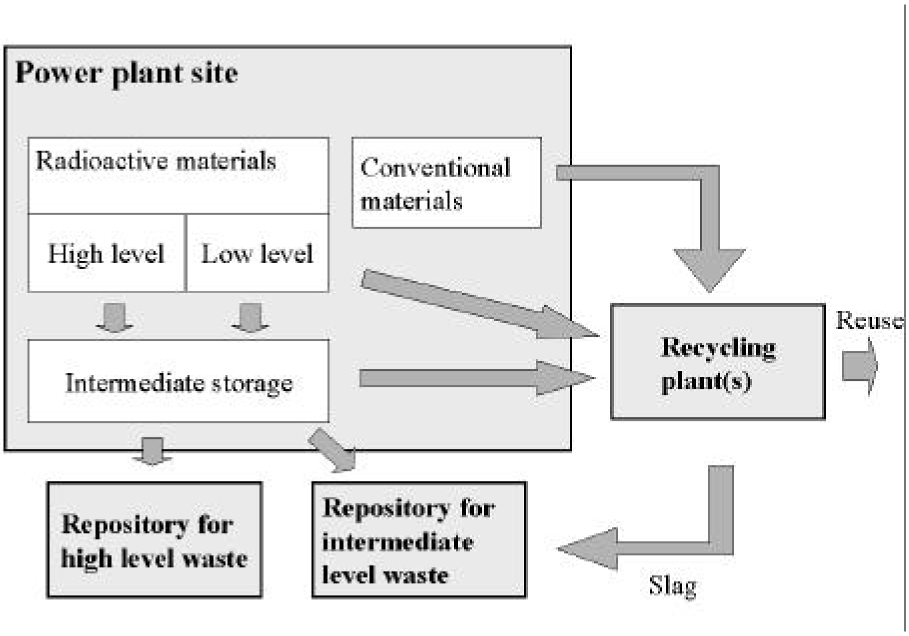


Figure 2. A schematic picture of radioactive waste management of a commercial fusion plant.

Separate 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.

A probable distribution of fusion waste, in the present practice (PP) scenario, will be that the shield, blanket, first wall and divertors will be taken to Gorleben, while the vacuum vessel and toroidal field coils will be transferred to Konrad [Brodén and Olsson, 2001].

In the Rocco and Zucchetti (RZ) scenario only Gorleben will receive waste for final disposal.

Recycling

Several recycling schemes for activated parts have been suggested, one of which proposes using recycled fusion components when building new fusion reactors (RZ). This leads to different scenarios as regards material streams for activated recyclable parts and "common" recyclable parts. The regulations regarding transports and handling of radioactive materials will govern how they are treated. Some components will be possible to recycle only after up to 100 years of cooling, during which it must be stored. Even after that, some parts may have to be taken to final repositories. This amount varies between designs.

Non-contaminated and decontaminated materials may be 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. The activities include segmentation, packaging and transportation to one or more recycling plants.

Recycling of waste material was assumed to take place at a site somewhere in the EU together with the facility for manufacturing of new fusion plant components. A conservative assumption was made, that recycling and manufacturing will take place quite far from the site at Lauffen am Neckar, within the range of 1 000-2 000 km.

Site restoration

A summary description of how site restoration may be achieved is given in this section. There are possibilities to reuse some of the buildings for new activities, after decommissioning. If all, or some, of the buildings are taken into use, external costs will be less than those calculated in this report. As a conservative assumption, however, it was assumed that the site should be restored to conditions similar to those before the building started.

In order to prepare for the building works, large excavations will be made. The earth and rock so removed can either be kept at the site throughout the time of operation, or be transported away. When it is time to restore the site, buildings will be demolished, and building materials transported for recycling or to depositories. The excavations need to be filled, e.g. with fresh rock, but there is also a possibility to use concrete from the buildings. This is the most probable approach, because it saves transport costs. Lastly, topsoil will be added to landscape the site, whereupon vegetation will be replanted.

Impacts considered

Occupational accidents and diseases

Occupational hazards on site were estimated similarly as was made for fission power, see EC, 1995c. This was done indirectly from data about accidents and diseases per person-year, the number of which was determined from the part of this cost that pertains to replacement of components and decommissioning, cf. Appendix A.

Release of effluents and traffic accidents during transport

Transport will be in heavy radiation-shielded containers that are designed to withstand even high-speed collisions without breaking. There is vast experience of radioactive waste transport in the European countries. Radiological impact from transports is therefore assumed to be negligible in this report.

Transport vehicles will cause releases to air, noise, and an increased number of accidents. Impact due to noise is not treated here. Releases to air will consist of the off-gases from vehicles used for transport, mainly NO_x, CO, HC and particles.

The ExterneE methodology for estimation of external costs of transports were used generally in this study and a case study of Germany specifically [Friedrich and Bickel, 2001]. Exposure-response functions for public health, impact on agriculture and deterioration of materials were applied. The damage cost per kilometre for different types of vehicles was given. Only heavy lorries or trains are feasible for the transport of radioactive material. In order to cover the inherent uncertainty in the calculated values for damage costs, the whole range from electric goods train to lorry was applied.

Increased number of traffic accidents due to transports was considered in EC, 1995b, the methods of which were employed in this report. Accident rates regarding deaths, major accidents, and minor accidents were given per tonne-km, and the value of a statistical life (VSL) was used to compute the external cost of deaths. Costs for injuries were likewise taken from ExternE studies.

Release of dust and radioactivity from recycling plants to air

Concentration of particles for each point in a 100 by 100-km grid, with a 5-km grid-point distance, was computed using a straight-line gaussian plume model [Pasquill and Smith, 1983]. A yearly average concentration for each grid point was then found by weighing with the frequency of occurrence for different weather conditions. The particles were assumed to be in the PM10 range, i.e. they are small enough for their gravitational settling to be negligible compared to the action of turbulent diffusion. This is a conservative approach, because heavy particles will not be inhaled.

External costs for concentration in air of TSP (totally suspended particles) around a fictive coal fired plant in Lauffen have been calculated by EC, 1995b. Acute and chronic public health impacts were considered, e.g. hospital admissions and bronchitis. The results of that study were then scaled with the ratio between the concentration obtained in this study and the ExternE study. Allowance for different operation time of the recycling plant divided with that of the coal-fired plant was made in the same manner. It is of course not strictly correct to assume that the recycling plant should be located in Lauffen, but it will probably give a reasonable approximation for German conditions. Mid estimates of local and regional external costs for primary PM10 were used.

The dose to the most exposed individual due to release of radioactivity to air from the Studsvik recycling plant for radioactive materials is calculated on a yearly basis. External exposure from the radioactive cloud and activity deposited on the ground, as well as internal exposure due to inhalation and intake of food and water are considered, see Bergström and Nordlinder, 1991. For intake, the dose commitment integrated over 50 years is computed.

The individual dose for the recycling plant was estimated by scaling with the ratio of processed amounts of the Studsvik melting plant and the recycled amount of fusion waste. The collective dose was then found by multiplying the individual dose with the population around Lauffen. External costs were then calculated by using estimations of the occurrence of fatal cancers, non-fatal cancers, and severe hereditary effects per manSv [EC, 1995b] as well as monetary values for these categories [Ciemat, 2000].

Global doses due to release of carbon-14

The nuclide C-14 deserves special attention because it enters the global carbon exchange, and thus causes global exposure. The estimated amount of C-14 in the activated material for two of the plant models (PM4 and PM6) [Ward, 2001], was after 100 years of decay normalised to the amount recyclable material for the two scenarios and respective plant model. For PM5, the amount was found by using the estimated amount of C-14 in the activated material for plant model 2 (PM2) [Brodén *et al*, 1998], since PM5 is analogous to PM2 except for the coolant [Ward, 2001]. The collective effective dose commitment, integrated over up to 100 000 years, was calculated according to the methodology used in EC, 1995c. External costs due to release of C-14 during recycling were then calculated by using estimations of the occurrence of fatal cancers, non-fatal cancers, and severe hereditary effects per manSv [EC, 1995b] as well as monetary values [Ciemat, 2000].

Results

Decommissioning

Impact of occupational accidents and diseases as well as impact of transports were considered. Estimates of external costs for decommissioning are given in Table 10.

The decommissioning phase is completely dominated by the external costs for occupational accidents and diseases which, since this cost is the same for all models and both scenarios, implies that the resulting total cost is the same for all models and both scenarios.

Recycling

Removable blanket module lifetimes are assumed to be 5 full power years. Divertor replacements are assumed to occur at 20 full power month intervals and fixed components have a useful lifetime of 25 full power years. Amounts of activated recyclable waste and cleared recyclable waste for the present practice scenario were estimated by Brodén and Olsson, 2001, while the corresponding data for the future prospective scenario was found in Rocco *et al*, 2001.

Residue from the recycling (slag and filters) is radioactive, and transports to Konrad for final storage should then be the case. The amount is small compared to that of the decommissioned materials, and the external costs due to transport of slag were therefore deemed to be negligible.

For the Rocco and Zucchetti scenario (RZ), an average transport distance of 1 500 km, with a range from 1 000-2 000 km was assumed for activated waste.

External costs due to transport of conventional materials as well as recyclable cleared radioactive waste from the fusion power plant site to a recycling plant were also calculated. However, in this case the transport distance was set to vary between 100 and 300 km, since conventional recycling plants are more common.

Meteorological data [Lechon, 1998], representative for the Lauffen area, was used to calculate atmospheric dispersion statistics

Data about radioactive releases to air was found in Sandell, 2001. The collective dose was found by multiplying by the number of inhabitants in the local scale around Lauffen (3 839 020 in a 10 by 10 km grid). Estimates of occurrence of cancer and severe hereditary effects per collective dose were found from EC, 1995c. Impact-cost factors were taken from Ciemat, 2000.

It was assumed that C-14 was released in proportion to the content in the materials. The estimated amount of C-14 in the activated materials for the three different plant models, after 100 years of decay, was normalised with the amount of recyclable material for the two scenarios and respective plant model. Data from a recycling plant at Studsvik RadWaste (Chyssler *et al*, 1998) were used to estimate the fraction of dust that is released during recycling.

The global collective effective dose commitment, integrated over 100 000 years, was calculated according to the methodology used in ExternE [EC, 1995c]. External costs due to release of C-14 during recycling were then computed by using estimations of occurrence of fatal cancers, non-fatal cancers, and severe hereditary effects per manSv [ExternE, EC, 1995], as well as monetary values [Ciemat, 2000], see Table 9.

Table 9. External costs, for release of C-14 during recycling of waste from three different plant models, in two scenarios: present practice scenario (PP) and future prospective scenario (RZ). The costs are given in mEuro/kWhe.

	Present practice scenario (PP)			Future prospective scenario (RZ)		
Time after release (years)	PM4	PM5	PM6	PM4	PM5	PM6
10	8.5E-06	6.0E-05	1.7E-05	2.1E-05	1.6E-04	4.5E-05
100	1.9E-05	1.3E-04	3.7E-05	4.6E-05	3.6E-04	1.0E-04
1 000	4.9E-05	3.4E-04	9.4E-05	1.2E-04	9.3E-04	2.6E-04
10 000	1.4E-04	9.7E-04	2.7E-04	3.4E-04	2.6E-03	7.3E-04
100 000	***2.1E-04***	***1.5E-03***	***4.1E-04***	***5.1E-04***	***4.1E-03***	***1.1E-03***

Estimated external costs for recycling are summarised in Table 10.

External costs due to release of dust during recycling are the dominating contributors during recycling, in both scenarios.

Site Restoration

The case of total demolition of the buildings and restoration of the site is used in this study, i.e. activities that will restore the site to conditions as similar as possible to the original state.

Soil will be excavated when building the plant. Some of the excavated material will be back-filled. The net amount has been estimated at about 811 000 m^3 [Hamacher, 1998]. This volume will after demolition have to be filled out, and vegetation replanted.

External costs of occupational accidents and releases for restoring the site to conditions as they were before the building of the plant were judged to be negligible. External costs due to release of effluents and increased number of traffic accidents during transport of filling materials were considered.

Externalities of site restoration have been described and calculated in Hallberg and Nordlinder, 1998, and is not treated in this report, except for recalculations using a range of external costs due to transport of filling materials and calculations for the additional plant model. Estimates of external costs of the considered aspects of the Site Restoration Phase are given in Table 10.

Summary of external costs of decommissioning and site restoration stages

External costs for decommissioning and site restoration calculated are summarised in Table 10 below.

Table 10. Normalised external costs (mEuro/kWhe), for the present practice scenario (PP), and the future prospective scenario (RZ).

	PP			RZ		
	Median	Min	Max	Median	Min.	Max
		Decommissioning				
All models	0.26	0.08	0.82	0.26	0.08	0.82
		Recycling				
PM4	0.053	0.028	0.091	0.067	0.037	0.11
PM5	0.054	0.028	0.091	0.081	0.037	0.12
PM6	0.053	0.028	0.091	0.059	0.037	0.10
		Site Restoration Phase				
All models	1.0E-03	6.4E-04	1.5E-03	1.0E-03	6.4E-04	1.5E-03

By and large, there is little difference between plant models and waste handling scenarios. Comparing with earlier results for PM1-3 [Aquilonius and Hallberg, 2000], we note little difference: about 0.01 mEuro/kWhe higher recycling external costs for PM 4-6.

Decommissioning, i.e. decontamination, removal of components and material, demolition of buildings, preparation for recycling and transport to storage, is the phase with the highest external cost, mainly due to the high costs for occupational accidents and diseases.

4.1.4 Externalities of waste disposal

Externalities of waste disposal have been assessed by VTT. Main findings are summarised below and further details can be found in Korhonen, 2002.

Disposal cases studied

Radioactive waste is assumed to be disposed in geologic repositories and different disposal options have been considered. Releases due to disposal to the biosphere can in a relatively simple way be calculated by using two time parameters: 1) when the release begins, 2) the duration of the release (material is assumed to be diluted by a constant rate). Three release cases are constructed and the assumptions from the SEAFP study are also considered.

Waste is disposed in packages so that releases of radionuclides to the groundwater are delayed some time, as packages have first to be broken. If copper canisters are used as packages it can take millions of years before groundwater reaches wastes and releases begin. The form of waste (e.g. metal, ceramic waste) also influences the time that radionuclides take to be released from repository. Activation products in stainless steel are assumed to be released relatively easily in some thousand years also in deep repositories if they are in contact with groundwater flow. If buffering materials are used retention of radionulclides is increased. In the case of C-14 concrete is an effective retention material. Bentonite could also be used. However, shield materials of about 10000 tons are not easily packed in copper or bentonite.

Part of C-14 inventory will be in SiC structures. Ceramic materials will retain radionuclides longer than steel.

After that the release begins groundwater flow takes time to reach the biosphere. Radionuclide migration could still cause that part of nuclides doesn’t reach the biosphere. Of course nuclides decay during these processes. To simplify, migration is not considered to cause any final dispersion of radionuclides. Steady-state situation for biospheric transfer is often assumed. This assumption is relevant if emissions continue at a constant rate for long time spans. It also depends very much on the considered nuclide and space scale. Steady-state condition can require even one million year in some cases /Korhonen 1991/. In the local scale steady-state assumption is often more relevant than in the global scale.

Local scenarios presented are similar to those used in the safety analysis of disposal of spent fuel and decommissioning waste from Finnish nuclear power plants. In the local scale generally two well scenarios are considered. A small local well is considered. Drinking water from the well is the dominant dose pathway, but also irrigation has been considered /Vieno et. al. 1993b/. A small lake could also be studied. Individual doses would be lower for that case. The population of the well scenario (a small well, relatively small flow) is smaller than the population when the scenario of contaminated lake water is considered.

In this study regional scale (North Sea) is not considered. A simple model for accumulation into ocean and caused collective doses in the global scale is used for Nb-94. Doses due to C-14 are estimated using a global carbon cycle model.

Inventories

In Table 11 some important activation product nuclides are given (UKAEA 2002). The inventories in wastes correspond to the lifetime electricity production in a 1500 MW fusion plant. Important nuclides are C-14 and Nb-94. Only these two nuclides are considered in the impact calculation.

Shield materials are estimated to include relatively high amounts of C-14. The decrease of C-14 inventories is relatively small in the model designs using silicon carbide structures. Also carbon in SiC can activate into C-14 and then also activation in shield can be more efficient due to increased neutron flux in shield. Tritium generating materials include oxygen, which also activates into C-14 and has some impact on inventories. In the case of Model plant 4 the C-14 production in the shield will be so low, that total C-14 inventory will decrease.

Inventories of Nb-94 have been also considered (UKAEA 2002).

Table 11. Some important nuclides in fusion waste.

Nuclide	Half-life (a)	Inventory of Model plants 4 - 6 (Bq) Model 4	Model 5	Model 6
C-14	5700	$0.40 \cdot 10^{15}$	$0.73 \cdot 10^{15}$	$0.81 \cdot 10^{15}$
Nb-94	20000	$1.06 \cdot 10^{13}$		$1.4 \cdot 10^{13}$

Assumptions concerning release period

Four release cases are considered and also for C-14 an additional “case 0” with no initial retention has been evaluated. Cases 1 – 3 have been estimated by using assumptions from the Finnish safety analysis experience for the nuclear decommissioning waste. Concrete, sand and bentonite are assumed to be used to cause retention. The important barriers in the case of C-14 are concrete and such conditions that the water flow rate is small. Cases include also the SEAFP study case assumption (last case) about the releases (Broden and Olsson 1994).

In the case 0 releases start immediately after closure of repository and continue 10000 years. The impact to the total C-14 amount released (and collective doses) is rather small, when compared with no retention at all. Impact on dose rates (individual or collective) is much more marked.

In the first case releases are assumed to begin 20000 years after disposal and to continue 10000 years. As the half-life of C-14 is 5700 years, this causes that about 5 % from the initial activity will be released from the repository in the case of release period 20000 - 30000 years (Table 12). As migration is not considered to cause retention, total releases to the biosphere are about 20 TBq (for Model plant 4) 36 TBq (Model plant 5) and 40 TBq (Model plant 6).

In the second case releases begin after 50000 years and continue 10000 years. Then only 0.13 per cent from initial C-14 inventory will reach the biosphere. In the third case a somewhat longer duration time of the release 25000 years is assumed. This case is used in reference /Vieno et.al. 1993/.

To simplify the same release cases 1 - 3 are also evaluated for Nb-94 (Table 13). Relatively high percentage of Nb-94 will reach the biosphere in studied three cases and disposal would have only a minor impact on possible collective doses.

Table 12. C-14 releases from repository to the biosphere when different release period assumptions (four/five different disposal cases) are used.

Release period	Amount released (percentage)	Total amount released (TBq)		
		PM4	PM5	PM6
0 – 10000	58.0	232	423	470
20000 – 30000	5.0	20.0	36.5	40.5
50000 – 60000	0.13	0.52	0.95	1.1
50000 – 75000	0.072	0.29	0.53	0.58
0 – 40000000	0.021	0.084	0.15	0.17

Table 13. Nb-94 releases from repository to the biosphere when different release period assumptions (four different release cases) are used.

Release period	Amount released (percentage)	Total amount released (TBq)		
		PM4	PM5	PM6
20000 – 30000	43	4.6		6.0
50000 – 60000	16	1.7		2.2
50000 – 75000	12	1.3		1.7
0 – 5000000	0.58	0.06		0.08

In the early SEAFP-study it has been assumed that duration time of C-14 releases from the repository to the rock is $40 \cdot 10^6$ years /Broden and Olsson 1994/. The retention time in geosphere is assumed to be only some hundred years. The relatively long release time span causes that C-14 has time to decay so that only 0.021 per cent will reach the biosphere (Table 12). Conditions in disposal place should in the considered case be very unfavourable for ground water flow and other factors causing solubility as shield material (stainless steel) otherwise would be diluted more effectively. Also the use of effective technical barriers is necessary if these conditions are assumed. In SEAFP-study situation where releases to the biosphere begin rather soon after the disposal were studied but the assumption about the long duration time of the release impacts the total release effectively. In this study also less favourable conditions in disposal have been estimated.

Results

Local scale estimates

The biospheric modelling applied uses simple dose conversion factors, which are based on model studies at VTT (Korhonen and Savolainen 1984, Korhonen 1991, Vieno et. al. 1991, Vieno et al. 1993). The methodology has been tested in international cooperation in projects BIOMOVS and VAMP (NRPB 1991, IAEA 2000). In this study only drinking water from a local well has been considered.

The maximum individual doses due to C-14 release cases are presented in Table 14. When deep geologic repositories are assumed smaller dose conversion factors are applied than for shallower repositories.

The release of C-14 to the biosphere could be via well by using the considered first case release assumptions (release period 20000 - 30000 years) and will cause individual doses about 1 mSv/a (Model plant 4) and about 2 mSv/a. (Model plants 5 and 6). When dose conversion factors for deep repositories are applied individual dose rate for the Model 4 were 0.01 mSv/a and somewhat smaller for model plants 5 and 6. The dose limit according to Finnish regulations is 0.1 mSv/a /Vuori 1996/. So this case (release period 20000 - 300000 years) would be smaller than this limit if conditions for deep repository are assumed. The constraint 0.3 mSv/a by ICRP for natural processes is somewhat higher than the Finnish value.

When longer retention is caused dose rates decrease drastically in the case of C-14 already when 50000 years is assumed instead of 20000 years. Dose limits 0.3 mSv/a or 0.1 mSv/a are not exceeded in any considered case of Table 14.

The maximum individual dose in the case of third constructed case (release period 50000 - 75000 years) is only somewhat higher than in the case of SEAFP case (release period 0 - 40000000 years).

The value 10 mSv/a for human intrusion is about of the order maximal dose rates in the release period case 0 – 10000 years (“case 0”) and shallow repositories.

Collective dose integrated over the release period, when ten people are assumed to use the first well and hundred people are assumed to use the other more diluted well are given in Table 14. Dose rates in the well scenario are calculated using dose conversion factors from releases. If hundred people are assumed to use the well water (500 liters per year per person), then almost five per cent from the flow of the well were used for drinking. (The doses for irrigation pathways are not given. Also only some ten acres can be irrigated due to assumed water flow. If on the other hand more efficient water flow is assumed, more effective dilution is caused, but then a higher population amount could be assumed.) Collective doses and caused external costs are very small. Lake scenario might give individual dose rates at about the same level as the well scenario for C-14 as dose conversion factors in the case of a small local lake are estimated to be about at the level of considered well.

Table 14. Estimated maximum individual dose rates and local collective doses due to C-14 releases to the biosphere.

Release period	Individual dose rate (Sv/a)			Collective dose (manSv)		
	PM4	PM5	PM6	PM4	PM5	PM6
0 – 10000	$1.2\cdot10^{-4}$-$1.2\cdot10^{-2}$	$2.1\cdot10^{-4}$-$2.1\cdot10^{-2}$	$2.4\cdot10^{-4}$-$2.4\cdot10^{-2}$	67-670	130-1300	140-1400
20000 – 30000	$1.0\cdot10^{-5}$-$1.0\cdot10^{-3}$	$1.9\cdot10^{-5}$-$1.9\cdot10^{-3}$	$2.1\cdot10^{-5}$-$2.1\cdot10^{-3}$	5.8-58	11-110	12-120
50000 – 60000	$2.7\cdot10^{-7}$-$2.7\cdot10^{-5}$	$4.8\cdot10^{-7}$-$4.8\cdot10^{-5}$	$5.4\cdot10^{-7}$-$5.4\cdot10^{-5}$	0.15-1.5	0.28-2.8	0.32-3.2
50000 – 75000	$1.1\cdot10^{-7}$-$1.1\cdot10^{-5}$	$1.9\cdot10^{-7}$-$1.9\cdot10^{-5}$	$2.1\cdot10^{-7}$-$2.1\cdot10^{-5}$	0.084-0.84	0.15-1.5	0.16-1.6
0 – 40000000	$2.9\cdot10^{-8}$-$8.1\cdot10^{-6}$	$5.4\cdot10^{-8}$-$5.4\cdot10^{-6}$	$6.0\cdot10^{-8}$-$6.0\cdot10^{-6}$	0.024-0.24	0.044-0.44	0.044-0.44

Other important nuclides might be also Nb-94, Zr-93, Tc-99 or Ni-59 which have rather long half-lives. Only estimation of Nb-94 has been performed. The results for maximum doses are given in Table 15. The collective doses due to Nb-94 from the local scale are higher, especially in the cases of long term retention, or about of the same order than the C-14 collective doses.

Table 15. Estimated maximum individual dose rates and local collective doses due to Nb-94 releases to the biosphere and estimated local collective doses in four disposal cases.

Release period	Individual dose rate (Sv/a)		Collective dose (manSv)	
	PM4	PM6	PM4	PM6
0 – 10000	$9.0\cdot10^{-6}...9.0\cdot10^{-4}$	$9.0\cdot10^{-5}...9.0\cdot10^{-3}$	7.8-78	10.2-100
20000 – 30000	$4.5\cdot10^{-6}...4.5\cdot10^{-4}$	$5.9\cdot10^{-6}...5.9\cdot10^{-4}$	3.9-39	5.1-51
50000 – 60000	$1.6\cdot10^{-6}...1.6\cdot10^{-4}$	$2.1\cdot10^{-6}...2.1\cdot10^{-4}$	1.4-14	1.9-19
50000 – 75000	$6.3\cdot10^{-7}...6.3\cdot10^{-5}$	$8.3\cdot10^{-7}...8.3\cdot10^{-5}$	1.1-11	1.5-15
0 – 5000000	$1.8\cdot10^{-8}...1.8\cdot10^{-6}$	$2.4\cdot10^{-8}...2.4\cdot10^{-6}$	0.05-0.5	0.068-0.68

Global scale estimates

Global dispersion of radionuclides occurs, when radionuclides are transferred to global atmosphere, hydrosphere or terrestrial biosphere. This is possible especially in the case of easily transferred radionuclides as H-3, C-14 or I-129, which transfer between atmosphere and hydrosphere. Also other less mobile radionuclides might be globally dispersed due to deposition from the atmosphere or due to transferring to the oceans via rivers.

Two radionuclides are studied C-14 and Nb-94. C-14 is distributed among the reservoirs of the global carbon cycle: the atmosphere, the terrestrial biosphere and the hydrosphere. Doses are caused via ingestion of food from terrestrial biosphere. Nb-94 might be transferred to seas and might then accumulate into fish or other seafood.

Carbon cycle model has been built for the estimation of global transfer of C-14. Model structures are relatively simple compartment models. Compartment structure has been solved using model DETRA /Korhonen 1991, Suolanen and Iivonen 1998/ or by analytic calculations. Doses are assumed to be caused via ingestion of carbon in food. Concentrations in food are assumed to be in balance with the concentrations in atmosphere (C-14/C-12). Doses via inhalation and consumption of fish are relatively low. They give an extra dose of only a few per cent of the dose caused by ingestion of carbon in food (other than fish).

The global impacts of Nb-94 have also been estimated for model plant designs 4 and 6. For that purpose a simple analytic ocean model has been built. It includes ocean water and two sediment layers. Nb-94 will be transferred to the sediments. Dose impacts are assumed to be caused via ingestion of fish.

C-14

C-14 collective doses are estimated using integration factors: 93 manSv/TBq (integration over 10000 years) and 140 manSv/TBq (integration over 100000 years). They are in accordance with the used carbon cycle model used in dynamic calculations. Collective doses and external costs produced in the C-14 release cases are presented in Table 16 and Table 17.

Table 16. Estimated collective doses (global scale) for Model plant due to C-14 releases from waste repository in the cases of different release periods.

Release period	Collective dose (manSv) Model plant 4 Integration time		Collective dose (manSv) Model plant 5 Integration time		Collective dose (manSv) Model plant 6 Integration time	
	10000a	100000a	10000a 100000a	100000a		10000a
0 – 10000	22000	32000	39000	59000	44000	66000
20000 – 30000	1900	2800	3400	5100	3700	5700
50000 – 60000	49	73	88	130	98	147
50000 – 75000	28	40	49	74	54	82
0 – 40000000	7.9	12	14	21	16	24

Table 17. Estimated external costs (global scale) for Model plants due to C-14 releases from waste repository in the cases of different release periods.

Release period	External costs (mEuro/kWh) Model plant 4 Integration time		External costs (mEuro/kWh) Model plant 5 Integration time		External costs (mEuro/kWh) Model plant 6 Integration time	
	10000a	100000a	10000a	100000a	10000a	100000a
0 – 10000	12.9	19.5	23.6	35.6	26.2	39.5
20000 – 30000	1.1	1.7	2.0	3.1	2.3	3.4
50000 – 60000	0.03	0.04	0.05	0.08	0.06	0.08
50000 – 75000	0.02	0.02	0.03	0.04	0.03	0.05
0 – 40000000	0.005	0.007	0.008	0.01	0.01	0.01

Case 0 (release period 0 – 10000 years) is a case, in which water comes into contact with the disposed material immediatively and starts to dissolve material. External costs are rather high.

For case 1 (release period 20000 - 30000 years) and Model plant 4 collective doses are about 2000 manSv (integration time 10000 years) or 3000 manSv (integration time 100000 years). For Model plants 5 and 6 collective doses are about equal, 3500 manSv (integration time 10000 years) or 5000-6000 manSv (integration time 100000 years). Using monetarization in line with ExternE this would give for Model 4 external costs 1.1 mEuro/kWh (integration time 10000 years) or 1.7 mEuro/kWh (integration time 100000years). For Model 5 External costs would be 2.0 mEuro/kWh (integration time 10000 years) and 3.1 mEuro/kWh (integration time 100000 years) and 2.3 mEuro/kWh and 3.4 mEuro/kWh for Model plant 6. Results for release period case 20000 – 30000 years are rather high, at least for models 5 and 6, especially compared with the other components of fusion externalities.

For case 2 (release period 50000 - 60000 years) and Model plant 4 doses are already much lower, about 50 manSv (integration time 10000 years) or 70 manSv (integration time 100000 years) and somewhat more for 5 and 6. Using monetarization this would give for Model 4 external costs 0.03 mEuro/kWh (integration time 10000 years) or 0.04 mEuro/kWh (integration time 100000 years). For Model 5 External costs would be 0.05 mEuro/kWh (integration time 10000 years) and 0.08 mEuro/kWh (integration time 100000 years) and 0.06 and 0.08 mEuro/kWh for plant 6. For release case 3 costs are even lower: 0.02 – 0.05 mEuro/kWh.

The doses due to C-14 inventories using SEAFP assumptions (case 4) and ExternE dose factors are then very small. They are lower than in earlier cases, but disposal requires very much from technical barriers and other disposal conditions.

Nb-94

Use of silicon carbide structures in first wall and blanket causes, that the activated amount of Nb-94 is relatively small.

If released to sea Nb-94 accumulates more effectively than C-14 also when sedimentation is more effective than in the case of C-14. Accumulation of Nb-94 in ocean food chains is also more effective than accumulation of C-14. Carbon cycle is effective in causing doses via transfer from atmosphere to vegetation, thought. As diluting volume of C-14 is actually only the amount of carbon in the atmosphere accumulation into food is rather effective. Oceans are the main sink of C-14, but impacts via fish or other seafood are rather small.

About 3.5 TBq Nb-94 is estimated to accumulate in the ocean in case of Model 4 and release period 20000 – 30000 years, when accumulation of C-14 in the atmosphere is estimated to be about 0.3 TBq. For release period case 50000 – 75000 years about 0.7 TBq is estimated to accumulate maximally in the ocean in the case of Model plant 4 and somewhat more in the case of Model plant 6. Accumulation time in ocean is estimated to be relatively long. More than half from the total release accumulates maximally in the ocean in the release cases 1 – 3. The caused doses are very dependent on the assumed concentration to fish. In the parameter study of reference /IAEA 1994/ values ranging from 100 to 30000 l/kg have been given. Values are given for lake water only. The expected value for lake water 300 l/kg has been given.

Estimations of global impacts are given in Table 18. Integration has been performed over 100000 years. The upper range is caused when concentration factor 30000 (l/kg) is assumed. In that case a relatively high value 65 manSv/TBq (long term integration) will be caused.

Table 18. Estimated global collective doses and external costs due to Nb-94 releases to the biosphere estimated in four disposal cases.

Release period	Collective dose (manSv/a)		External costs (mEuro/kWh)	
	PM4	PM6	PM4	PM6
20000 – 30000	3-300	3.9-390	0.002… 0.2	0.002… 0.02
50000 – 60000	1.1-110	1.4-140	0.0006...0.06	0.0008…0.08
50000 – 75000	0.8-80	1.1-110	0.0005...0.05	0.0007…0.07
0 – 5000000	0.04-4	0.052-5.2	$2 \cdot 10^{-5}$..0.002	$3 \cdot 10^{-5}$...0.003

Doses and external costs due to Nb-94 are rather small also when integrated over long time spans. This is true also in the case of the upper range of estimates when rather high concentration into fish is assumed. However, the values might in the upper range be of the order of the external costs due to C-14 in the release cases starting at 50000 years.

Discussion

It is not easy to find any best estimate value for external costs of fusion waste disposal. Any best estimate case has not been chosen but the range for external cost has been given on the basis of three release cases. The range has release periods 20000 – 30000 years, 50000 – 60000 years and 50000 – 75000 years. This gives cost range 0.02...1.1 mEuro/kWh for Model 4, range 0.03...2.0 mEuro/kWh for Model 5 and range 0.03…2.3 mEuro/kWh for Model 6 when 10000 years integration time is used. If integrated 100000 years range 0.02…1.7 mEuro/kWh for Model 4, range 0.04...3.1 mEuro/kWh) for Model 5 and range 0.05...3.4 mEuro/kWh for Model 6 are estimated.

If retention about 50000 years can be assumed (due to waste disposal solution) external costs from waste disposal are very small for all three model plants. Best estimate values can, however, as well be the values for shorter retention periods. Especially, because waste disposal is not necessarily based on consideration of global collective doses.

4.1.5 Externalities of fusion accident

Externalities of a fusion accident have been evaluated by CEPN. Main findings are summarised below, and further details can be found in Lepicard et al, 2002a. This study section is aiming at the assessment of the external costs of a fusion accident, taking into account recent developments in fusion technology and new plant models. The objective is to complete the externalities of fusion accident which were performed in SERF2 for one plant model and site location. Radiological impacts associated with an accident have been re-evaluated for three new plants models (PM 4, 5 and 6) and three site locations (Lauffen/Neckar, Flamanville and Marcoule). The selected accident scenario was the same as in SERF2. Complementary calculations were performed by considering, for each studied site, a larger panel of dispersion conditions and two distinct regulatory limits sets for tritium contents in major foodstuffs. These calculations served as a basis for re-evaluating direct external costs of fusion and allowed a sensitivity analysis of the major parameters mostly influencing the results, especially regarding to potential local food restrictions.

It must be noted that individual exposures which have been calculated in SERF2 were low enough to not consider relocation of the affected population as a relevant countermeasure in case of a fusion accident. In view of the source terms associated with the new plant models, the evaluation of individual exposures did no fall in the scope of the present study.

Accident scenario and source terms

The accident scenario adopted in this study refers to the study performed in the SEAFP project (Raeder et al, 1995). The reference scenario is called BDBA: «beyond design basis accident ». In this case, it is considered that a first event occurs leading to a DBA scenario (« design basis assessment »): i.e. a major in vessel loss-of-coolant (LOCA).

For models 4, 5 and 6, assessment of the influence of silicon carbide on the safety performance of the plant has been done by evaluating the potential consequences of a bounding accident scenario. As in SEAFP, the assumptions for this scenario are a complete loss of all cooling for a prolonged time period (up to three months) with no operation of any safety system or operator intervention. The results thus represent the enveloping temperatures that could be reached in any decay-heat driven transient.

Some differences can be pointed out between previous model 2 and models 4, 5 and 6 in accidental case:

- Releases of tritium should be assumed to be the same as model 2.
- Fe-55, Mn-54 and Co-60 were all due to activation products in the cooling water (crud) in PM2, and are entirely absent in the SiC/SiC models (which are helium cooled). Thus, crud is assumed to be negligible in new plant models 4, 5 and 6.
- The aerosol releases could be assumed to be 1% of PM2.
- In the accident analysis, a potential for release is from the dust inside the vessel. The activation of SiC dust is calculated to be approximately 1% of that found for tungsten (both in terms of activity and hazard potential) and so is not expected to be important. The main nuclides (5 hours after shutdown) are Na-24 and Si-21. In the designs of Plant Models 4, 5 and 6, different assumptions were made about the use of protective armour to cover the first wall (models 4 and 6 had no armour). For the purpose of accident analysis, however, the suggestion is to use the most pessimistic assumption: i.e dust is the same as for PM2.

Other differences that do not affect the radioactive releases in case of an accident are:

- Temperature excursions following an accident are eliminated with SiC/SiC (for PM4 and PM6) so breaches of containment are much less likely.
- Coolant pressures are lower in PM4 and 5 than in previous plant models so containment breaches are less likely.
- Thermodynamic efficiency is higher for PM4, 5 & 6 (1.5 GW), so the normalised cost per kWh is reduced accordingly (the electrical power of previous models PM1, 2 & 3 was 1 GW).

Table 19. Activity released in accident BDBA – models 4, 5 and 6

Products released	Activity (in Bq)
Tritium (HTO)	1.8×10^{16}
W dust aerosol	3.2×10^{13}
Crud	0
Structure aerosol	3×10^{8}

Considering the results from SERF2 study, it could be concluded that the radiological impacts associated with the activation products presented in Table 19 are negligible as compared with those of 50 g of tritium. Thus the external costs of fusion accident have been derived from the radiological impacts of tritium solely.

Due to the technical capabilities of the fusion power plant from the safety point of view, as evaluated in the SEAFP study, the occurrence of such an accident is considered to be well below 10^{-7} per year. As a conservative approach, this value has been retained for the calculations of external costs.

Collective doses for accident scenario

Collective doses at local scale

The collective doses at the local scale (0-100 km) associated with an accidental release of 50g of tritium (HTO) have been calculated on the basis of a recent study on tritium impacts (Lepicard et al, 2002b). These impacts were calculated using the UFOTRI calculation code and results were given for a reference site location, assuming a 100 people.km^{-2} uniformly distributed population density within the local 0-100 km radius area.

In order to assess the radiological impacts in a more accurate way than a single situation, a wide variety of atmospheric dispersion conditions have been considered in separate runs, which are supposed to cover most of the various situations that can be observed, including the upper and lower bounds. Accordingly, calculations have been performed for five different sets of meteorological conditions, three release heights and two durations of release.

Results from these calculations are presented in this report – as far as possible for clarity reasons – in terms of minimum (min), maximum (max) and average (mean) values of these sets of calculations.

Collective doses at local scale (0-100 km) calculated with UFOTRI code are summarised in Table 20.

Table 20. Collective dose at local scale (0-100 km) associated with a fusion accident (50g HTO release)

	Collective dose Mean (Min-Max)* in man.Sv
Neckar (Germany)	84 (30-150)
Flamanville (France)	5 (2-8)
Marcoule (France)	26 (9-46)

* Over a total of 30 run cases for each site location

The total collective dose at local scale is estimated to range from a few to a few dozen of man.Sv. These values are in accordance with those presented in SERF-2 (30 man.Sv associated with tritium were estimated at local scale (Schneider and Lepicard, 2000). It must be noted that in SERF-2, the estimated contribution of activation products was estimated in the same order of magnitude (36 man.Sv), but appear negligible in new plant models 4, 5 & 6.

A complementary study (Lepicard et al, 2002b) has shown that the radiological impacts at local scale were predominantly due to (by decreasing degree of importance):

- Site location
- Meteorological conditions
- Release height
- Release duration

Collective doses at regional scale

Collective doses at regional scale (100-1000 km) were extrapolated from the results at local scale by weighting the latest with the adequate population density corresponding to the three selected sites: Lauffen/Neckar (Germany), Flamanville (France) and Marcoule (France).

Table 21. Collective dose at regional scale (100-1000 km) associated with a fusion accident (50g HTO release)

	Collective dose Mean (Min-Max)* in man.Sv
Neckar (Germany)	230 (84-413)
Flamanville (France)	214 (78-385)
Marcoule (France)	212 (77-380)

* Over a total of 30 run cases for each site location

The collective dose at regional scale is less affected by the site location. It ranges from 80 to 400 man.Sv, the results being predominantly affected by the meteorological conditions. These results also confirm that the collective dose ratio r = regional/local is strongly affected by the site location (r ˜ 3 for Neckar, r ˜ 43 for Flamanville and r ˜ 8 for Marcoule).

Potential food restrictions

Regulatory limits for tritium in food products

At present there is no well-defined tritium concentration limit values for foodstuffs in European countries regulations regarding to emergency situations. Thus, the potential food restrictions (food bans) have been studied on the basis of two sets of limit values. Set 1 refers to proposed guidance values, currently under discussion at the European level (Lepicard et al, 2002b). Set 2 is based on derived values from IAEA methodology (IAEA, 1998). These two sets can be interpreted as lower and upper bounds of tritium concentration limits in foodstuffs.

Table 22. Concentration limit values for tritium in food products in emergency situations

Limits Set 1	• 10 000 Bq/L for milk • 12 500 Bq/kg for other food products
Limits Set 2	• 220 000 Bq/L for milk • 280 000 Bq/kg for meat • 430 000 Bq/kg for green and root vegetables • 370 000 Bq/kg for grain

Methodology for calculating food restrictions

Due to the peculiar modelling of transfer of tritium in the environment, the potential food restrictions were estimated on the following basis and assumptions. For each category of food products, e.g. cow milk, green vegetables, root vegetables (potatoes), grain (wheat) and cow meat, the total number of days for which the tritium contents exceed the regulatory limits were calculated for all dispersion, separately in each cell of a geographic grid (angular sectors) around the site location. These results were then combined with the agricultural production data, taken from PC-CREAM software package (EC, 1997) in order to calculate the total amount of food products to be lost, with the following assumptions:

- For green vegetables, cow milk and cow meat: the production lost (Q) during the restriction time period (N in days) is supposed to be directly proportional to the total annual production (P), e.g. $Q \cong N \times \frac{P}{365}$.
- For root vegetables and grain (single crop a year): the production lost (Q) during the restriction time period is supposed to be equal to the whole annual production (P), e.g. $Q \cong P$.

Economic valuation of radiological impacts

Health effects

Using the risk factors for the occurrence of health effects associated with public exposure as proposed by ICRP in its publication 60 (ICRP, 1990) and assuming by prudence the linear dose effect relationship for low levels of exposure, the health effects are derived directly from collective doses calculated before. **Table 23** presents the results of direct costs associated with the health effects at local and regional scales using the monetary valuation proposed by the ExternE methodlogy and with a 0% discount rate.

Table 23. Direct costs associated with health effects of a fusion accident (50g HTO release, no discounting)

	Local (0-100 km) Mean (Min-Max)[*] in Euro	Regional (100-1000 km) Mean (Min-Max)[*] in Euro
Neckar (Germany)	17.4×10^6 (6.3-31.2×10^6)	47.7×10^6 (17.3-85.6×10^6)
Flamanville (France)	0.9×10^6 (0.3-1.7×10^6)	44.5×10^6 (16.2-79.9×10^6)
Marcoule (France)	5.3×10^6 (1.9-9.5×10^6)	43.9×10^6(16-78.9×10^6)

[*] *Over a total of 30 run cases for each site location*

Food restrictions

Costs associated with potential food bans can be calculated on the basis of two types of actions: a temporary storage of concerned foodstuffs until the activity content drops down below the regulatory limit (radioactive decay and migration), or a complete destruction or disposal of contaminated foodstuffs. Temporary storage was not considered as a relevant option in the present study for several reasons:

- The storage time can exceed several months, which may be more expensive than complete destruction of the product,
- There is a potential risk of radiological exposure of people working on the storage place,
- Population will not accept to consume the same contaminated food, even if its activity concentration has dropped down below the regulatory limit after a certain time period.

On the basis of the total amount of food products concerned by restrictions (see Section 0), costs associated with the complete loss of contaminated products were calculated on the basis of recent RODOS economic data (Schieber and Benhamou, 1999). For each food product, a reference value per unit of production lost is used. An additional cost was also taken into account for the disposal or elimination of the contaminated product (transport, destruction and wastes disposal). In absence of any precise evaluation of these costs, they were roughly estimated to reach 10% of the basic price of the product.

Table 24 summarises the direct costs associated with the potential food restrictions at local scale, taking into account the two sets of concentration limits for tritium in food (

Table 24. Direct costs associated with potential food restrictions at local scale after an accident (50 g HTO release)

	Limits Set 1 Mean (Min-Max)[*] in Euro	Limits Set 2 Mean (Min-Max)[*] in Euro
Neckar	9.4×10^6 (3.7-16.5×10^6)	142 000 (9 000-624 000)
Flamanville	2×10^6 (0.094-7.1×10^6)	32 000 (5 000-103 000)
Marcoule	2.2×10^6 (1-4.3×10^6)	32 000 (3 000-133 000)

Limits Set 1: 10 000 Bq/L for milk and 12 500 Bq/kg for other food products.

Limits Set 2: 220 000 Bq/L for milk, 280 000 Bq/kg for meat, 430 000 Bq/kg for green and root vegetables and 370 000 Bq/kg for grain.

[*] *Over a total of 20 run cases for each site location*

It must be noted that considering the Limits Set 2 does not lead to a significant economic impact (dealing with direct costs only), the direct costs of health effects being largely higher by about three orders of magnitude. Nevertheless, Limits Set 1 is much more constraining and leads to food restrictions which direct costs are estimated to be in the same order of magnitude than direct costs of health effects at local scale (Figure 3.).

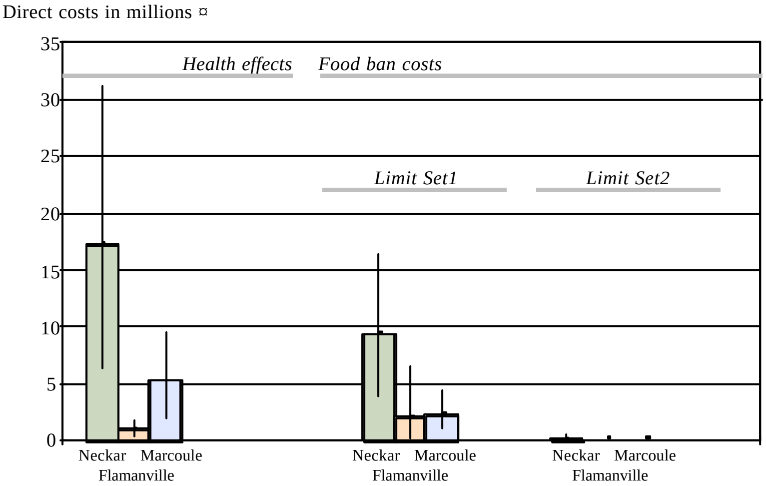


Figure 3. Comparison of direct costs associated with health effects and potential food restrictions at local scale 0-100 km *(bars represent mean values, lines represent min-max range)*

Summary of external costs associated with a fusion accident

Assuming a probability of occurrence for the BDBA(1) scenario of 10^{-7} per fusion plant.year for each new plant model (PM 4, 5 & 6), and an annual production of electricity equal to 9.85 TWh[1], the external costs associated with the selected accident scenario have been estimated in mEuro per kWh. It must be noted that this evaluation does not take into account risk aversion, which contribution was found quite not significant in SERF2, because of the limited radiological impacts the populations surrounding the plant would have to support if such an accident occurred, according to these estimates.

Table 25 summarises the total direct external costs and normalised external costs obtained by considering different atmospheric dispersion conditions for each of the three site locations studied.

---

[1] This value refers to a 1.5 GW electrical power plant, with 75% availability.

Table 25. Total external costs and normalised external costs (direct costs) associated with a BDBA(1) accident scenario (50g HTO release)

	Foodstuffs limits Set 1		
	DR = 0% Mean (Min-Max)	DR = 3% Mean (Min-Max)	DR = 10% Mean (Min-Max)
Total cost of the accident, in 10^6 Euro	60 (20-130)	40 (10-100)	30 (10-80)
Cost mEuro per kWh†	6.1x 10^{-7} (2-13 x 10^{-7})	4.1 x 10^{-7} (1-10 x 10^{-7})	3.1 x 10^{-7} (1-8 x 10^{-7})
	Foodstuffs limits Set 2		
Total cost of the accident, in mEuro	50 (20-120)	40 (10-90)	30 (10-70)
Cost mEuro per kWh†	5.1 x 10^{-7} (2-12 x 10^{-7})	4.1 x 10^{-7} (1-9.3 x 10^{-7})	3.1 x 10^{-7} (1-7.3 x 10^{-7})

† *Assuming a 1.5 GW electrical power, with 75% availability over 35 years of operation*

These results are comparable to those presented in SERF2 (Figure 4). The total cost of the accident (45 millions Euro, without risk aversion) calculated in SERF2 is slightly lower (by 25%) than the value presented in Table 25 (50 or 60 millions Euro, depending on the considered tritium limits in foodstuffs). It must be noted that results in SERF2 were based on a single value of radiological impacts while the value presented in the present study is an average value over a wide panel of calculations, with various atmospheric dispersion conditions. Moreover, keeping in mind that health effects associated with activation products in the accident scenario retained for plant model 2 in SERF2 were also of a significant contribution (in the same order of magnitude than those of tritium), it is interesting to notice that the result from SERF2 remains in the range of values calculated in this study, but should to be closer to the lower bound of all situations considered.

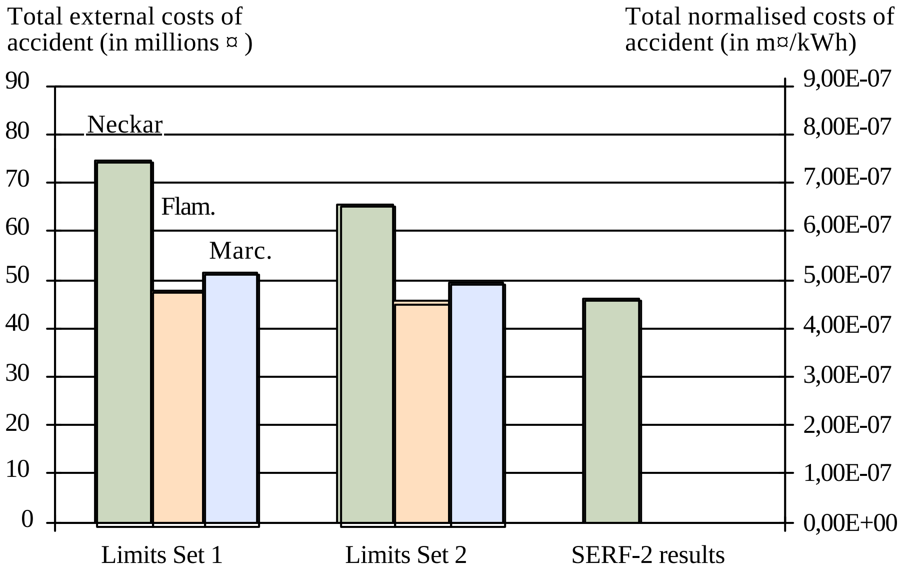


Figure 4. Total external costs and normalised external costs (direct costs) associated with a BDBA(1) accident scenario (50g HTO release)

The external costs (direct costs) estimated for the selected fusion accident scenario in new plant models (PM 4, 5 & 6) are in the range of 10^{-7} – 10^{-6} mEuro.kWh^{-1}, which remains rather low as compared with the total external costs of fusion (Table 26).

4.1.6 Summary of the external costs of fusion

External costs of silicon carbide fusion models have been estimated by several work teams as it has been described above. The external costs of upstream and power generation stages have been estimated by CIEMAT in this document, in section 4.1.2. External costs of decommissioning and waste recycling have been estimated by Studsvik EcoSafe&SafetyAB/VR in section 4.1.3. External costs of waste disposal have been estimated by VTT/TEKES in section 4.1.4. External costs of a fusion accident have been estimated by CEPN in section 4.1.5.

Results obtained for the fusion fuel cycle are summarised in Table 26, considering a 10000 years integration time, 0% discount rate, the present practice recycling scenario, a release period for waste disposal of 50000-60000 years and limits set1 for fusion accident scenario.

Table 26. External costs of the fusion fuel cycle (silicon carbide models)

	External cost (mEuro/kWh)		
	Model 4	Model 5	Model 6
Upstream and power generation stages	0.27 (0.07-1.06) [0.33(0.09-1.37)]	0.27 (0.07-1.07) [0.33(0.09-1.37)]	0.27 (0.07-1.06) [0.33(0.09-1.37)]
Decommissioning, recycling and site restoration	0.31 (0.12-0.93)	0.31 (0.12-0.93)	0.31 (0.12-0.93)
Waste disposal	0.03 (0.02-1.1)	0.05 (0.03-2)	0.06 (0.03-2.3)
Accidents	6.1e-07 (2-13e-07)	6.1e-07 (2-13e-07)	6.1e-07 (2-13e-07)
Subtotal	***0.62 (0.21-3.10)*** ***[0.68(0.22-3.40)]***	***0.64 (0.22-4.00)*** ***[0.70(0.23-4.30)]***	***0.65 (0.22-4.29)*** ***[0.71(0.23-4.60)]***

Expressed between square brackets are the external costs calculated considering the CO_2 abatement costs of 19 Euro/t of CO_2.

The relative contribution of the different stages to the final external costs can be observed graphically in Figure 5.

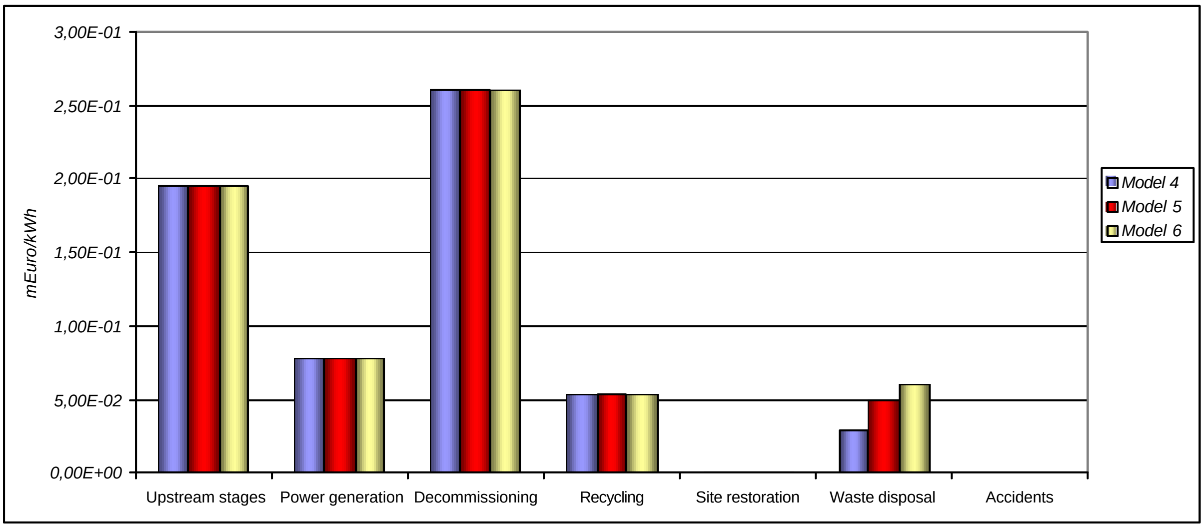


Figure 5. External costs of the fusion fuel cycle (silicon carbide models).

Since radiological effects of the emissions of the power plant on the general public have been reduced considerably in the new models, occupational aspects become important.

Especially noticeable are those related to accidents in the construction and decommissioning of the power plant. It is important to stress that these external costs have been calculated on the basis of accident statistics in the several sectors involved in the construction of the power plant for the year 1995. Accident rates could decrease considerably by the year 2050 when the construction of the power plant would start, reducing accordingly the external costs produced.

The next cause of external cost is the disposal of waste dominated by the effects of the collective doses due to C-14 releases from the waste repositories. The magnitude of these impacts largely depends on the release period selected. In order to compute the reported main value of the fusion external costs, an intermediate value for waste disposal impacts has been selected, but the impacts could have been much higher if other release assumption had been made. This aspect is highly uncertain thought and the results must be taken with great care.

Following occupational accidents and waste disposal impacts, global collective doses due to tritium operational releases are other important cause of external costs.

Energy use and emissions in the manufacturing of materials produces also noticeable external costs. It is important to note that these impacts have been estimated on the basis of the current energy mix. Future energy systems composed of cleaner technologies could have lower emissions associated, and therefore the external costs associated to this stage could decrease accordingly.

In general, the impacts generated by the fusion fuel cycle are not very dependant on the location of the specific power plant since they are mainly occupational impacts and global nature impacts

4.2 External costs of non nuclear advanced technologies

This part of the work has been performed by CIEMAT. A summary of the contribution is included below. For a detailed description of the assessment performed see Lechón and Sáez, 2002.

4.2.1 Selection of non nuclear advanced technologies

Several studies on energy scenarios for the 21st century have been consulted in order to assess what are the predictions for the contribution of different technologies in the energy generation of 2050 (Nakicenovik and Riahi, 2002; Interlaboratory working group, 2000; Cabinet Office, 2002). Scenarios in the literature offer a large set of alternative future developments that may include the actual development path but this need not necessarily be the case. Nevertheless, the analysis of a range of future technology characteristics is one of the few options available. The other is polling the views of experts. Some prospective studies of this type have also been consulted (OPTIa, OPTIb, OPTIc).

The approach used by the International Institute for Applied Systems Analysis IIASA (Nakicenovik and Riahi, 2002) study is to assess the ranges of deployment and characteristics of future energy technologies on the basis of 34 different scenarios from the IIASA-WEC and IPCC studies. The scenarios are based on different assumptions about energy demand, resource availability etc, and they use these scenarios to determine which of the technologies play important roles across a range of scenarios in the future and which are limited to some of them. Technologies that appear to be invariant across scenarios can be considered to be robust and resilient with respect to different assumptions.

From the analysis of these scenarios the study concludes that the relative roles of traditional electricity technologies such as coal power plants decrease consistently while the role of advanced such as fuel cells, combined cycles with carbon removal, solar and nuclear power become more important as time progresses in the scenarios.

The structure of the electricity generation by 2020 does not change radically compared to the current situation due to the rigidities of the energy system with much of the current generating capacity surviving through 2020. Changes are much more significant by 2050 since half a century is long enough for the replacement of most of the current energy system by new technologies. There is then a shift from conventional coal, gas and nuclear to advanced systems:

- IGCC (Integrated coal gasification combined cycle)
- NGCC (Natural gas combined cycle)
- High temperature nuclear reactors.

Fuel cells diffuse rapidly after 2020 predominantly powered by natural gas and later also by hydrogen. Carbon scrubbing and storage technologies are also introduced.

Among renewable technologies solar PV is the most deployed technology followed by hydro and wind.

As a conclusion of this study the most robust technologies across scenarios resulted to be:

- Combined cycles in the medium term (first half of the century)
- Fuel cells, solar PV and nuclear energy in the long term (second half of the century)

Wind energy is also very important across scenarios while biomass is considered not to be very robust although is very important in some scenarios.

Production of hydrogen is considered to be done predominantly from natural gas through 2050 and, after that point, solar thermal becomes the main source.

Following these findings we have selected some advanced technologies to be compared with fusion with regards to their external costs. These technologies are the following: Advanced coal technologies with carbon capture and disposal; Natural gas combined cycle with carbon capture and disposal; Fuel cells powered by natural gas; Renewable technologies: biomass gasification, wind power, solar photovoltaics, and geothermal energy.

Long-term advances in the different technologies are not known but we can identify trends that are presented in the next sections.

Advanced coal technologies

Advanced technologies for coal electricity conversion are being developed both in Europe and the U.S., capable of providing energy at affordable costs while meeting future environmental requirements. These research and development efforts are directed to mainly three areas: advanced pulverised coal combustion systems, fluidised bed combustion systems and integrated gasification systems (DOE web site, http://www.fe.doe.gov).

Fluidised Bed Combustion technology can be atmospheric or pressurised. Atmospheric fluidised bed combustion is crossing over the commercial threshold, with most boiler manufacturers currently offering fluidised bed boilers as a standard package. PFBC systems pressurise the fluidised bed to generate sufficient flue gas energy to drive a gas turbine and operate it in a combined-cycle. The 1st generation pressurised fluidised bed combustor uses a “bubbling-bed" technology. A 2nd generation pressurised fluidised bed combustor, currently under development, uses "circulating fluidised-bed" technology and a number of efficiency enhancement measures. These combined cycle mode of operation of PFBC systems significantly increases the efficiency and efficiencies higher than 50% are expected. Second generation pressurised fluidised bed combustion is expected to achieve a 52 percent fuel-to-electricity efficiency level and have near-zero NOx, SO2, and particulate emissions. Market entry is projected for 2008 (DOE web site, http://www.fe.doe.gov).

Coal gasification represents the next generation of coal-based energy production. Rather than burning coal directly, coal gasification reacts coal with steam and carefully controlled amounts of air or oxygen under high temperatures and pressures. The heat and pressure break apart the chemical bonds in coal's complex molecular structure, setting into motion chemical reactions with the steam and oxygen to form a gaseous mixture, typically hydrogen and carbon monoxide. The fuel-grade coal-derived gas rivals natural gas in environmental quality. Coal gasification offers the prospects of boosting efficiencies to 45-50% in the short-term and potentially to nearly 60% with technological advancements. First generation IGCC plants have already demonstrated outstanding operability and environmental performance at commercial scale.

PFBC systems and IGCC systems are considered to have the higher possibilities to be still in use in 2050 when the first fusion power plant would be in operation. Other further developments are possible although highly speculative. Therefore we have selected these technologies for detailed analysis of external costs and its comparison with the external costs of fusion.

Carbon sequestration technologies.

Carbon capture and sequestration has been extensively studied by the IEA greenhouse gas R&D programme (IEAa,b,c, www.ieagreen.org.uk). Most of the information summarised in this section has been taken from this source and also from the DOE carbon sequestration programme (DOE, www.fe.doe.gov).

After the fossil fuel has been burnt to produce power, the CO_2 has to be separated from the flue gas stream. Then the CO_2 would be stored, for a long time, if it cannot be put to some useful purpose. The general scheme of the capture and main sequestration options is shown in Figure 6.

Other possible options are (DOE, www.fe.doe.gov)

- **Carbon sequestration in terrestrial ecosystems** is either the net removal of CO2 from the atmosphere or the prevention of CO2 net emissions from the terrestrial ecosystems into the atmosphere.
- **Advanced Chemical and Biological Approaches**. Two promising chemical pathways are magnesium carbonate and CO2 clathrate, an ice-like material. Both provide important increases in volume density compared to gaseous CO2. Concerning biological systems, the options considered are enhancements to the carbon uptake of photosynthetic systems and harnessing of microbiological processes capable of converting CO2 into useful forms, such as methane and acetate.

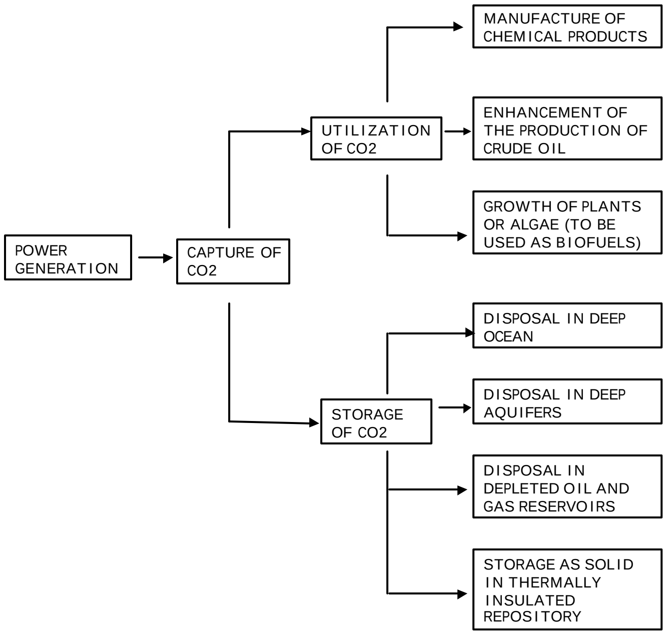


Figure 6. Capture and sequestration of CO_2

Capture of CO_2

CO_2 has to be separated from the flue gas before disposal. Following capture the CO_2 requires drying and compression to a dense fluid for efficient transport to the disposal site. According to IEAGHG the main available technologies for CO_2 capture are the following: Absorption technologies involving either chemical or physical solvents; Adsorption technologies; Cryogenic technologies; Membrane technologies. Details on these technologies can be found in Lechón and Sáez 2002.

Disposal of CO_2

Once CO_2 has been captured it has to be dried and compressed to a dense phase which can be efficiently transported to the disposal site.

The major options available for large-scale disposal of CO_2 are: Disposal in the deep ocean; Disposal in deep aquifers; Disposal in exhausted gas and oil reservoirs; Disposal as solid in thermally insulated repositories. However this last option much more expensive than the other ones and the feasibility of constructing such a repository is questionable.

These options have been also reviewed in detail by the IEAGHG programme (IEAb,c). Details can be also found in Lechón and Sáez, 2002.

Fuel cells

A fuel cell is a device for directly converting the chemical energy of a fuel into electrical energy in a constant temperature process.

A fuel cell consists of a fuel electrode (anode) and an oxidative electrode (cathode) which are separated by an ion conducting electrolyte. The electrodes are connected by a metallic external circuit. In this circuit, electricity is transported by a flow of electrons, whereas inside the electrolyte it is transported by a flow of ions (H^+, OH^-, CO_3^{2-}, or O^{2-} depending on the type of fuel cell). Theoretically any kind of substance capable of chemical oxidation can be burned galvanically in the anode of a fuel cell. Gaseous hydrogen has become the major used fuel. Hydrogen can be generated of natural gas or other compounds by a reforming process. Fuel cells can then be run on a wide range of fuels from gaseous fuels such as hydrogen or natural gas to liquid fuels such as methanol or gasoline. The most common oxidant is oxygen. The different types of fuel cells are characterised by the working temperature and the composition of the electrolyte.

There are five main classes of fuel cells:

- alkaline (AFC) with an operating temperature of 60-90ºC
- Solid polymer (SPFC) with an operating temperature of 80-100ºC.
- Phosphoric acid (PAFC) with an operating temperature of 200ºC.
- Molten carbonate (MCFC) with an operating temperature of 650ºC
- Solid oxide (SOFC) with an operating temperature of 800-1000ºC.

The main applications of fuel cells are likely to be stationary power generation, transportation and battery replacement. There are several different fuel cell types at various stages of development. The larger-scale stationary fuel cell systems are the furthest from commercialisation. They are expected to be available on the market around 2010 (Brandon and Hart, 1999).

Advanced renewable technologies

Biomass

Long-term improvements can be expected in the development of biomass resources and conversion technologies. Among these technologies biomass gasification has the potential to have a major impact (Interlaboratory working group, 2000; European Commission, 1996) with the development of efficient systems for electricity production namely combined cycles (EUREC, 1996).

Wind.

Wind is one of the renewable technologies closest to being economically competitive today.

However, market penetration require addressing the impact of the intermittent output of wind through:

- modification of system operation
- hybrids with other technologies
- energy storage
- transmission and infrastructure
- and improved wind forecasting.

There will continue to be advances in higher towers, lightweight blades, direct drive systems, advanced power conversion devices and development of durable structural components (Interlaboratory working group, 2000).

Prospective studies consulted also identify as important topics in the future development of wind energy, the use of large generators and the use of advanced energy storage systems (OPTIa).

Advanced energy technologies under development include processes that are mechanical (flywheels, pneumatic), electrochemical (advanced batteries, reversible fuel cells, hydrogen) and purely electrical (ultracapacitors, superconducting magnetic storage). Flywheels and electrochemical batteries have been selected to analyse the possible external costs of energy storage systems to be added to the external costs of intermittent renewable energies.

Photovoltaics

Solar energy produced by photovoltaics solar cells is one of the most promising options to provide energy in the future. The technology has been based in the past on silicon wafers and cells which have the advantage of high efficiency but the disadvantage of high costs. PV modules available are predominantly flat-plate types with 18 to 180 monocrystalline or multi-crystalline Si cells in a module with efficiencies of 11-13%. The development of thin film photovoltaic technology started with the use of amorphous Si with lower production costs but with also lower efficiencies (stabilised efficiency at 5%) (European Commission, 1996). There is now a transition to a potentially much lower-cost polycrystalline thin-film technology with efficiencies of more than 15% (Green, 2000; European Commission, 1996). There are however some concerns about the environmental impacts of these cells based on materials such as CdTe and $CuInSe_2$. Efficiency of cells is restricted to 33%. However, the thermodynamic limit on the conversion of sunlight into electricity is 93%. It is possible for solar cells to come closer to this limit by using tandems of cells, which will constitute the third generation of solar cells reaching efficiencies over 25% (European Commission, 1996). Another approach to attain higher efficiencies is represented by the use of concentrators (EUREC, 1996).

Prospective studies consulted identify as important topics in the future development of photovoltaic energy, the use of thin film technology with efficiencies over 15% and the use of concentrators (OPTIa).

Geothermal energy

A geothermal resource can be defined as a reservoir from which heat can be extracted and utilised for generating electric power or any other suitable industrial, agricultural or domestic application.

Geothermal systems can be classified in:

- Hot water systems: The geothermal system contains water at 50-100ºC and can be used for heating homes or for various agricultural and industrial applications.
- Liquid dominated systems: The system contains pressurised water a t temperatures higher than 100ºC and limited quantities of steam. The system is covered by a impermeable layer and is kept under pressure.
- Vapour dominated systems: These systems are similar to the previous ones, in them water and steam coexist, being the steam a prevalent and continuous phase. These systems produce dry and superheated steam with small quantities of other gases, and the typical utilisation is electricity generation.

Additionally, new technologies in geothermal energy, still experimental, are (Palmerini, 1993): Geopressured geothermal systems; Hot dry rock systems and Magma systems.

Energy storage

Since the variable character of renewable energy, one of the key aspects of the development of renewable energies is to find efficient and low-cost storing systems.

Energy storage can increase the value of photovoltaic and wind generated electricity by making supply coincident with periods of peak consumer demand, and can facilitate large-scale integration of intermittent renewable resources such as wind and solar onto the electric grid (EREN, 2002). Energy storage is commonly used in stand-alone applications where it can serve as an uninterruptible power supply unit.

A number of energy storage technologies have been developed or are under development:

- Pumped hydropower
- Compressed air energy storage (CAES)
- Batteries
- Flywheels
- Superconducting magnetic storage (SMES)
- Supercapacitors

Technologies suitable for integration with renewable energies are batteries, flywheels and SMES.

Batteries

In a chemical battery, charging causes reactions in electrochemical compounds to store energy in a chemical form. Upon demand, reverse chemical reactions cause electricity to flow out of the battery and back to the grid. Batteries are manufactured in a wide variety of capacities ranging from less than 100 watts to modular configurations of several megawatts. Batteries can be used for various utility applications.

Flywheels

A flywheel storage service consist of a flywheel that spins at a very high velocity and an integrated electrical apparatus that can operate either as a motor to turn the flywheel and store energy or as a generator to produce electrical power on demand using the energy stored in the flywheel. Energy losses are high but can be reduced by the use of magnetic bearings and a vacuum chamber.

There are two types of flywheels of use with renewable energies (Cruz, 2002):

- Flywheels with medium term storage capacity, specially suited for PV applications

Flywheels with short term storage capacity, more associated to wind energy since they can eliminate the power fluctuations of generators produced by wind turbulence.

Superconducting Magnetic Energy Storage

A SMES system stores energy in the magnetic field created by the flow of direct current in a coil of superconducting material. To maintain the coil in its superconducting state, it is immersed in liquid helium contained in a vacuum insulated cryostat. SMES systems have a high cycle life. Although research is conducted on large SMES systems (10-100 MW), the recent focus has been on micro-SMES devices.

4.2.2 External costs of advanced fossil technologies

Advanced fossil technologies without carbon sequestration

Estimation of external costs of these technologies is taken from the work performed in ExternE (EC, 1999c). In this work the three cycles selected were analized and their external costs calculated. However, from the date when these analyses were made and today some modifications in the methodology have been introduced (Bickel et al, 1999). These modifications are the following:

- Dispersion modelling. A new model for regional ozone formation and transport is available, the SROM model.
- Health E-R functions have been reviewed and fine tuned. Main changes affect the E-R functions for chronic mortality (Pope at al, 1995) and chronic bronchitis (Abbey et al, 1995) which were scaled down by factor 3 and 2 to account for the difference between recent and historical estimates of exposure and the higher particle effect in time series studies in the USA compared to Europe.
- New E-R function for materials are available now
- In monetary valuation, the use of the VLYL (Value of Life Year Lost) concept for valuing changes in mortality risk is recommended, and new morbidity estimates and endpoints have been introduced based on new European Contingent Valuation studies. Monetary values have been updated to EURO 2000 values.
- Global warming damages estimates. Now the central estimate for marginal costs due to CO_2 emissions is set in 2.4 EURO/t CO_2, with a 67% confidence interval ranging from 1.4 to 4.1 EURO/t CO_2. These values are considerable lower than the previous estimates of the ExternE methodology.

Not all of these modifications can be applied since we have aggregated results of the damages. However the two most important modifications, change in the dose-response function for mortality and the change in the damages estimates for global warming, can be applied in order to obtain figures more comparable with the ones obtained for the fusion fuel cycle.

For a detailed description of the estimation of external costs of these technologies see Lechón and Sáez, 2002. The results are shown in Table 27. Natural gas combined cycle is the advanced fossil technology with lowest external costs due to the low airborne emissions of the cycle and to the high efficiency of the plant. IGCC fuel cycle follows in terms of external costs. Differences with the PFBC arise mainly in the effects on public health due to the much lower atmospheric emissions of SO_2 of the IGCC technology.

Table 27. External costs of IGCC, PFBC and NGCC fuel cycles (adapted from EC, 1999c and d) mEuro/kWh.

	IGCC	PFBC	NGCC
Power generation			
Public health	**1.59**	**4.90**	**1.19**
Mortality	*1.15*	*3.60*	*0.8*
TSP	0.03	0.07	0.00
SO2	0.11	1.90	0.00
Nox	1.01	1.63	0.8
Morbidity	*0.44*	*1.30*	*0.39*
Occupational health	**0.12**		
Crops	**0.003**	**-0.03**	**0.004**
Materials	**0.02**	**0.20**	**0.03**
Ozone	**0.68**	**0.70**	**0.05**
Global warming	**1.76 (1.03-3) [13.92]**	**1.68(0.98-2.86) [11.55]**	**0.84(0.49-1.43) [6.61]**
Other fuel cycle stages			
Public health	**0.30**	**0.60**	**0.5**
Occupational health	**0.29**	**0.60***	**0.004***
Crops	**0.003**	**0.04**	**Ng**
Materials	**0.01**	**0.03**	**0.01**
Ozone	**Nq**	**0.45**	
Global warming	**0.19(0.12-0.31) [0.63]**	**0.18(0.11-0.30) [0.63]**	**0.11(0.07-0.18) [0.34]**
Subtotal	***4.97(1.96-14.77) [17.58(15.33-26.09)]***	***9.35(3.05-32.22) [19.89(14.23-41.68)]***	***2.73(1.00-8.72) [8.74(7.37-14.11)]***

*Including generation stage. Nq: Not quantified

Expressed between brackets are the external costs calculated considering the CO_2 abatement costs of 19 Euro/t of CO_2.

The influence of the global warming damage costs in the global external costs value of these technologies is dramatic illustrating the effect that different assumptions regarding this extremely uncertain impact might have on the final figure of the external costs of specially fossil technologies.

Carbon sequestration technologies.

Capture of CO_2

Carbon capture technologies selected for each fuel cycle are the ones considered as more appropriate in the IEA study (IEAa):

- Shift unit and physical absorption for the IGCC fuel cycle
- Chemical absorption using MEA for the PFBC and NGCC fuel cycles.

The main effect of the CO_2 capture devices is that the net efficiency of the power plant is reduced considerably due to the energy consumption of the CO_2 capture systems.

The PF case result has been assimilated to our PFBC case study and a reduction of 11% in efficiency has been considered. However, it is clear (IEAGHG) that CO_2 capture will be less energy intensive if the flue gas is available at higher pressured which will be the case of pressurised fluidised bed combustion. Therefore our estimations will be somehow overestimating the costs. However, the extent to which this overestimation is made cannot be assessed.

In the case of the IGCC fuel cycle a reduction of 6% in the efficiency of the power plant has been considered, and for the NGCC fuel cycle a 10% has been considered.

It is worthy to be noted that with chemical absorption systems applied in PFBC and NGCC, in order to apply any CO_2 capture system, SO_2 must be removed (level below 1 ppmv) from the flue gas before entering the absorber. Then, the efficiency penalty of CO_2 removal will be compensated with these very low SO_2 emissions. NOx content of the flue gas is composed mainly (90%) of NO that poses no problem to the absorption process and therefore does not need to be removed. In order to account for these reductions in emissions in the external costs of the power production stage, the following approximations have been done:

- No SO_2 has been considered in the flue gas
- A decrement of 10% in NOxs emissions in the flue gas has been considered.

Disposal of CO_2

Two options for CO_2 disposal have been considered for each of the fossil technologies studied:

- Ocean disposal using a pipeline
- Disposal in an offshore gas reservoir

The conceptual design for these two options has been taken from the IEA study (IEAb).

Ocean disposal

The assessment of the external costs of ocean disposal is performed based on the conceptual design selected in the IEA study above mentioned. It is large scale scheme for disposing the CO_2 produced by a 2GW coal fired power plant (600kg/s CO_2) into the ocean at a depth of 500m. This injection depth would result in a re-entry of CO_2 to the atmosphere in about 50 years. At these depths plant and animal life is still abundant. The effect on marine organisms of this high concentration of CO_2 can be significant. Depths of at least 1000 m should be reached in order to extent the re-entry times considerably and to avoid a significant biological impact.

The design consists of 5 nozzles each one above a control valve and supported in a cradle. The nozzle unit would be laid as a final section of a 100 km pipeline (made of mild steel 864 mm Ø and 38 mm thickness).

Inspection, maintenance and repair work of the injector will be made by a remotely operating vehicle that would operate from a diving support vessel.

Additional pressure is required to overcome pressure losses in the pipeline and injector system and maintain the pressure above the critical pressure. Then additional pressurisation of 4MPa (5 MW compressor) would be required.

Of the external costs calculated for this scheme we will only assign to the fuel cycles analysed the share corresponding to the CO_2 production from the total production of the scheme (600 kg/s). The CO_2 productions of each plant are:

- 37 kg/s of CO_2 captured in the IGCC power plant.
- 21 kg/s of CO_2 captured in the PFBC power plant
- 47 kg/s of CO_2 captured in the NGCC power plant

A detailed calculation of the external costs of this squeme of disposal can be found in Lechon and Sáez, 2002. Results obtained are summarised in Table 28.

Table 28. External costs of disposal of CO_2 in the deep ocean (mEuro/kWh)

	IGCC	PFBC	NGCC
Pipeline construction			
Occupational accidents	4.5e-03	3.28e-03	1.62e-03
Atmospheric emissions	9.06e-03[1.26e-02]	7.25e-03[9.82e-03]	3.59e-03[4.87e-03]
Pipeline operation			
Occupational accidents	Nq	Nq	Nq
Leaks from pipeline	2.47e-03 (1.44e-03-4.22e-03) [1.96e-02]	2.52e-03 (1.47e-03-4.31e-03) [2.00e-02]	1.25e-03 (7.28e-04-2.13e-04) [9.89e-03]
Atmospheric emissions from compression station	3.73e-04 (3.73e-04-3.74e-04) [3.74e-02]	2.45e-04 (2.45e-04-2.45e-04) [2.46-02]	1.22e-04 (1.21e-04-1.22e-04) [1.22e-02]
Subtotal	**1.64e-02** **(5.9e-03-5.21e-02)** **[3.70e-02 (2.49e-02-8.15e-02)]**	**1.33e-02** **(4.84e-03-4.18e-02)** **[3.33e-02 (2.40e-02-6.77e-02)]**	**6.59e-03** **(2.40e-03-2.07e-02)** **[1.65e-02 (1.19e-02-3.35e-02)]**

Expressed between square brackets are the external costs calculated considering the CO_2 abatement costs of 19 Euro/t of CO_2.

Non quantified damages include:

- Effects on marine environments
  - pH and narcotic effects on marine organisms
  - altered nutrient distribution
- Effects of the pipeline lying on terrestrial ecosystems
- Accidental release of CO_2 from a fracture in the pipeline

<u>Disposal in an offshore gas reservoir</u>

The conceptual design is also based in the same IEA study (IEAb). The scheme involves the disposal of CO_2 in an exhausted offshore gas reservoir that is closed.

The scheme has 4 wells each with an injection capacity of 2500 tCO_2/day and a well head pressure of 11MPa. CO_2 will be injected through a 140 mm tube to a depth of 1000m. CO_2 will be transported to the injection platform by means of a 50 km pipeline. Additional pressurisation, 3.5 MW compressor, would be required.

Of the external costs calculated for this scheme we will only assign to the fuel cycles analysed the share corresponding to the CO_2 production:

- 37 kg/s of CO_2 captured in the IGCC power plant.

- 21 kg/s of CO_2 captured in the PFBC power plant
- 47 kg/s of CO_2 captured in the NGCC power plant

A detailed calculation of the external costs of this squeme of disposal can be found in Lechon and Sáez, 2002. Results obtained are summarised in Table 29.

Table 29. External costs of disposal of CO_2 in an exhausted gas reservoir (mEuro/kWh)

	IGCC	PFBC	NGCC
Well drilling activities			
Occupational accidents	3.97e-04	5.28e-04	2.62e-04
Atmospheric emissions	Nq	Nq	Nq
Pipeline construction			
Occupational accidents	2.63e-03	2.68e-03	1.33e-03
Atmospheric emissions	7.35e-03[1.0e-02]	8.24e-03[1.12e-02]	4.08e-03[5.53e-03]
Pipeline and injection platform operation			
Occupational accidents	1.47e-04	8.57e-04	9.51e-05
Leaks from pipeline	2.47e-03 (1.44e-03-4.22e-03) [1.96e-02]	2.52e-03 (1.47e-03-4.31e-03) [2.00e-02]	1.25e-03 (7.28e-04-2.13e-03) [9.89e-03]
Atmospheric emissions from compression station	1.61e-03 (1.50e-03-1.79e-03) [3.37e-03]	1.15e-03 (1.04e-03-1.34e-03) [2.94e-03]	5.69e-04 (5.16e-04-6.62e-04) [1.46e-03]
Subtotal	**1.47e-02** **(6.10e-03-4.37e-02)** **[3.64e-02** **(2.68e-02-7.20e-02]**	**1.52e-02** **(5.89e-03-4.68e-02)** **[3.74e-02** **(2.70e-02-7.58e-02]**	**7.58e-03** **(2.94e-03-2.33e-02)** **[1.86e-02** **(1.34e-02-3.77e-02]**

Expressed between square brackets are the external costs calculated considering the CO_2 abatement costs of 19 Euro/t of CO_2.

Non quantified damages include:

- Potential for accidental release of CO_2 from the reservoir
- Effects of the pipeline lying on terrestrial ecosystems
- Accidental release of CO_2 from a fracture in the pipeline

The difference between storage in gas reservoir and in the deep ocean is not very important and mainly is due to the larger pipeline required for the disposal in the deep ocean.

Advanced fossil technologies with carbon sequestration

External costs of advanced fossil fuel technologies with CO_2 capture and disposal have been calculated considering the effect of CO_2 capture devices in the efficiency of the power plant and the external costs of CO_2 disposal calculated before. Results are shown in Table 30.

Table 30. External costs of advanced fossil fuel technologies with CO_2 capture and disposal (mEuro/kWh)

	IGCC	**PFBC**	**NGCC**
Power generation			
Public health	**1.66**	**2.74**	**1.06**
Mortality	*1.20*	*1.99*	*0.85*
TSP	0.04	0.09	0.00
SO2	-	-	0.00
Nox	1.16	1.90	0.85
Morbidity	*0.46*	*0.76*	*0.21*
Occupational health	**0.14**		
Crops	**-**	**-**	**-**
Materials	**-**	**-**	**-**
Ozone	**0.78**	**0.81**	**0.05**
Global warming	**0.37 (0.21-0.62) [2.89]**	**0.47 (0.28-0.80) [1.49]**	**0.15 (0.09-0.25) [1.18]**
CO_2 capture and disposal			
Disposal in deep ocean	**1.64e-02[3.7e-02]**	**1.33e-02[3.33e-02]**	**6.59e-03[1.65e-02]**
Disposal in gas reservoir	**1.47e-02[3.64e-02]**	**1.52e-02[3.74e-02]**	**7.58e-03[1.86e-02]**
Other fuel cycle stages			
Public health	**0.35**	**0.78**	**0.59**
Occupational health	**0.33**	**0.78***	**0.005***
Crops	**0.00**	**0.58**	**Ng**
Materials	**0.01**	**0.05**	**0.01**
Ozone	**Nq**	**0.04**	**Nq**
Global warming	**0.22 (0.14-0.36) [0.73]**	**0.24 (0.15-0.39) [0.82]**	**0.13 (0.08-0.21) [0.41]**
Subtotal with ocean disposal	***3.89 (1.25-13.45) [6.95 (4.48-16.19)]***	***6.50 (1.99-23.20) [8.41 (3.99-24.90)]***	***2.01 (0.60-7.36) [3.32 (1.99-8.54)]***
Subtotal with disposal in gas reservoir	***3.90 (1.25-13.49) [6.99 (4.50-16.27)]***	***6.52 (1.99-23.25) [8.45 (4.01-24.98)]***	***2.01 (0.60-7.38) [3.34 (2.00-8.58)]***

*Including generation stage; Nq: Not quantified Ng: negligible

Expressed between brackets are the external costs calculated considering the CO_2 abatement costs of 19 Euro/t of CO_2.

External costs calculated for these technologies are considerably lower than reported elsewhere mainly due to the advanced characteristics of the technologies regarding control of pollutant emissions as well as the consideration of CO_2 sequestration concepts.

External costs calculated using the abatement costs of CO_2 are also higher although the effect is attenuated by the fact of the much lower direct CO_2 emissions due to the use of CO_2 sequestration devices.

An study performed by the IEA (IEAd) about the external costs of fossil technologies with CO_2 sequestration reported values of 4.05 mEuro/kWh for an IGCC power plant, 3.59 mEuro/kWh for a pulverized coal power plant operating in ultrasupercritical conditions and 1.27 mEuro/kWh for a NGCC power plant. These results are therefore comparable with the ones obtained here.

4.2.3 External costs of fuel cells for stationary applications

The analysis of externalities performed is based in the ExternE study published in (European Commission, 1999c) adjusted for the latest changes in the ExternE methodology. Not all of these modifications can be applied since we have aggregated results of the damages. However the two most important modifications, change in the dose-response function for mortality and the change in the damages estimates for global warming, can be applied in order to obtain figures more comparable with the ones obtained for the fusion fuel cycle.

A detailed calculation of the external costs of fuel cells can be found in Lechon and Sáez, 2002. Results obtained are summarised in Table 31 and in Figure 7.

Table 31. External costs in mEuro/kWh of the PAFc and MCFC fuel cycles.

	PAFC	MCFC
Upstream stages		
Natural gas cycle	***1.42 [1.76]***	***1.41 [1.66]***
Atmopsheric emissions	1.29E+00	131E+00
Occupational accidents	1.78E-02	1.59E-02
Global warming	1.13E-01	8.37E-02
	(6.88E-02-1.86E-01)	5.09E-02-1.38E-01)
	[4.51E-01]	[3.34E-01]
Construction of the fuel cell	***2.74 [2.83]***	***1.29 [1.33]***
Atmospheric emissions	2.73E+00	1.29E+00
Global warming	1.30E-02	5.18E-03
	(7.62E-03-2.21E-02)	(3.03E-03-8.81E-03)
	[9.76E-02]	[3.93E-01]
Power generation	***1.14 [8.13]***	***0.87 [6.10]***
Atmospheric emissions	1.29E-01	1.19E-01
Global warming	1.01E+00	7.56E-01
	(5.90E-01-1.73E+00)	(4.41E-01-1.29E+00)
	[8.00E+00]	[5.98E+00]
Subtotal	***5.31 (1.71-18.6)***	***3.58 (1.18-12.4)***
	[12.7(9.57-25.2)]	*[9.09(7.03-17.3)]*

Expressed between square brackets are the external costs calculated considering the CO_2 abatement costs of 19 Euro/t of CO_2.

In the case of the PAFC main impacts come from the construction of the fuel cells due to the atmospheric emissions in the manufacturing of the materials; followed by the impacts produced by the provision of the fuel. In the case of MCFC main impacts are produced in the provision of fuel.

The impacts originated in the power generation stage are smaller and are dominated by the effect of the greenhouse gases emitted on global warming. Sequestration of CO_2 could therefore reduce the external costs of PAFC although effects on the overall efficiency of the system and the own external costs of the sequestration activities could counteract this reduction. This alternative has not been considered in this study.

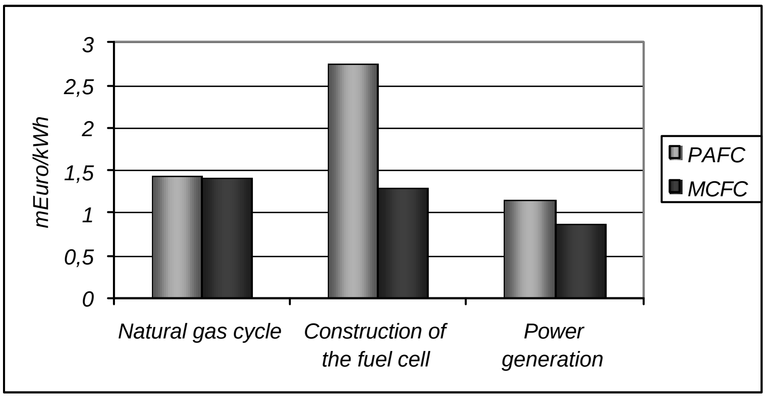


Figure 7. External costs of the different stages of the fuel cells fuel cycles.

The consideration of the abatement costs for climate change impacts of 19 Euro/t of CO_2 alters the picture completely. External costs increase considerably and the most important costs are produced in the power generation stage due to the production of CO_2 emissions.

4.2.4 External costs of advanced renewable technologies

Biomass gasification power plant

The estimation of externalities of the biomass power plant is based in the LCA analysis performed by NREL (Spath and Mann, 1997). The LCA analysis considered for this study took into account all the emissions to the environment and the energy use in all the processes of the fuel cycle including upstream and downstream processes. The growth of the biomass was taken into account considering all the agricultural operations needed and the machinery and products used as well as the processes of production and transport of these products. Biomass transport to the power plant was considered to be made by diesel trucks (70%) and fuel oil trains (30%) and the transport distance is considered to be 27.6 km. Construction and decommissioning of the power plant were also considered.

A detailed calculation of the external costs of fuel cells can be found in Lechon and Sáez, 2002. Results obtained are summarised in Table 32 and Figure 8.

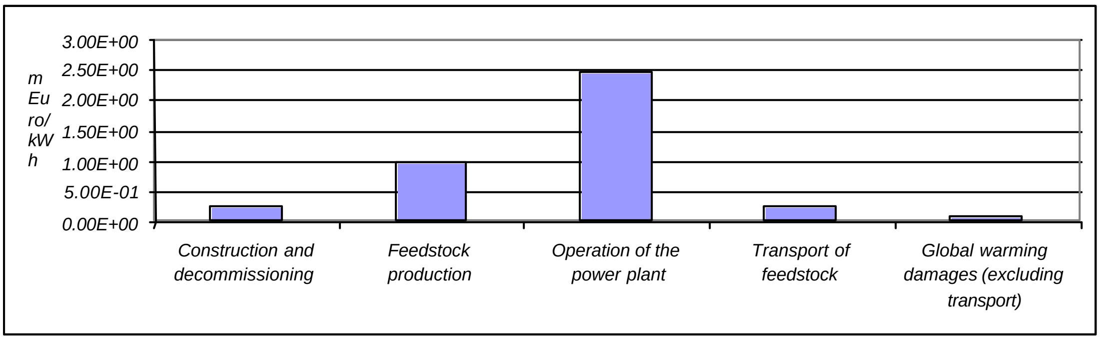


Figure 8. Summary of the external costs of different stages of biomass gasification fuel cycle.

External costs are dominated by the effect of the atmospheric emissions produced in the normal operation of the power plant. Atmospheric emissions in feedstock production are the next cause of external impacts. Global warming damages are small compared to the damages quantified for the other effects.

Table 32. Summary of external costs of the biomass gasification power plant

Stage	mEuro/kWh
Construction and decommissioning	
Atmospheric emissions	2.05E-01
Occupational accidents	7.70E-02
Feedstock production	
Atmospheric emissions	9.88E-01
Operation of the power plant	
Atmospheric emissions	2.46E+00
Occupational accidents	2.63E-02
Transport of feedstock	
Atmospheric emissions	1.76E-01
Road accidents	2.02E-01
Global warming damages (excluding transportation)	1.04E-01[7.75E-01]
Subtotal	***4.24 (1.14-16.3) [4.91(1.85-16.9)]***

Expressed between square brackets are the external costs calculated considering the CO_2 abatement costs of 19 Euro/t of CO_2.

In the case of biomass gasification fuel cycle, CO_2 emissions are very reduced due to the sink effect of the growing biomass. Consequently, the consideration of a different factor for global warming damages did not alter the external costs results significantly.

Wind energy

The analysis of externalities performed is based in the ExternE National Implementation study published in (European Commission, 1999d) adjusted for the latest changes in the ExternE methodology in the damages estimates for global warming and airborne pollutants. Calculation of the externalities of flywheels was not performed in the above mentioned study but has been included here to take into account the necessity of wind energy of some kind of energy storage.

A detailed calculation of the external costs of wind energy can be found in Lechon and Sáez, 2002. Results obtained are summarised in Table 33.

Table 33. External costs of the wind fuel cycle

	External costs (mEuro/kWh)
Wind life cycle	
Atmospheric emissions	0.18
Occupational impacts	9.70E-05
Global warming	0.13 (0.08-0.22) [1.01]
Noise	0.06
Visual intrusion	0.06 (0-0.6)
Subtotal without flywheel	0.43 (0.32-1.06) [1.32(1.06-2.33)]
Flywheel	
Atmospheric emissions	1.25E-04
Global warming	4.16E-05 (2.44E-05-7.08E-05) [3.12E-04]
Subtotal flywheel	1.67E-04(1.49E-04-1.96E-04) [4.37E-04(3.43E-04-8.14E-04)]
Subtotal with flywheel	***0.43 (0.12-1.53)*** ***1.32(1.06-2.33)***

Expressed between square brackets are the external costs calculated considering the CO_2 abatement costs of 19 Euro/t of CO_2.

Most of the external costs produced are related to the effect of the life cycle emissions in the production of the wind turbines. These life cycle data is characteristic of the current energy system and therefore their use can be misleading when we try to evaluate the future development of this technology.

Photovoltaic energy

The analysis of externalities performed is based in the ExternE National Implementation study published in (European Commission, 1999d) adjusted for the latest changes in the ExternE methodology in the damages estimates for global warming and airborne pollutants. Calculation of the externalities of batteries was not performed in the above mentioned study but has been included here to take into account the necessity of PV energy of some kind of energy storage.

A detailed calculation of the external costs of photovoltaic energy can be found in Lechon and Sáez, 2002. Results obtained are summarised in Table 34.

Table 34. External costs of the PV fuel cycle

	External costs (mEuro/kWh)
PV life cycle	
Atmospheric emissions	8.68E-01
Occupational impacts	-0.28*
Global warming	0.13 (0.08-0.23) [1.02]
Subtotal without batteries	0.72 (0.18-3.00)
Batteries	
Atmospheric emissions	1.23
Global warming	0.08 (0.05-0.14) [0.61]
Subtotal batteries	1.31(1.28-1.37) [1.85(1.12-3.79)]
Subtotal with batteries	***2.03 (0.54-8.06)*** ***[3.45(2.04-9.34)]***

Expressed between square brackets are the external costs calculated considering the CO_2 abatement costs of 19 Euro/t of CO_2.

*Occupational impacts have been calculated taken into account net risks, that is the difference between the risks of average industrial activities and the specific activities related to the life cycle. In the case of photovoltaics this lead to negative damage costs (EC, 1999d)

As explained for wind energy, most of the external costs produced are related to the effect of the life cycle emissions in the production of the PV modules and batteries. These life cycle data is characteristic of the current energy system and therefore their use can be misleading when we try to evaluate the future development of this technology.

Geothermal energy

The analysis of externalities performed is based in the ExternE study published in (European Commission, 1999c) adjusted for the latest changes in the ExternE metholodogy in the damages estimates for global warming. A detailed calculation of the external costs of geothermal energy can be found in Lechon and Sáez, 2002. Results obtained are summarised in Table 35.

Table 35. Summary of results of the geothermal fuel cycle

	mEuro/kWh
Global warming	9.80E-01 (1.82e-02-3.3) [7.76(2.47e-01-1.53e+01)]
Seismic and volcanic effects	1.14E-02 (1.8e-04-3.82e-02)
Impacts on water quality during heat mining	3.16E-01 (1.13e-01-6.11e-01)
Impacts from geothermal fluid release	Nq
Impacts from induced seismicity or subsidence	Ng
Impacts of air pollutants	Ng
Occupational health impacts	2.50E-02 (1.20e-02-3.40e-02)
	1.33 (0.143-3.98) [8.11(0.38-16.0)]

Expressed between brackets are the external costs calculated considering the CO_2 abatement costs of 19 Euro/t of CO_2.

4.3 External costs of advanced nuclear fission

Externalities of a advanced nuclear power plants have been evaluated by CEPN. Main findings are summarised below, and further details can be found in Vaillant et al, 2002a.

4.3.1 Selected advanced reactors

Three selected innovative reactors were identified:

- The Energy Amplifier (EA), which is a hybrid reactor (developed by Carlo Rubbia). The construction of a European demonstrator for hybrid accelerator driven system is not considered before 2010. Progresses in the field of linear accelerator are necessary. An industrial development could be envisaged around 2050.
- The High Temperature Reactor (HTR). In France, the first High Temperature Reactor could be introduced in 2040, but a prototype could already work in Russia around 2010.
- The AMSTER concept (developed by EDF and CEA), which is a molten salt reactor. A molten salt reactor prototype will need a lot of work in the field of pyrochemistry and will not be used at an industrial scale before 2050.

The Energy Amplifier

This hybrid reactor is a sub-critical reactor, in which an external source of neutrons is necessary to keep a constant neutron population. For the Energy Amplifier (Rubbia et al, 1995), the external source is an accelerator associated with a lead target (the spallation target).
In order to keep a fast neutron spectrum and to evacuate heat, liquid metal is used as a cooler. Lead was chosen for safety reasons but it generates several inconveniences (chemical toxicity, corrosion, production of radionuclides, viscosity). Lead allows to keep a low pressure in the core like sodium and thus to reach a good thermodynamic yield.

The fuel considered is a mixture of ^{232}Th and ^{233}U oxides. An EA module consists more precisely of a 1500 MW_{TH} unit with its dedicated 1.0 GeV proton accelerator of 12,5 mA. A plant may be made of several modules.

A cluster of three modular units will produce about 2000 MW_{El}. In order to keep a fast neutron spectrum and to evacuate heat, liquid metal is used as a cooler.

Environmental impacts of the EA were studied through a quantification of gaseous discharges generated by 2 steps of the fuel cycle, the electricity generation and the reprocessing. Details can be found in Vaillant et al, 2002.

High Temperature Reactor

Gas-cooled reactors are considered as a breakthrough towards an economic, safe and sustainable nuclear power. Gas cooled reactors are not expected before 2030 in France. A prototype should be built in Russia around 2010 in the field of the GT-MHR project supervised by the IAEA aiming at the diminution of Russia plutonium stock (Birraux, 1997).

In a HTR reactor, graphite is used as a moderator and helium as a coolant. Helium has numerous advantages: it is chemically inert, transparent to neutrons and not corrosive. Furthermore, there is no secondary circuit. Helium heated in the core (850°C) goes directly through a turbine to produce electricity (this leads to a yield of 48%).

The Pebble Bed Modular Reactor (100 MWe) is an industrial concept of such a reactor.

High Temperature Reactors use coated fuel particles. This technology is quite different from PWR fuel elements. The silicon carbide coatings that surround the uranium fuel particles form a miniature pressure vessel. This pressure vessel provides a highly efficient barrier against the release of fission products during operation. The effective containment of radioactivity at the source results in low levels of contamination in the primary circuit. Within 2040, it is thought that plutonium or minor actinides fuel will be available and that it will be possible to burn them in a HTR (THTR experience personal communication)

^{3}H and ^{14}C discharges during the electricity generation stage are rather low as far as water is no more present in the core. In fact, water is a source of ^{3}H and it carries ^{3}H and ^{14}C from the core to other parts of the reactor in a PWR.

Data concerning releases into the environment from experimental reactors based on gas-cooled reactor technology can be found in Vaillant et al, 2002.

Furthermore, it has been demonstrated that the fuel particles can operate at 1600ºC without losing its capability as a highly efficient barrier against the release of fission products. It is possible to find some information concerning accidental releases for small pebble-bed HTR (125 MWe) (Moorman et al, 1999). Core heat-up events are not dominant, but fission product transport during water ingress accident and depressurisation is relevant.

No economic valuation dealing with accidental releases has been carried out. Occupational collective doses during the electricity generation and the dismantling of experimental reactors were used. Occupational exposure data for the AVR reactor lead to a collective dose of 0.57 person.Sv/year. Collective doses corresponding to the dismantling of the THTR reactor from 1990 to 1996 were measured. An average value of 0.0102 person.Sv/year was observed.

The AMSTER concept

AMSTER is a concept for a graphite-moderated molten salt reactor, in which the salt treatment installation has been redesigned in order to reduce waste production. Using this concept, a large number of configurations can be defined according to the products loaded and recycled. This section presents a configuration in which self-consumes transuranium elements and generates fissile material with a mixed thorium and uranium support. This gives a highly economical reactor for uranium and thorium consumption leading to only a few grams of transuranium elements per TWhe in the ultimate wastes (Lecarpertier, 2001 and Vergnes at al, 2000).

The core of the molten salt reactor consists of an array of graphite hexagons. Each hexagon contains a hole through which the salt circulates. The molten salt envisaged is the same as the one of the MSBR project ($61LiF$-$21BeF_2$-$18HNF_4$). When the salt enters the array (550°C-600°C), it becomes critical and heats up (800°C).

Once heated, the salt is dragged by pumps and passes through salt/salt exchangers (the secondary salt heats up either steam or helium, which can feed a combined cycle turbine plus alternator).

When leaving the core, an on-line reprocessing unit takes a small fraction of the fuel for reprocessing. It consists in extracting the fission products from the salt and is accompanied by the injection into the salt of new nuclei to replace the heavy nuclei fissioned.

The use of lithium and beryllium in the salt generates an important quantity of tritium (around 0.5 grams per day). If several answers are envisaged, one can reasonably wonder how much tritium would be discharged into the environment during the electricity generation stage.

Unfortunately, it was not possible at the time of the study to find any reliable source term for this reactor and thus, no economic valuation of the external costs had been carried out for this reactor.

4.3.2 Calculations of radiological impacts in terms of collective doses

As mentioned above, a detailed description of the radiological impacts associated with the releases into the environment is not possible for the innovative fission technologies studied. Source terms are only available for a few steps of EA and HTR fuel cycles. But considering previous studies carrying out in the field of nuclear fuel cycle external costs, it is thought that those results allow a "reasonable comparison" as far as the main releases are known (mining, electricity generation, reprocessing).

Calculations had been carried out for the HTR and the EA but not for the AMSTER reactor.

Considering electricity generation, calculations were carried out at the same location, Marcoule, and the same meteorological conditions. Calculations dealing with the reprocessing stage releases (EA) were carried out in the La Hague location (North Cotentin, France).

Collective doses resulting from atmospheric discharges were calculated with PC-CREAM (NRPB, 1998) software funded by the European commission. Local (0 – 100 km), regional (0 km – 1000 km) and European collective doses were calculated and integrated over 1, 50, 500, 10 000 and 100 000 years. The results presented hereafter correspond to collective doses integrated over 100 000 years. The global component of the collective dose was taken into account. The global component of the collective dose is the dose associated with dispersion of radionuclide in the area that is not located under the plume.

Collective doses associated with liquid routine releases to the river were calculated with the RIPARIA software (Raffestin et al, 1995) developed by the CEPN to assess the consequences of radioactive releases into the Rhône river. Collective doses associated with liquid releases into the river lead to a radiological impact far less important (several order of magnitude) than those associated with gaseous discharges, located in the local area.

Details on the calculations of collective dosis for the different reactors studied can be found in Vaillant et al, 2002.

4.3.3 Calculations of the external costs

The risk factors per person.Sv used are those derived from the ICRP publication 60 (Table 36) .

Table 36. Risk factors per person.Sv

Exposed population	Fatal cancer	Non fatal cancer	Serious heredity effect
Workers	0.04	0.10	0.008
Public	0.05	0.12	0.013

For valuing the health effects, the monetary values proposed by the ExternE methodology, have been adopted.

To normalize the costs calculated starting from the radiological impacts, the following assumptions are made:

- THTR generates 2.37 TWh/year.

- EA generates 17.5 TWh/year.
- The fusion plant generates 6.6 TWh/year.

Energy Amplifier results

As indicated in Table 37, ^{14}C gaseous release at the reprocessing step could have a very important radiological impact. There is more than one order of magnitude between external costs calculated with or without taking them into account. In the first case, the discount rate has a great importance in reducing the cost linked to releases into the biosphere (one order of magnitude) because it reduces a lot the contribution of ^{14}C to the costs of the radiological impact.

Table 37. Economic valuation of radiological impacts

	DR 0%	DR 3%	DR 10%
Cost in Euro/ year	$1.04\ 10^{8}$	$9.22\ 10^{6}$	$5.37\ 10^{6}$
Cost in Euro/ kWh	$5.94\ 10^{-3}$	$5.27\ 10^{-4}$	$3.07\ 10^{-4}$

Including ^{14}C gaseous release at the reprocessing step

	DR 0%	DR 3%	DR 10%
Cost in Euro/ year	$4.77\ 10^{6}$	$1.90\ 10^{6}$	$1.02\ 10^{6}$
Cost in Euro/ kWh	$2.73\ 10^{-4}$	$1.08\ 10^{-4}$	$5.85\ 10^{-5}$

Not taking into account ^{14}C gaseous release at the reprocessing step

As indicated in Table 38, the reprocessing step is always responsible for most of the radiological impact associated with the EA fuel cycle (from 86.58 to 99.74%).

Table 38. Contribution of the identified step of the EA fuel cycle to the external costs

	DR 0%	DR 3%	DR 10%
Electricity generation	0.26%	2.07%	2.56%
Reprocessing	99.74%	97.93%	97.44%
Mining	0%	0%	0%

Including ^{14}C gaseous release at the reprocessing step

	DR 0%	DR 3%	DR 10%
Electricity generation	5.67%	10.07%	13.41%
Reprocessing	94.33%	89.93%	86.58%
Mining	0%	0%	0%

Not taking into account ^{14}C gaseous release at the reprocessing step

High Temperature Reactor results

HTR shows rather low external costs from 0.0583 to 0.033 mEuro / kWh (Table 39).

As a matter of fact, gaseous releases, which are usually associated with the most important part of the radiological impacts, are quite low for the electricity generation step. Furthermore, as there is no reprocessing stage, gaseous release over the fuel cycle should be quite low.

Table 39. Economic valuation associated with the HTR fuel cycle

	DR 0%	DR 3%	DR 10%
Cost in Euro / year	$1.38\ 10^{5}$	$9.64\ 10^{4}$	$7.82\ 10^{4}$
Cost in Euro / kWh	$5.83\ 10^{-5}$	$4.07\ 10^{-5}$	$3.30\ 10^{-5}$

One should notice that the values presented in Table 39could not be taken as accurate values, as many steps (fuel fabrication, transportation of radiological material, storage of spent fuel…) were not taken into account within the field of this study.

Occupational exposure at the electricity generation stage is the most penalizing step and a growing contribution of mining with the discount rate is observed (Table 40).

Table 40. Contribution of the identified step of the HTR fuel cycle to the external costs

		DR 0%	DR 3%	DR 10%
Public exposure	Mining	14.48%	20.77%	25.59%
	Electricity generation River release	0.01%	0.01%	0.00%
	Electricity generation Gaseous release	14.31%	2.55%	2.04%
Occupational exposure	Electricity generation	69.95%	75.33%	71.09%
	Dismantling	1.25%	1.35%	1.27%

4.3.4 Summary and discussion

External costs values are close for the different technologies considered in this study. The highest values are obtained for the EA, independently of the discount rate. Both technologies should be associated with low external costs. The most penalizing radionuclide, as far as routine releases are concerned, is ^{14}C. We carried out our calculations in the local, regional and European areas. If we had considered the global dispersion of ^{14}C over the world, radiological impacts calculated with PC-CREAM would have been increased by a factor 10, and, as a consequence, external costs. We would have found values around 10^{-3} Euro / kWh.

The radiological impact associated with the disposal of waste was not considered here. Considering the EA and the HTR, several studies can be used to demonstrate the very weak radiological impact associated with this stage for both technologies in terms of individual annual dose rate. Within SERF, this step is dealt with in a rather different way and taking it into account could modify the very qualitative comparison carried out above.

Other stages of the fuel cycles such as manufacturing of the necessary materials and construction and decommissioning of the power plant have not been considered in this study and this fact should be taken into account when comparing the results with those of other technologies.

Furthermore, if the calculations are carried out at the world scale, external costs for both technologies would be higher because of the global dispersion of ^{14}C.

4.4 Comparison of external costs

External costs of the different technologies calculated are compared in this section. External costs of previous fusion plant concepts calculated in SERF3 are also included in the comparison. External cost calculated for advanced technologies are summarised in Table 41.

Table 41. External costs of advanced fossil and renewable technologies

Technology	Stage of technology development	External costs (mEuro/kWh)	Main causes of impacts
IGCC	Demonstration	4.97 (1.96-14.77) [17.58(15.33-26.09)]	Atmospheric emissions in operation (46%) Global warming (39%)
PFBC	Development	9.35 (3.05-32.22) [19.89(14.23-41.68)]	Atmospheric emissions in operation (60%) Global warming (20%)
NGCC	Commercial	2.73 (1.00-8.72) [8.74(7.37-14.11)]	Atmospheric emissions in operation (45%) Global warming (35%)
IGCC with CO2 seq.	Development	3.90 (1.25-13.47) [6.97(4.49-16.23)]	Atmospheric emissions in operation (63%) Global warming (15%)
PFBC with CO2 seq.	Development	6.51 (1.99-23.23) [8.43(3.4-24.894)]	Atmospheric emissions in operation (55%) Global warming (11%)
NGCC with CO2 seq.	Development	2.01 (0.60-7.37) [3.33(2.00-8.56)]	Atmospheric emissions in operation (55%) Global warming (14%)
Biomass gasification	Development	4.24 (1.14-16.30) [4.91(1.85-16.9)]	Atmospheric emissions in operation (58%) Upstream emissions (32%) Global warming (25%)
Fuel cells PAFC	Development	5.31(1.71-18.60) [12.7(9.57-25.2)]	Secondary and upstream emissions (76%) Global warming (21%)
Fuel cells MCFC	Development	3.58 (1.18-12.40) [9.09(7.03-17.3)]	Secondary and upstream emissions (73%) Global warming (24%)
Geothermal	Demonstration	1.33 (0.14-3.98) [8.11(0.37-16.0)]	Global warming (74%) Water quality (24%)
PV with batteries	Commercial	2.03 (0.54-8.06) [3.45(2.04-9.34)]	Secondary emissions (87%) Global warming secondary (13%)
PV without batteries	Commercial	0.72 (0.18-3.00) [1.60(1.12-3.79)]	Secondary emissions (91%) Global warming secondary (9%)
Wind with flywheels	Commercial	0.43 (0.12-1.53) [1.32(1.06-2.33)]	Secondary emissions (42%) Global warming secondary (30%) Noise (14%) Visual intrusion (14%)
Energy amplifier	Development	5.94*	Global collective doses C-14 in reprocessing (99,74%)
HTR	Demonstration	0.06**	Occupational exposure (70%) Global collective doses C-14 in electricity generation (14%) Mining (14.5%)

Expressed between square brackets are the external costs calculated considering the CO_2 abatement costs of 19 Euro/t of CO_2.

*Several stages of the fuel cycle have not been considered in particular the waste disposal, the construction and dismantling of the power plant, and the manufacturing of materials. Furthermore, the global impacts of C-14 have not been evaluated

** Some important stages of the fuel cycle have not been considered: fuel fabrication, transportation of radiological material, storage of spent fuel, waste disposal, construction and dismantling of the power plant and manufacturing of materials. Furthermore, the global impacts of C-14 have not been evaluated

When comparing the external costs of different technologies several considerations have to be taken into account. Firstly is should be noted that in the analysis of the externalities of the fusion fuel cycle most stages of the fuel cycle and most impacts have been considered. In contrast, in other cycles several impacts or stages are missing. For instance, the estimation of external costs of nuclear advanced concepts include only the damage of radiological impacts of the operation and reprocessing stages, other important stages and impacts being excluded from the analysis. External costs calculated for HTR cannot be used for comparison since much of the stages of the fuel cycle have not been taken into account.

Fossil and nuclear fission power plants do not include secondary emissions (emissions from the manufacturing of the construction materials) which are taken into account in renewable technologies and fusion. Secondary emissions have been considered to be trivial in fossil fuel plants compared to the operational emissions, and therefore have been excluded from the analysis (EC, 1995a). However this is not true for renewable energies and fusion in which it has been demonstrated that secondary emissions are capable of causing significant externalities compared to the final externality figure (EC, 1995a; CIEMAT, 1998). Comparison of external costs of technologies that consider secondary emissions and those that do not, are depicted separately in Figure 9.

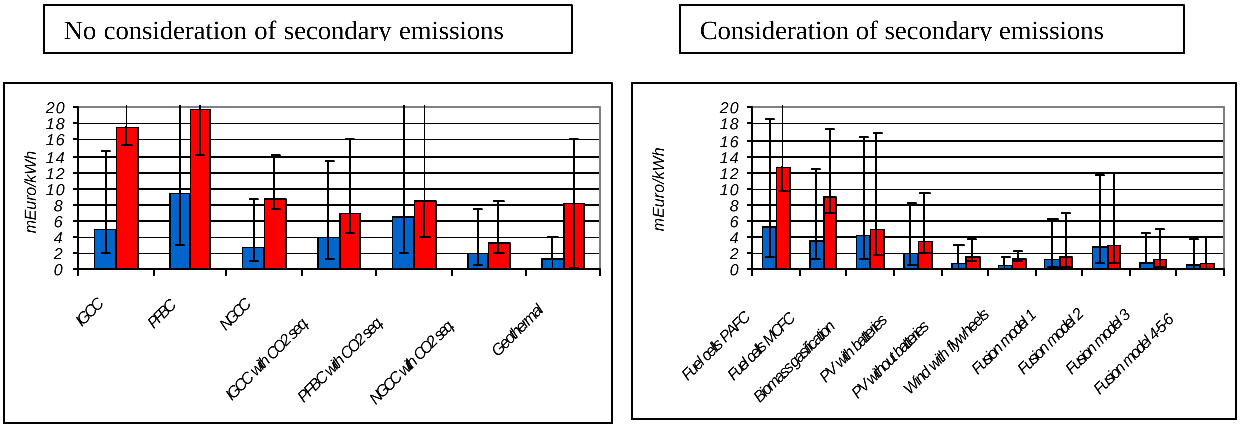


Figure 9. Comparison of external costs of advanced technologies taking into account or not secondary emissions

Renewable technologies considered in this study are current commercial technologies and not advanced concepts. In contrast in other technologies such as fusion, advanced fission and advanced fossil technologies future technological improvement have been explicitly considered. External costs of renewable technologies could experience significant decrements if improvements in efficiency would have been considered. Comparison of external costs of commercial or demonstration technologies and those technologies in development stage are depicted separately in Figure 10.

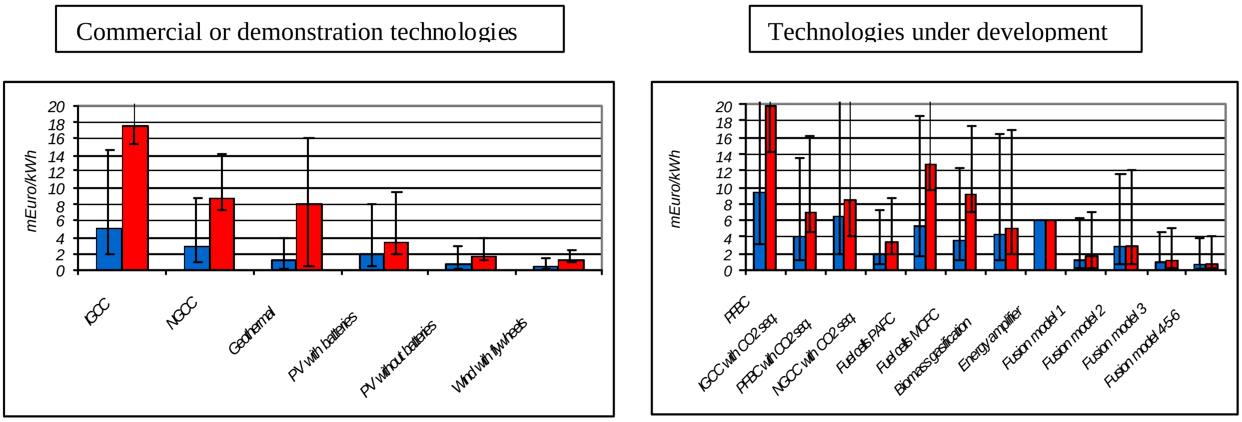


Figure 10. Comparison of external costs of technologies taking into account or not technological advances.

A significant part of the external costs produced in the renewable fuel cycles and fusion are related to the effect of the life cycle emissions in the production of the wind turbines, PV modules or fusion materials, the so call secondary emissions. These life cycle data is characteristic of the current energy system. Future energy systems composed of cleaner technologies could have lower emissions associated, and therefore the external costs associated to renewable technologies could decrease accordingly.

Bearing all these comparison limitations in mind and in order to provide a complete picture of the whole range of technologies considered, a figure showing in blue the external costs of all the technologies has been also included, Figure 11. In this figure it can be seen that fusion, specially the new silicon carbide models, is the energy generation technology of lowest external costs with the only exception of wind energy. Geothermal energy and PV energy follow in external costs. Biomass gasification is the renewable technology of highest costs. Among fossil technologies, NGCC has the lowest external costs and, if CO_2 sequestration is implemented this technology situates very close to renewable technologies as PV. Fuel cells technologies show high external costs mainly due to the fossil origin of H_2.

External costs of the different technologies using the abatement costs of CO_2 of 19 Euro/t are also depicted in red in Figure 11. Some of the technologies are highly affected by this modification, especially fossil technologies, fuel cells and geothermal energy. These technologies show much higher external costs. Renewable technologies are almost not affected due to the very reduced CO_2 emissions of these cycles, especially biomass gasification. Fusion technology is not affected either and becomes the technology with lowest external costs. Consequently the comparison of fossil and renewable technologies changes dramatically when CO_2 abatement costs are considered.

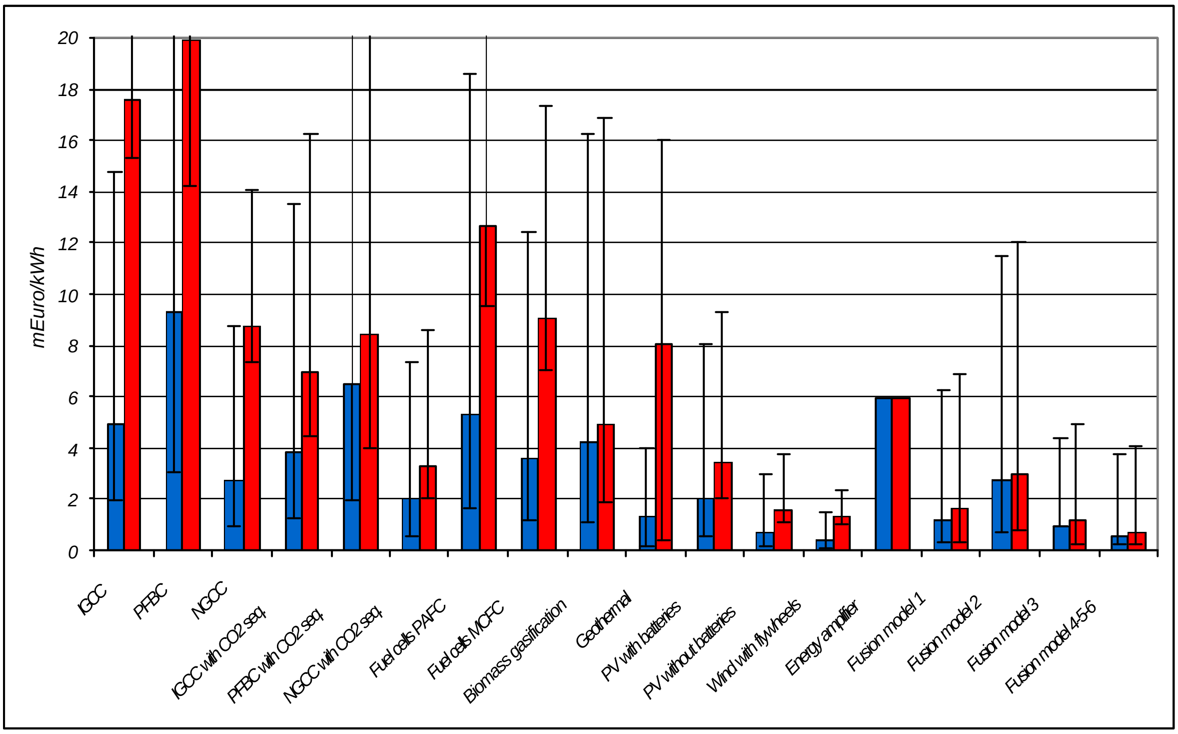


Figure 11. External costs of advanced fossil and renewable technologies in comparison with fusion (in blue colour global warming damage costs of 2.4 Euro/t and in red colour global warming damage costs of 19 Euro/t). (0% discount rate, 10000 years integration time for radiological impacts, 100 years for global warming impacts).

Sensible and uncertain points in the estimation of the external costs of the different fuel cycles have been highlighted along the document but they are summarised here:

- Global warming damages factors considered specially in the case of fossil fuels. Consideration of ExternE damage factor of 2.4 Euro/t of CO_2 or abatement costs of 19 Euro/t of CO_2 changes dramatically the external costs of fossil technologies.
- Period of release of radionuclides from waste repositories and occupational accidents rates in the fusion fuel cycle. Consideration of different release periods or different accident rates can change the value of the external costs obtained.
- Monetary valuation of mortality. Most of the impacts of specially fossil fuels are mortality related impacts. Consideration of different monetary values for these mortality impacts could change the results considerably.
- Inclusion of global impacts. Consideration of global impacts has major implications in the size of the total impact, since some pollutants, radioactive and conventional, may become widely dispersed through global ranges and in many cases global effects are far greater than effects on the regional and local scale. This is specially true in the case of H-3, C-14 and CO_2.
- Integration time of impacts. Impacts expected to have effects over long periods of time should be integrated using a time horizon that includes the full time course of the impact. For radiological impacts of long lived radionuclides such as C-14, consideration of 10000 or 100000 years of integration changes the results considerably. The same should be true for global warming impacts that only are integrated over 100 years, though.

4.5 Reevaluation of C-14 externalities based on safety and environmental studies

Externalities related to the emissions of C-14 in several stages of the fusion fuel cycle have been identified as the main contributor to the total external cost figure. Due to the importance of these impacts, they have been analysed using other approaches than the external costs calculation approach in order to overcome the criticisms that the concept of external costs have. This has been done by IPP using the indicator "Life expectancy". The main results are summarised in section 4.5.1 below, and further details can be found in Hamacher, 2002.

The behaviour of C-14 in a future environment with increasing concentrations of CO_2 in the atmosphere has been evaluated in order to assess the influence of this increased concentration in the C-14 impacts calculated. This has been done by VTT. Main findings are summarised in section 4.5.2 below, and further details can be found in Korhonen, 2002b.

4.5.1 External costs versus environmental standards or other sustainability indices

The concepts of "sustainability" and "sustainable development" are rather fashionable in these days. Measurement of sustainability can be done by very different methodologies: starting from extensions of the national accounting systems like the GDP over the introduction of taxes covering "external costs" up to certificates granted for special products or services. Prominent example is the World Banks "Genuine Savings Indicator". Until now no agreement nor on an international nor on an national level could be established on a set of indicators. Just from this point of view it seems not wise to focus just on one indicator to work out the consistency of "sustainability" and fusion.

The following section starts from shortcomings of the ExternE (EU-Methodology,1995) methodology especially to deal with problems of the very long term and discusses the general problem of making valuations automatically. The debate about the valuation process and the long-term are genuine in most of the indicator discussions. A simple resolution can not be expected for both problems. Instead it is proposed to leave the valuation as an explicit step to be done by the political responsible as a result of a public debate while finding indicators which make the impacts more transparent. This is a very pragmatic approach in respect to the valuation step, which will be done in the "real" world anyhow this way. The problems of the very long-term remain, since no real advocates of future generations are present during the decision process.

The impact on the "life expectancy" might be one of these handy indicators. It is obvious that this indicator in itself will not be able to cover all impacts properly and that more indicators need to be established, it should also be clear that a lot of the technical problems in the evaluation process remain.

What is the problem?

The Socio-Economic Studies on Fusion (SERF) (Borelli, 2001) evaluated the external costs of fusion with help of the ExternE methodology (EU-Methodology,1995). As a matter of fact some items were identified which let to severe problems in the evaluation procedure. The most pronounced was the evaluation of the external costs of ^{14}C releases from possible final repositories. The different values of the external costs varied considerable between the different discount rates. Another major problem is to define a retention time for the final repository (Hamacher,2001) . Another major problem is the valuation of greenhouse gas emissions.

It is therefore doubtful, that the produced numbers can deliver helpful guidelines for a political decision process since the input variables, which can differ over a very broad spectrum, alter the picture completely. The external cost would be as high as 4.7 EUcents/kWh for the case that all ^{14}C is immediately released to the atmosphere and a discount rate of zero is assumed. Keeping the ^{14}C for more than 10000 years reduces the cost to 0.7-0.8 EUcents/kWh and the introduction of a discount rate diminish the cost completely.

Similar problems arise in other areas. While it will not be possible to solve some of the uncertainty in the technical input parameters, like in the ^{14}C retention time, the valuing process might be established in a different form.

It seems in any case wise to stop the analysis at first on the levels of the impacts and to develop indicators to make these impacts transparent. The valuing step involves in any case various ethical and legal problems which can hardly be solved by an easy algorithm.

What is the goal?

The goal of introducing external costs

The concept of external costs was established to explain market disturbances, which occur by costs which are not covered by the consumers. But the concept is used in a broader sense today, especially if applied to environmental impacts:

* external costs could be introduced as taxes to establish a true market again

* the concept of external costs is established to have a scale to compare very different technologies on behalf of their environmental performance

* the concept could be used in a wider scope to be the nucleus to construct a sustainability index.

All of these applications hint in the same direction. They try to find ways and means to correct an economic development that takes environmental aspects not properly into account.

The hope is that the "internalisation" of external costs into the market price will lead to a "sustainable development".

Some remarks to "sustainable development"

The concept of sustainable development is of course a kind of ethical postulation and can be no means be concluded from purely scientific reasoning. The concept itself in the crudest form became prominent because it was and is considered as one of the major guidelines for global politics. The term sustainable is quite old and found one of the first application in forestry. It became famous as being the key term in the report "Our Common Future" widely known as "Brundtland report" issued 1987 by the World Commission on Environment and Development. From then on the term dominated the political rhetoric culminating in the Rio summit 1992 where a number of international processes were launched, including the international efforts to save the global climate, widely known as Kyoto process, and the Agenda 21 process. The definition of "sustainable development" in its simplest form is: **sustainable development is a development that suffices the needs of the current generations without challenging the needs of future generations.**

To clarify it seems wise to distinguish “sustainability” as a future goal and “sustainable development” as steps in this direction.

The transformation of this very general concept to applications in the "real" world is of course more than trivial. The connection between sustainable development and external costs is the hope that in an ideal world (ideal in the sense of the neo-classical economy, the basic ideas of the neo-classical economy about the rational behaviour of the actors was challenged by the recipients of the most recent noble prize in economy) the introduction of external costs would direct the overall development of the economy into a direction that would be sustainable. Introduction of the "true" costs would reflect the "true" consumption of scare resources. This is of course highly debatable, the already mentioned struggle for the correct discount rate is just an example which shows the difficulties.

The concept of "sustainable development" is actually used by different schools in different ways and forms. The two main schools are characterised by the terms strong and soft sustainability. Strong sustainability postulates that the "nature" has a "right" to be preserved. Men is only allowed to use those resources that are renewed all the time. Soft sustainability confines the concept only to the right of humans. "Nature" might be altered, as it always was in the past, as long as the needs of humans today or in the future are not challenged.

Shortcomings of the ExternE method

All the technical problems involved in making an environmental, economic or social appraisal of a technology should be ignored for a second. Only the step from the impact analysis to the valuation should be discussed here. In case of the ExternE method this step is done by a monetary valuation, all impacts from the nuisance of looking at a windmill up the flood victim in Bangladesh are all converted to money. The amount of money assigned to every value is inferred from “preferences” which are analysed by “empirical” methods.

This method faces two major criticisms: first in major ethical systems there is a clear hierarchy of values, which can not be traded against each other. But there is of course a second more technical shortcoming: can we extract peoples value systems from their preferences. Preferences can of course be extracted by social empirical science methods. But are these preferences really identical with the value system of the researched people. This becomes even more questionable, when it is assumed that consumers have deep insights in the impact of a special device. Hardly anyone knows how his or her probability to die in an accident changes when she or her buys a new safety belt. In the evaluation of the Value of a Statistical Life it is of course a very important assumption, that this knowledge is well known.

“Life expectancy” as impact indicator

Impacts on human life and health dominate the composition of external costs.

Most of the external costs are contributed by health effects mainly mortality. Therefor it seems wise to look for an indicator which is strongly coupled to human health. An indicator summing up all the effects on human life and health is the life-expectancy.

The advantage of the life-expectancy is that it does not only “measure” environmental impacts, it depends also on social issues, like violence and education. Another advantage is that an analysis of the life-expectancy values “positive” externalities.

Life expectancy as indicator covering health and social factors

The following part is based on the article (Sen,1993). Sen starts form the idea, that common measures of economic "welfare" like the GDP do not account well enough for the standard and quality of life and the distribution of wealth. He argues that new indicators need to be developed. One proposal is to look into the development of the life-expectancy.

The Impact of the energy system on the life expectancy

The energy system causes huge material movements including the emission and releases of various toxic and non-toxic substances to the environment. Impacts on human health and environment are rather obvious. This makes the energy system to be of major concern for environmental and health debates.

A very simple model of the life expectancy is developed. Male and female population of age i are described by $p_{i,m}$ and $p_{i,f}$ respectively. The number of children born depends on the number of women $p_{i,f}$ and there age dependent fertility rate f_i:

$$p_{0,w} = D_w \sum_{i=0}^{i=\max\_age} p_{i,f} f_i$$

$$p_{0,m} = D_m \sum_{i=0}^{i=\max\_age} p_{i,f} f_i$$

The distribution between boys and girls is given by D_w and D_m with $D_w + D_m = 1$. The development of the population is from then on determined by the age dependent mortality rate $m_{i,m}$ for male and $m_{i,f}$ for female.

$$p_{i,f} = p_{i-1,f}(1 - m_{i-1,f})$$

$$p_{i,m} = p_{i-1,m}(1 - m_{i-1,m})$$

The number of people of one age i that die are given by:

$$d_i = p_{i,f} m_{i,f} + p_{i,m} m_{i,m}$$

The often quote number children per women is then given by:

$$\#C/W = \sum_{i=0}^{\max\_age} f_i \prod_{j=0}^{i-1} (1 - m_{j,f})$$

The life expectancy is then given by:

$$LE = \frac{\sum_{i=0}^{\max\_age} d_i i}{\sum_{i=0}^{\max\_age} d_i}$$

A few examples should illustrate the methodology. If we assume the electricity sector would lower the life expectancy by one year and that 6 billion people live in the world and produce 12000 TWh of electricity. To reach such a high impact each TWh of electricity produced would need to be responsible for 152 fatalities equally distributed over the age structure. The age structure is assumed to be flat for simplicity.

A sector which actually leads to a substantial number of fatalities is the traffic sector. With 8000 people killed of the 80 million inhabitants in Germany every year a reduction in life expectancy of 119 days is connected.

The impact of 14C emissions of an intense fusion economy on the development of the life expectancy

The impact of ionising radiation on human health are matter of broad scientific debate. Until now it seems reasonable to assume a linear doses-response function (EC-Nuclear, 1995), (ICRP, 1991).

In a first example the impact of the natural background radiation on the life expectancy should be analysed. The background radiation accounts for roughly 1 mSv/a per person. With the values from table this leads to a probability of a fatality of roughly $5*10^{-5}$/capita. This translates to a loss of life expectancy of 59 days.

An intense fusion economy as discussed in (Hamacher,) would in the worst case lead to an increase of the radiation level of roughly 1 % of the natural background radiation. The impact on the overall life expectancy would then be roughly 0.59 days or 14 hours.

The impact of an intense coal economy on the life expectancy

The underlying assumption is, that coal becomes again the primary source for electricity production. Second assumption is that no emission reductions compared to current plants are expected for the future. All impact values are taken form [ExternE-coal].

If we do assume that all 500 TWh of electricity production in Germany would be supplied by coal. The external costs caused by fatalities account for roughly 1 EuroCent/kWh. This would mean 2000 fatalities, if we assume that a human life is valued with 2.6 Meuro. In the underlying model this would lead to a decrease of life expectancy of 28 days.

Dicussion

The success of fusion to gain first further R&D money and second to win a major share in the energy market will strongly depend on the ability of the fusion proponents to prove that fusion goes very well along with the concept of sustainable development. A large number of sustainability indicators exist. None of these indicators is finally established neither on a national nor on an international political platform. The ExternE methodology finds strong support from the European Commission and is actually used in practical decisions. Nevertheless it seems wise to look for more possible indicators.

The ExternE method has a number of shortcomings – beside technical shortcomings inherent in every discussion of future developments. Therefor it is suggested to look for additional indices. The idea is to look first for indicators that make the impacts today and in the future more transparent. The indicators should show the areas that are effected and the way they are effected.

Life-expectancy could be one of these indicators. Life-expectancy is studied already in other context to be an indicator for social development. But it should be clear, the indicator life-expectancy just illustrates the impact, a final decision on technologies will definitely not be done on behalf of this information alone. Insofar is the indicator “life-expectancy” not as powerful as the ExternE methodology.

The impacts of fusion on the life-expectancy are only marginal, even in the worst case. This is not the case for other technologies, especially for the traffic.

4.5.2 Impacts and transfer of C-14 releases in the future environment

Introduction

Global impacts of radionuclide C-14 releases due to operation and waste repositories were found to dominate the radiological impact in SERF1 and SERF2 studies. Factors that contribute to radiation doses caused by C-14 in the atmosphere and accumulation into vegetation are therefore among the key variables. In these studies, circulation of C-14 has been assessed as a part of the natural carbon cycle without considering the impact of carbon flows caused by increased amounts of carbon dioxide in the atmosphere (Saez et al. 2001, Korhonen 2000a).

In the future environment the carbon dioxide levels in the atmosphere will increase. This has impact on the transfer of C-14. Besides dilution impact (so called Suess effect) anthropogenic carbon dioxide has impact on the flows of carbon in the environment. Some basic evaluations of the impact of the future increase of the atmospheric carbon dioxide concentration levels on the estimation of the global impacts of C-14 emissions are presented in this section.

Carbon cycle

Simple models have been used to describe the preindustrial distribution of carbon between some most important environments (atmosphere, terrestrial reservoirs, surface ocean and deep ocean). Naturally produced nuclide C-14 has cycled in the environment with the carbon flows and the natural C-14 background in the atmosphere has been about 140 PBq before the nuclear tests started after about 1950. Natural amount in the atmosphere can be estimated on the basis of the same models when the radioactive decay of C-14 decay is included.

Estimation of amounts of carbon in the atmosphere in a situation in which "extra" carbon is released to the atmosphere differs from the stationary situation. Marginal behaviour can differ from the average behaviour of natural carbon flows. Amounts of releases can have an impact on the behaviour of carbon. Also the time scale could have has impact on the transfer.

Flows of carbon can be divided into two components: 1) the natural flow and 2) flow caused by anthropogenic influence. The natural flows are the preindustrial flows, which have caused the atmospheric concentration about 280 ppm. Anthropogenic component is caused due to carbon dioxide emissions to the atmosphere. Use of fossil fuels and deforestation are the main causes for these emissions. The second flow component behaves differently from the first component.

The capacity of the seas to take up CO_2 is closely connected with the carbonate equilibrium of sea water. Seas can take up CO_2 due to its solubility but especially due to chemical reactivity with carbonate ions:

$$H_2O + CO_2(aq) + CO_3^{\,2-} \leftrightarrow 2HCO_3^{\,-}$$

CO_2 in seawater is found in three forms. Dissolved CO_2 is only about 1% from the total amount of carbon in sea water. It can be exchanged with the atmosphere. Most CO_2 are in the form of bicarbonate ions $HCO_3^{\,-}$ (presently about 90% from the total). Carbonate ions $CO_3^{\,2-}$ are important in the reaction. Earth crust and sediments include great amounts of $CaCO_3$, which also dissolves into water and is transferred to seas especially via rivers. Sedimentation causes an output term for carbonate ions.

Preindustrial CO_2 concentration is mainly a long term equilibrium concentration. When extra CO_2 compared to equilibrum flows is transferred into the surface seas (marginal model case), the total CO_2 in the surface sea increases much less than the total amounts in equilibrium give. A ”buffering” effect produces that the extra CO_2 is transferred much more effectively back to the atmosphere than in the case of average flow (average model).

Buffering factor has been implemented in the compartment model so that the flow from surface sea back to the atmosphere has been assumed to be by a factor ten (approximately the buffering factor) more rapid than in the case of the average flow.

Two models (Korhonen 2000b, Saez et al. 2001) are presented. They are simple compartment models, which include only main flows of carbon. The model for transfer of carbon in the preindustrial situation is called the average model). The model for the extra flow is called the marginal model. The difference in models is that flow from surface sea to the atmosphere is much more rapid in the situation of the anthropogenic flow component. Models are rather approximate versions of actual transfer. Especially regional differences have not been included, but only average flows have been considered. In real environment cold northern sea areas are efficient in transferring carbon from the atmosphere, when warm sea areas cause net transfer to the atmosphere.

Details on the calculations performed using the models can be found in Korhonen 2002b.

The difference between the behaviour of carbon in the two studied cases, the case of the natural carbon flow and the case of extra carbon flow is rather big. In the following indices for the evaluation of carbon emissions are evaluated by using built models and re-evaluated results for C-14 emissions are presented.

Indices for the evaluation of C-14 impact

The response function used -a*r(t)- gives the time behaviour of a unit release, e.g. amount in the atmosphere or an impact, which can be estimated by multiplying r(t) with the constant a. Integration of a*r(t),

$$a * R(t) = a * \int_0^t r(t)\,dt, \qquad (1)$$

gives a) integrated impact due to a unit release, b) time behaviour (accumulation) of impacts in the case of constant unit release rate. Behaviour of carbon in two model situations for two carbon nuclides, C-12 and C-14 is considered.

Impacts studied in the following are:

a) time integral of carbon (tonne-years of carbon in megatons, MtC) in the atmosphere (MtCa per MtC released or TBqa per TBq released)

b) accumulation of carbon in the atmosphere (MtC per release rate 1 MtC/a or TBq per release rate 1 TBq/a; or a, accumulation time).

Use of interpretation b is often restricted to a more limited time span (time span when constant emissions occur) than interpretation a (emission pulse). Also relevancy of models can be restricted; both marginal model and natural flow model have a limited time span when they can be used adequately.

Integrals of response functions are presented in Figure 12 y Figure 13. Time period up to 1000 years is given in Figure 12. Time period 0 – 10,000 is presented in Figure 13. Marginal model is adequate for about the order of 5000 years, natural flow model also for longer time spans (if environmental changes e.g. warming excluded).

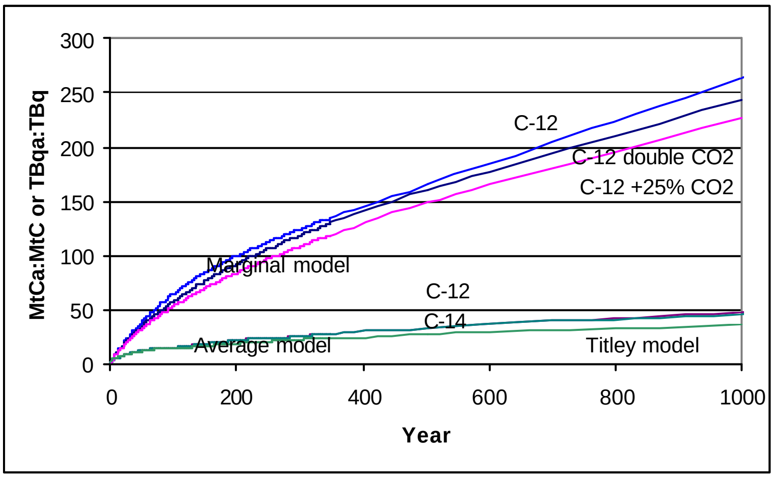


Figure 12. Time integral (0 - 1000 years) of carbon releases in the atmosphere (MtCa:MtC released or TBqa:TBq released) or accumulation of constant releases (MtC:MtC/a or TBq:TBq/a) evaluated by natural flow model (average model) and model for increased carbon flows (marginal model). Models of Maier-Reimer for carbon dioxide(or C-12) and Titley for C-14 also given.

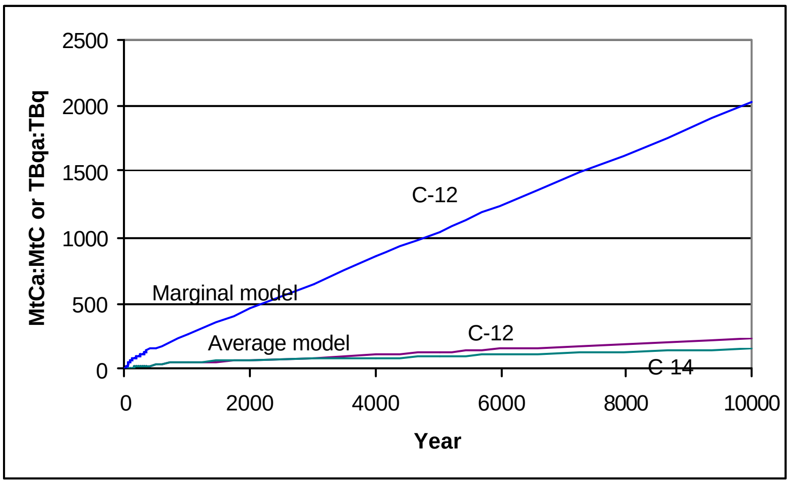


Figure 13. Time integral (0 - 10,000 years) of carbon releases in the atmosphere (MtCa:MtC released or TBqa:TBq released) or accumulation of constant releases (MtC:MtC/a or TBq:TBq/a) evaluated by natural flow model (average model) and model for increased carbon flows (marginal model).

Tonne years proposed to be used in the estimation of impacts of carbon could also be called AGTY(P) or Absolute Global Tonne Year(s Potential). Atmospheric tonne years for carbon dioxide emissions are very analogous to Atmospheric Global Becquerel Years (AGBqY).

Impact of C-14 emissions to humans

Dose impacts are estimated on the basis of C-14 in the atmosphere. Dose due to C-14 in atmosphere can be estimated by assuming that the specific activity of carbon (Bq C-14 per g carbon) in the atmosphere will be same as the specific activity of carbon in food (vegetation). Collective Dose Commitment per unit release CDC (manSv per TBq) can then be estimated on the basis of the integral of the response function R(t):

$$CDC = a^* R(t) = Pop^*Use^*C^{-1}{}^* DF^*R(t), \qquad (2)$$

where Pop is the population of the world,

Use is the amount carbon ingested (kg/a per person),

C is the amount of carbon in the atmosphere (GtC),

DF is effective dose factor due to ingestion (Sv/Bq).

If population is 10^*10^9 people and amount of carbon were the preindustrial amount 600 GtC, the constant a ($Pop^*Use^*C^{-1}{}^*DF$) is 1.0 Sv/TBqa. (Use of carbon 100kg/a per person, DF 5.8^*10^{-10} Sv/Bq.) Therefore it is easy to present the results either as Becquerel years or as manSv.

Impact index CDC is analogous to AGWP (Absolute Global Warming Potential) which is estimated using formula (1); a is in the calculation of AGWP the extra warming at the tropopause (W/m^2 per amount of extra carbon in the atmosphere). Both indices give global impacts due to carbon in the atmosphere (carbon dioxide or C(C-12) given in tons or C-14 given in Bq). For the nuclide C-14 impact will be collective dose (or health impacts estimated on the basis of doses), for carbon dioxide warming impact given as W/m^2 or totally in watts. Index CDC could be called AGDP (Absolute Global Dose Potential) to be more analogous. The indices AGDP and AGWP are based on more basic indices AGBqY and AGTY.

The future behaviour of carbon dioxide concentrations is the most important assumption to be considered. As amounts of C-14 are small (mass of C-14) and it flows as a part of carbon (C-12) flows, C-14 will transfer with the total flow of carbon. The model for that flow is built as a combination of average model and marginal model. The combined model has been used in cases of double (550 ppm) and triple concentration level (825 ppm) compared to the preindustrial level. The simplified basic assumption has been that flow to the surface seas will increase in proportion to atmospheric CO_2 concentration. Flow from surface seas to the atmosphere will increase due to the marginal kind of behaviour of carbon. Extra flow to vegetation due to increased concentration level has not been considered. This is similar to the assumption in the marginal model of CO_2 emissions.

C-14 impacts and stabilisation of CO_2 concentration levels 550 ppm (double) and 825 ppm (triple the preindustrial concentration)

Indices evaluated for the situation of double concentration are: a) Collective effective dose commitment by the year t due to a “unit” release (manSv per TBq released), or index corresponding to other interpretation b) of formula (1), which considers continuing releases (manSv/a per release rate TBq/a). Then dose commitment by the year t due to a “unit” release rate is given (manSv per release rate TBq/a).

Becquerel years in the atmosphere would, according to model calculations, be higher in the case of increased CO_2 concentration than in the preindustrial situation. The amounts of C-14 in the atmosphere would increase, if constant releases would continue. Becquerel years are in the case of triple concentration level less than half the tonne years in the time span 0 – 100 years. Collective dose commitment would not increase. They decrease, but relatively little compared to the concentration increase. Especially in the long term collective dose commitments will decrease relatively little.

In Figure 14 and Figure 15 integrated impacts due to constant emissions are given. Accumulation integral, integrated Becquerel years (TBqa:TBq/a) are given for the time scale 0 – 1000 years. Long term emissions are possible e.g. in the scenarios of large scale use of fossil or fusion energy for 1000 years or due to waste disposal also when energy is not produced. In Figure 14 tonne year indices (MtCa:MtC/a) are also given for comparison. In the considered time scale the impact of the radioactive decay is so small that difference in the tonne and Becquerel year indices is only caused by the difference of the flows (average or marginal or combined). The CDC values (manSv:TBq/a) give collective dose commitment in the situation of double CO_2 concentration and also in the case of preindustrial concentrations (same numerical value than response integral in the case of average model in TBqa). Integrated impacts are absolutely high as also total releases are thousandfold the annual release. In Figure 15 collective dose commitment indices are studied. For the preindustrial CO_2 concentration the values integrated Becquerel years are the same as the values of collective dose commitments per continuing unit release. For double and triple CO_2 concentration levels integrated Becquerel years increase compared to preindustrial situation. Integrated collective dose commitment indices are smaller than in the preindustrial CO_2 concentration situation. However, especially in the long term they are relatively little smaller when compared to the ”diluting impact” increased CO_2 concentration.

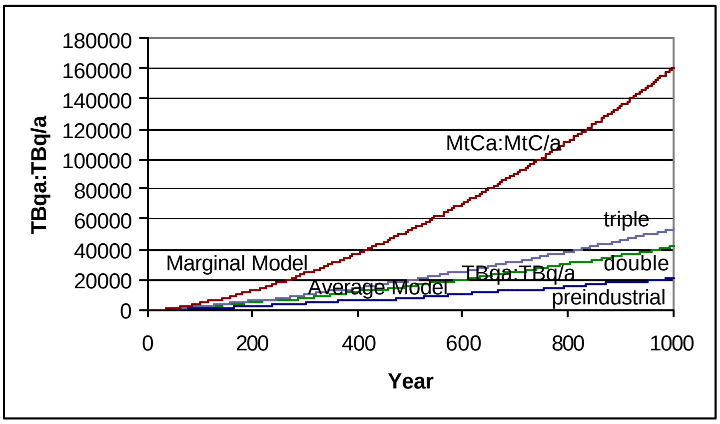


Figure 14. Integrated Becquerel year indices for C-14 for constant release rate (TBqa:TBq/a or a^2) in the case of preindustrial concentration about 275 ppm and CO_2 stabilisation level 550 ppm (double the preindustrial level) and 825 ppmm (triple the preindustrial level). For comparison integrated tonne year indices also presented. Time span 0 – 1000 years.

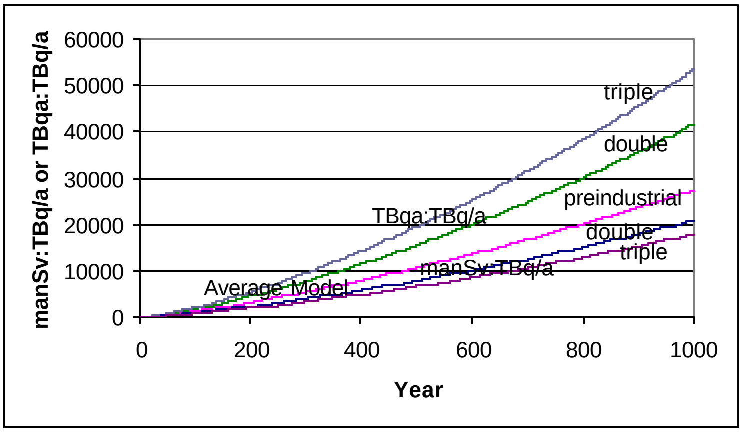


Figure 15. Estimated Collective Dose Commitment indices for C-14 for constant release rate (manSv:TBq/a) in the case of preindustrial concentration and CO_2 stabilisation level 550 ppm (double the preindustrial level) and 825 ppm (triple the preindustrial level). Time integral of C-14 (C-14 in the atm; TBqa:TBq/a) also presented for that situation. Time span 0 – 1000 years.

Summary and discussion

A methodology to consider the impact of increased atmospheric CO_2 concentration in the assessment of C-14 releases is presented. Especially accumulation of C-14 in the atmosphere and accumulation of collective dose commitments are studied. Models built have been rather simplified ones, which consider only the main flows of carbon. Values of paramaters and structure of modelling have not been considered in detail, as the aim has been to study some main differencies of the transfer and accumulation of anthropogenic CO_2 releases and C-14 releases and reconsider transfer of C-14 on the basis of these studies.

It seems evident, that accumulation of C-14 in the atmosphere will increase due to increased carbon dioxide concentrations in the atmosphere. The Suess effect or fossil fuel effect is often assessed to cause reduction of the ratio of radiocarbon C-14 to stable carbon, but it seems that the effect will be rather temporary and impacts to collective doses will in the long term be rather small. Especially evident will be the increase of the amounts of C-14 in the atmosphere. Studies give that impact of Suess effect seems to decrease and almost lose its importance in a few decades.

The methodology in the evaluation is based on the concepts of two kind of carbon cycling models: average natural flow models and marginal flow models. Global warming impacts due to CO_2 releases are caused due to marginal kind of behaviour of carbon releases. C-14 emissions are usually studied using average natural flow models. C-14 behaviour in the future environment where carbon dioxide level has increased has been evaluated by combining models. Inventories in the atmosphere and collective dose commitments (manSv:TBq) have been evaluated. Methods and concepts could be further applied in the estimation of release situations and also in the comparison of the evaluation of the impacts of CO_2 releases and C-14 releases.

The concept of Becquerel years in the atmosphere has been presented and is used in the evaluation of C-14 transfer. It is analogous to the concept tonne years in the atmosphere considered especially in the climate negotiations of forest sector and studied in the IPCC special report on land use, land use change and forestry LULUCF (IPCC 2000a, IPCC 2000b). Values of the quantity Becquerel years in the atmosphere increase when CO_2 concentration increases. This means that C-14 lifetime in the atmosphere increases and in the case of continuing emissions it accumulates for longer time spans in the atmosphere. Impacts on the collective doses are smaller due to diluting impact of increased CO_2 concentration. The diluting impact or Suess effect will in some decades decrease due to increased lifetime and the total impact will be that dose impact will decrease relatively little also in the case of e.g. triple concentration level compared to preindustrial concentration.

Assumptions about the future behaviour of carbon dioxide concentrations are important in the evaluation of the transfer of C-14 in the future environment. Amounts of C-14 in the atmosphere will increase, as “old” C-14 transfers to the atmosphere and accumulation times of new emissions (natural or anthropogenic) increase. However, it has been depicted that increased collective dose commitments of releases are relatively little dependent on the CO_2 concentration level in the range about 450 – 900 ppm.

5. CONCLUSIONS

External costs of new concepts of fusion power plants using silicon carbide as structural material have been evaluated and the results obtained compared to the external costs of other advanced energy generation technologies.

Fusion power plants with using silicon carbide have external costs of around 0.6-0.7 mEuro/kWh, which are lower than external costs previously obtained in SERF1 and 2 for fusion power plants using steel as structural material. The use of silicon carbide allows a higher thermal efficiency and this fact has a great impact in the external costs figure expressed in terms of external costs per unit of electricity produced. C-14 impacts, considered as the most important contributor to the external costs figure in previous models, have been reduced considerably, having only a major role in waste disposal impacts. Other nuclide having an impact on global doses is Tritium whose impacts dominate the power plant operation stage of the fuel cycle.

Since radiological impacts are very reduced, other aspects such as occupational aspects become important. Especially noticeable are the external costs related to accidents in the construction and decommissioning of the power plant. It is important to stress that these external costs have been calculated on the basis of accident statistics in the several sectors involved in the construction of the power plant for the year 1995. Accident rates could decrease considerably by the year 2050 when the construction of the power plant would start, reducing accordingly the external costs produced.

Two scenarios for waste handling have been considered. In the first, waste is treated according to present practice, and only the non heat-generating part of the radioactive is assumed to be recycled. In the second future prospective scenario, recycling of waste material will be much more extensive than according to present practice. Differences in external costs between these two scenarios are very reduced.

Waste disposal external costs are conditioned by the retention and release period considered. External costs can vary in 2 and a half order of magnitude depending on the assumption made.

External costs for a hypothetical accident of the fusion power plant have been evaluated asumming an accidental scenario of a complete loss of coolant for a prolonged time period with no operation of any safety system. The probability of occurrence of such an accident has been considered to be 10^{-7} per reactor year. Calculation of external costs of this accidental scenario gave values in the range of 10^{-7} to 10^{-6} mEuro/kWh which are very reduced compared to total costs calculated for the fusion fuel cycle. It must be noted that this evaluation does not take into account risk aversion.

External costs of other advanced technologies have been calculated. The technologies have been selected taking into account the expected share they will have in future energy scenarios. Only technologies expected to play a major role in future energy system have been assessed. The technologies selected are the following:

- Fossil technologies:
    - Advanced coal technologies with carbon capture and disposal: Pressurised Fluidized Bed Combustion (PFBC) and Integrated Gasification Combined Cycle (IGCC)
    - Natural gas combined cycle with carbon capture and disposal (IGCC)
- Fuel cells powered by natural gas

- Renewable technologies:
    - Biomass gasification
    - Wind power
    - Solar photovoltaics
    - Geothermal energy
- Advanced Nuclear fission:
    - The Energy Amplifier (EA)
    - The High Temperature Reactor (HTR).
    - The AMSTER concept

Technological advances have explicitly considered whenever possible. However, in the case of renewable technologies such as PV or wind energy, the technologies considered are current commercial technologies and not advanced concepts. Other limitation in the comparison of external costs is the consideration or not of secondary emissions in the different technologies and the inclusion or not of important fuel cycle stages and impacts.

Fusion is the energy generation technology of lowest external costs with the only exception of wind energy. Geothermal energy and PV energy follow in external costs. Biomass gasification is the renewable technology of highest costs. Among fossil technologies, NGCC has the lowest external costs and, if CO_2 sequestration is implemented this technology situates very close to renewable technologies as PV. Fuel cells technologies show high external costs mainly due to the fossil origin of H_2.

External costs using the abatement costs of CO_2 of 19 Euro/t are rather different in some technologies, especially fossil technologies, fuel cells and geothermal energy. These technologies show much higher external costs. Renewable technologies and fusion are almost not affected due to the very reduced CO_2 emissions of these cycles, especially in the case of biomass gasification. Consequently the comparison of fossil and renewable technologies changes dramatically when CO_2 abatement costs are considered. Fusion technology is not affected either and becomes the technology with lowest external costs.

A significant part of the external costs produced in the renewable fuel cycles and fusion are related to the effect of the life cycle emissions in the production of the wind turbines, PV modules or fusion materials. These life cycle data is characteristic of the current energy system. Future energy systems composed of cleaner technologies could have lower emissions associated, and therefore the external costs associated to renewable technologies decrease accordingly.

Externalities related to the emissions of C-14 in several stages of the fusion fuel cycle have been identified as the main contributor to the total external cost figure in previous SERF projects. Due to the importance of these impacts, they have been analysed using other approaches than the external costs calculation approach in order to overcome the criticisms that the concept of external costs have. This has been done using the indicator “Life expectancy”. The results showed that the impacts of fusion on the life-expectancy are only marginal, even in the worst case. This is not the case for other technologies.

The behaviour of C-14 in a future environment with increasing concentrations of CO_2 in the atmosphere has been evaluated in order to assess the influence of this increased concentration in the C-14 impacts calculated. The results show that the increased collective dose commitments of releases are relatively little dependent on the CO_2 concentration level in the range about 450 – 900 ppm, though.

6. REFERENCES

AP-42. 2002. Compilation of Air Pollutant Emission Factors AP.42, Fifth Edition. Volume I. Stationary point and Area Sources. Available in http://www.epa.gov/ttn/chief/ap42/

Aquilonius, K. and B. Hallberg. 2002. SERF3 Socioeconomic Research on Fusion (2001-2002). Task: External Costs of Fusion. Task Deliverable D2: Inclusion of further plant models into the analysis. Externalities of Decommissioning and Site restoration Stages. Final Report.

Aquilonius, K. and Hallberg, B. 2000a**.** Socio-Economic Research on Fusion 2, SERF 2 (1999-2000). Externalities of Fusion Task 1: Analysis of key variables influencing external costs. Subtask 1.1. Completion of specific studies on aspects not addressed in the previous SERF. 1.1.5. Recalculation of externalities considering new activated materials. 1.1.5.2. Decommissioning and site restoration. Studsvik Eco & Safety AB, Sweden, July 2000.

Bergström, U. and Hallberg, B. 2000b. Socio-Economic Research on Fusion 2, SERF 2 (1999-2000). Externalities of Fusion. Task 1: Analysis of key variables influencing external costs. Subtask 1.1. Completion of specific studies on aspects not addressed in the previous SERF. 1.1.6. Review and improvement of the methodology to calculate uncertainties. Studsvik Eco & Safety AB, Sweden, July 2000.

Bergström, U. and Nordlinder, S. 1991. Methods for Calculation of Reference Release Factors for Atmospheric Releases (in Swedish: Metodik för beräkning av referensutsläppsfaktorer för luftutsläpp). Studsvik Report S/NS-91/96, Studsvik Eco & Safety AB, 1991.

Borelli et al., 2001. Socio-Economic Research on Fusion, EFDA-RE-RE-1 July 20, 2001

Brandon, N. And D. Hart. 1999. *An Introduction To Fuel Cell Technology And Economics.* Imperial College. 1999.

Brodén, K, and Olsson, G. 2001. Evaluation of possibilities for clearance or repository disposal of tritiated and activated components of the SEAFP-99 plant models. Studsvik RadWaste AB, Sweden 2001 (Technical Note RW-01/57).

Brodén, K, Lindberg, M and Olsson, G. 1998. Repository analysis for fusion reactor waste. Studsvik RadWaste AB, Sweden 1998 (Technical Note RW-98/46).

Broden, K. and Olsson, G 1994. Waste management analysis quantification of waste for final disposal. SEAFP/R-A9.6(94), rev1.

BIRRAUX, c. 1997. La reconversion à des fins civiles des stocks de plutonium militaire, Rapport à l'OPECST N°2974, 1997.

Rubbia, C.; J.A. Rubio, S. Buono, F. Carminati, N. Fiétier, J. Galvez, C. Gelés, Y. Kadi, R. Klapisch, P. Mandrillon, J.P. Revol And Ch. Roche, 1995. Conceptual design of a fast neutron operated high power energy amplifier**,** Geneva, 29th September, 1995.

Cabinet Office. 2002. "The energy review". AQ performance and Innovation Unit report.

Caldeira and P.B Duffy 1998. Tracing the role of carbon dioxide in global warming. Science and Technology March 1998.

Caldeira, G. H. Rau and P. B. Duffy 1998. Predicted net effect of radiocarbon from the ocean and increase in atmospheric radiocarbon content. Goephysical Research Letters, vol. 25, no. 20, pp. 3811-3814.

Chyssler, J., Eriksson, A., Johnsson, B. and Wirendal, B. 1998. The 1997 Environmental Report According to the Environmental Protection Act (in Swedish: 1997 års rapport enligt miljöskyddslagen). Tech. Note RW-98/18, Studsvik RadWaste AB, 1998.

Ciemat 1998. Socio-Economic Research on Fusion, SERF 1997-98. Macro Task E2: External Costs and Benefits. Summary Final Report. Ciemat, Spain, December 1998.

Ciemat 2000. Socio-Economic Research on Fusion, SERF2 (1999-2000). Task1: Externalities of fusion. Exploitation and improvement of work performed under SERF1 (1997-1998).1.1.5 Recalculations of externalities considering new activated materials, 1.1.5.1 Upstream stages and power generation. Ciemat, Spain, July 2000.

Ciemat 2001. Socio-Economic Research on Fusion, SERF 2 (1999-2000). Externalities of fusion. Task 1: Externalities of fusion. Exploitation and improvement of work performed under SERF 1. Final report. Ciemat, Spain, January 2001.

Cline, W.R. 1992. Optimal carbon emissions over time: experiments with the Northaus DICE Model. Institute for International Economics, Washington, DC.

Cook, I., Marbach, G., Gulden, W., Di Pace, L., Rocco, P., Girard, C., Taylor, N. 1999. Safety and Environmental Assessment of Fusion Power. Report for the SEAL and SEAFP-2 Projects, 1999.

Cruz, I. 2002. Personal communication.

Lecarpentier, D. 2001. Le concept AMSTER, aspects physiques et sûreté, PhD, June 29th, 2001.

DOE, 1995. Coal: Energy for the future.

DOE, 1999. "Carbon sequestration research and development" Available in www.fe.doe.gov/coal_power/sequestration/reports/rd/index.shtml.

Dreicer M., Tort V., Manen P., 1995. Nuclear fuel cycle: Estimation of physical impacts and monetary valuation for priority pathways, Report 234 CEPN, 1995.

EREN, 2002. Energy Storage technologies. Web page: www.eren.doe.gov

EUREC, 1996. The future for renewable energy. Prospects and directions.

European Commission (1995a) ExternE, Externalities of Energy, Summary, Vol. 1,

European Commission (1995b) ExternE. Externalities of Energy. Vol 2. Methodology.

European Commission (1995c) ExternE. Externalities of Energy. Vol 4 Oil&Gas.

European Commission (1995d) ExternE. Externalities of Energy. Vol. 3. Coal & Lignite. EC, DG XII, Report EUR 16522 EN.

European Commission (1995e) ExternE. Externalities of Energy. Vol. 5. Nuclear. EC, DG XII, Report EUR 16524 EN.

European Commission (1996) Overview of energy RD&D options for a sustainable future.

European Commission (1999a). ExternE. Externalities of Energy. Vol 7. Methodology 1998 Update.

European Commission (1999b). ExternE. Externalities of Energy. Vol 8. Global Warming.

European Commission (1999c). ExternE. Externalities of Energy. Vol 9. Fuel Cycles for Emerging and End Use Technologies, Transport and Waste.

European Commission (1999d). ExternE. Externalities of Energy. Vol 10. National Implementation.

European Commission, PC-CREAM 97, PC system for assessing the radiological impact of routine releases, Report EUR 17791 EN, NRPB-SR296, June 1997.

Evertt and A. Wilks, The World Bank's Genuine Savings Indicator: a Useful Measure of Sustainability?, www.brettonwoodsproject.org

ExternE National Implementation Finland, Final Report December 1997.

Fankhauser, S. 1995. Valuing Climate Change. Earthschan, London.

Final Report on the Full-Power Operation of the AVR Experimental Nuclear Power Plant. Personal communication.

Friedrich, R. 2002. Personal communication.

Friedrich, R. and Bickel, P. 2001. *Environmental External Cost of Transport*. Ed Springer.

GEDEON WORKSHOP: Scenarios And Innovative Systems, November 19th And 20th, 2001. CNRS, Auditorium Marie-Curie, 3 Rue Michel Ange, 75016 PARIS.

Goldthorpe et al, 1992 as cited in Holloway et al, 1996. "The underground disposal of Carbon dioxide" Summary report. British geological survey, Keyworth, Nottingham, UK.

Green, M.A. Photovoltaics; technology overview. Energy Policy 28 (2000) 989-998.

Gruppelar, J. P. Schapira, Thorium As A Waste Management Option, Report For The European Commission Eur 19142 En, 2000.

Meyer, J. P. Witherspoon, J. P. Mcbride, E. J. Frederick, Comparison Of The radiological impact of thorium and uranium fuel cycles, NUREG/CR-2184 and ORNL/TM-7868, Oak Ridge National Laboratory, 1982.

Hallberg, B. and Nordlinder, S. Socio-Economic Research on Fusion, SERF 1997-98. Macro Task E2: External Costs and Benefits, Subtask 1.6. Evaluation of External Impacts of a Fusion Power Plant. Decommissioning and Site Restoration Final Report, Rev. 1, Studsvik Eco & Safety AB, Sweden, 27 November 1998.

Hamacher et al., Radiological impact of an intense fusion economy, Fusion Engineering and Design 56-57, (2001) 1037-1042

Hamacher, T., IPP, Germany, personal communication, 1998.

Hofman, D. and Bergström, U. PRISM/Windows 4.0 – User's Manual. Studsvik Eco & Safety AB, Sweden, (STUDSVIK/ES-00/31), 2000.

http://web.ead.anl.gov/resrad/home2

IAEA, 1994. Handbook of parameter values for the prediction of radionuclide transfer in temperate environments. International Atomic Energy Agency, Vienna, Austria. Technical Reports Series No. 364.

IAEA, 2000. Modelling of the transfer of radiocaesium from deposition to lake ecosystems. Part of the IAEA/CEC Co-ordinated research programme on the Validation of Environmental Model Predictions (VAMP). International Atomic Energy Agency, Vienna, Austria 2000. IAEA-TECDOC-1143. 343 p.

ICRP 2000. Radiation protection recommendations as applied to the disposal of long-lived solid radioactive waste. ICRP Publication 81, Annals of ICRP. 25 p.

ICRP, 1991 1999 Recommendations of the International Commission on Radiological Protection. Publication 60, Annals of the ICRP, Pergamon Press, UK

IEAa,"Carbon dioxide capture from power stations" Green House Gas R&D Programme. Available in www.ieagreen.org.uk

IEAb,"Carbon dioxide disposal from power stations" Green House Gas R&D Programme. Available in www.ieagreen.org.uk

IEAc,"Ocean storage of CO_2 " Green House Gas R&D Programme. Available in www.ieagreen.org.uk

IEAd "Global warming damage and the benefits of mitigation" Green House Gas R&D programme. Available in www.ieagreen.org.uk.

Interlaboratory Working Group. 2000. "Scenarios for a Clean Energy Future" Oak Ridge National Laboratory and Berkeley, CA; Lawrence Berkeley Laboratory. ORNL/CON-476 and LBNL-44029.

International Atomic Energy Agency, Derived intervention levels for application in controlling radiation doses to the public in the event of a nuclear accident or radiological emergency, Safety Series No. 81, IAEA, Vienna, 1988.

International Atomic Energy Agency, Principles for criteria in a nuclear or radiation emergency, Safety series No. 109, IAEA, Vienna, 1994.

International Nuclear Fuel Cycle Evaluation (INFCE). Waste management and disposal. Report of INFCE Working Group 7. Vienna: IAEA, 1980. 288 p.

IPCC, 1996. Revised 1996 IPCC Guidelines for National greenhouse Gas Inventories: Reference Manual.

IPCC 2000a. Land Use, Land-Use Change, and Forestry. A Special Report of the IPCC. Cambridge University Press. 377 p.

IPCC 2000b. Summary for Policymakers. Land Use, Land-Use Change, and Forestry. A Special Report of Intergovernmental Panel on Climate Change. 20 p. http://www.ipcc.ch/pub/SPM_SRLULUCF.pdf

IPCC 2001. Climate change 2001: The scientific basis. Contribution of Working group I to the third Assessment Report (TAR) of the Interncovernmental Panel of climate Change. Great Britain. Cambridge University Press. ISBN: 0521 01495 6. 881p.

ITERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Publication 60: Recommendations Of The ICRP, 1990.

J. Vergnes, Et *Al.*, The Amster Concept In Actinide And Fission Product Partitioning And Transmutation, Nea, Madrid, 2000.

JT Houghton, LG Meira Filho, B Lim, K Treanton, I Mamaty, Y Bonduki, DJ Griggs and BA Callender (Eds) 1996. "Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories" IPCC/OECD/IEA. UK Meteorological Office, Bracknel

Kugeler, H. Barnert, P.-W. Phlippen, W. Scherer, Sustainable Nuclear Energy with HTR for Future Application, Seminar on HTGR Application and Development, Beijing, China, March 19th – 21th, 2001**.**

Kohyama, A., Katoh, Y., Snead, L.L. and Jones R.H. “Development of SiC/SiC Composite for fusion application”

Korhonen, R and Savolainen I. 1984. Biospheric transfer model DETRA for assessment of radiation impacts. Espoo 1984. VTT Research Reports 323. 147p.

Korhonen, R. 1991. Model studies of the transfer of radionuclides in the Finnish environment. VTT, Espoo. 54 s. + annexes 60 s. Publications / Technical Research Centre of Finland : 81. ISBN 951-38-4060-3.

Korhonen, R. 1998. Comparison of external costs of nuclear fission and fossil fuels to fusion. E2 macrotask report of SERF1.

Korhonen, R. 2000a. Evaluation of doses and external costs due to long term disposal of fusion waste. Externalities Subtask 1.1.5.3 report of SERF2 August 2000. 27p.

Korhonen, R. 2000b. Identification of key variables in external costs due to long term disposal of fusion waste. Externalities Subtask 1.2.3 report of SERF2 December 2000. 28p.

Korhonen, R. 2000c. Impacts of future fusion economy to global warming and global ionizing radiation. Externalities Subtask 3.2 report of SERF2 December 2000. 21p.

Korhonen, R. 2002a. Socioeconomic Research on Fusion. SERF3 (2001-2002) Task: Externalities of fusion. Deliverable D2. Externalities of waste disposal. Final report.

Korhonen, R. 2002b. Re-evaluation of C-14 impacts in the future environment. SERF3 Externalities D3 Final report. November 2002. 23p.

Korhonen, K. Pingoud, I. Savolainen and R. Matthews 2002. The role of carbon sequestration and the tonne-year approach in fulfilling the objective of Climate Convention. *Environmental Science and Policy*, Vol.5, no.6, pp. 429–441.

Krewitt, W. 1999. Personal communication.

Krewitt, W. 2002. “External costs of energy-do the answers match the questions? Looking back at 10 years of ExternE”. Energy Policy 30, 839-848.

Lechón Y. and Sáez, R. 2002. SERF 3 SOCIO-ECONOMIC RESEARCH ON FUSION (2001-2002). Task: External Costs of Fusion. Task deliverable D1: Comparison of fusion with other technologies taking into account their expected technological change. Comparison with advanced fossil and renewable technologies. Task deliverable D2: Inclusion of further plant models into the analysis. Externalities of upstream and power generation stages. Final report.

Lechon, Y., Ciemat, Spain, personal communication, 1998.

Lechón, Y., Cabal, H., Sáez, R.M., Ward, D., Hallberg, B., Aquilonius, K., Korhonen, R., Hamacher, T., Schneider, T. and Lepicard, S. Exploitation and improvement of the external costs assessment of fusion power, Fusion Eng. Des. 58-59 (2001) 1027-1032.

Lepicard S., Raskob W., Vaillant L., Benhamou C., Schneider T., Impacts associated with a tritium release from a fusion power plant, CEPN-NTE/02/38, 2002.

Lepicard, S., Schneider, T. and Vaillant, L. Socio-Economic Research on Fusion, SERF 3 (2001-2002). Externalities of fusion. Deliverable D2. Inclusion of further plant models into the externalities assessment. Externalities of fusion accident: sensitivity analysis on plant model and site location. CEPN, France, 2002.

Maddison, D. 1994. The shadow price of greenhouse gases and aerosols. CSERGE. University College, London.

Maier-Reimer, K. Hasselmann 1987. Transport and storage of CO_2 in the ocean. An inorganic ocean-circulation carbon cycle model. *Climate Dynamics*, no. 2, pp. 62–90.

Mineral Resources, 1997 "Prospect for silicon carbide production in New South Wales, Australia . New South Wales Department of Mineral Resources. Available in www.minerals.nsw.gov.au.

Navicenovik, N. And K. Riahi. 2002. As assessment of Technological Change across selected energy scenarios" IIASA.

Nordhaus, W.D. 1994. Managing the global Commons: The Economics of Climate Change. MIT Press, Cambridge, MA.

NRPB 1991. BIOspheric MOdel Validation Study – an international study to test models designed to predict the environmental transfer and bioaccumulation of radionuclides andothertracesubstances. National Institute of Radiation Protection, Stockholm , Sweden. Technical reports 1-12 during 1989-1991.

OPTIa. 1999. "Primer Informe de Prospectiva Tecnológica Industrial. Futuro Tecnológico en el horizonte del 2015". EOI, AINIA, ASCAMM, CIEMAT, CITMA, ICT, INASMET, INESCOP, IQS.

OPTIb. 2000. "Segundo Informe de Prospectiva Tecnológica Industrial. Futuro Tecnológico en el horizonte del 2015". EOI, AINIA, ASCAMM, CIEMAT, CITMA, ICT, INASMET, INESCOP, IQS.

OPTIc. 2002. "Energía. Tendencias tecnológicas a medio y largo plazo". OPTI, MCYT, IDAE, CIEMAT.

Palmerini C.G. 1993. Geothermal energy. In: *Renewable energy: Sources for fuels and electricity*. Johansen T.B., Kelly H., Reddy A.K.N., and Williams R.H. eds. Island Press, Washington D.C., pp 549-591.

Pasquill, F. and Smith, F.B. Atmospheric diffusion. Study of the dispersion of windborne material from industrial and other sources. Third edition, Ellis Horwood Ltd, Chichester, 1983.

PBMR nuclear safety, http://www.pbmr.com,

PC-CREAM 97, PC system for assessing the radiological impact of routine releases, National Radiological Protection Board, Report EUR 17791 EN, NRPB-SR296, June 1997, updated in 1998.

Peck, S.C., Teisberg, T.J. 1993. CO2 emissions control: comparing policy instruments. Energy Policy 21, 222-230.

PRé Consultants BV, 2001. SIMAPRO 5.

Moormann, et *al.*, Source term estimation for small sized HTRs: status and further needs – a German approach in Survey on basic studies in the field of high temperature engineering, NEA, Paris, 1999.

Raeder, J. *et al.*, Safety and Environmental Assessment of Fusion Power (SEAFP), European Commission DG XII, Brussels, 1995

Raffestin D., Lepicard S., Michou P., Riparia : Logiciel D'évaluation De L'impact Radiologique Associé Au Relâchement De Matières Radioactives En Milieu Fluvial, Rapport Cepn N°237, Mai 1995.

Rantik, 1999. Life cycle assessment of fuve batteries for electric vehicles under different charging regimes. Chalmers University of Technology. Department of Transportation and Logistics.

Rocco P., Zucchetti, M. and Edwards R.A.H. Advanced waste management techniques for fusion reactors with SiC/SiC structures. Fusion Engineering and design 58-59 (2001) 997-1000, 2001.

Saez R., Et Al., Serf2 (1999-2000) Externalities Of Fusion, Sub-Activity 1.1.5. Recalculation Of Externalities Considering New Activated Materials, Ciemat Report, August 2000.

Sáez et al. 2001. Externalities of fusion. Exploitation and improvement of work performed under SERF1. Final report of SERF2 Externalities prepared by CIEMAT. January 2001. Participants: T. Schneider, S. Lepicard, CEPN, Association Euratom-CEA, France, T. Hamacher, Euratom/IPP Fusion association, Germany, B. Hallberg, K. Aquilonius, Studsvik Eco & Safety AB, Association Euratom-NFR, Sweden, D. Ward, Euratom/UKAEA Fusion Association, United Kingdom, R. Korhonen , VTT, Association Euratom-Tekes, Finland, R. Sáez, H. Cabal, Y. Lechón, Euratom/CIEMAT Fusion Association, Spain. ISBN:84-7834-389-x. 81p.

Saez R., Lechon Y., Cabal H., Et Al., Socio-Economic Research On Fusion Serf 1997-98, Ciemat, 1999.

Sáez, et al. 1999. Socioeconomic research on fusion Serf 1997-98. Informes Técnicos Ciemat.

Sandell, Y. Release of radioactive substances from AB SVAFO and Studsvik Holding AB. Monthly report for December 2000 (in Swedish: Utsläpp av radioaktiva ämnen från AB SVAFO och Studsvik Holding AB. Månadsrapport för december månad 2000). Tech. Note N(R)-01/012, Studsvik Nuclear AB, 2001.

Schieber C., Benhamou C., Unit Costs To Be Used For The Evaluation Of The Long Term Agricultural Countermeasures, Rodos(Wg3)-Tn(99)-30, 1999.

Schneider T., Lepicard S., Evaluation Of Radiological And Economic Consequences Associated With An Accident Of A Fusion Power Plant, Serf2 Sub- Task 1.1.8, Cepn-Nte/00/08, 2000.

Sigman, E. A. Boyle 2000. Glacial/interglacial variations in atmospheric carbon dioxide. Nature vol 407 (2000), pp.859 – 869.

Sen,1993 Lebensstandard und Lebenserwartung, Spektrum der Wissenschaft, 11, 1993

Sources and effects of ionising radiation, Vol. I, UNSCEAR 2000.

Sources and effects of ionizing radiation. United Nations Scientific Committee on the Effects of Atomic Radiation UNSCEAR 1982 Report to the General Assembly, with Scientific Annexes. New York, NY: United Nations, 1982. 773p.

Sources and effects of ionizing radiation. United Nations Scientific Committee on the Effects of Atomic Radiation UNSCEAR 1988 Report to the General Assembly, with Scientific Annexes. New York, NY: United Nations, 1988. 647p.

Sources and effects of ionizing radiation. United Nations Scientific Committee on the Effects of Atomic Radiation UNSCEAR 1993 Report to the General Assembly, with Scientific Annexes. New York, NY: United Nations, 1993. 922p.

Sources and effects of ionizing radiation. United Nations Scientific Committee on the Effects of Atomic Radiation UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes. New York, NY: United Nations, 2000. 1302 p.

Spath, P.L. and M.K. Mann. 1997. *Life Cycle Assessment of a Biomass Gasification Combined–Cycle System.* NREL Life Cycle Assessment.

Suolanen, Vesa and Ilvonen, Mikko1998. Generic uncertainty model for DETRA for environmental consequence analyses. Application and sample output. STUK-YTO-TR:149, Helsinki. 20p.

T. Seguchi et al., Heat Resistant SiC-Fiber Synthesis and Reaction Mechanisms from Radiation-Cured Polycarbosilane Fiber, Proc. 6th European Conference on Composite Materials (September 1993, Bordeaux) 51. As cited in JAERI http://inisjp.tokai.jaeri.go.jp.

Taylor N.P. and Sublet J.Ch. SEAFP-99. Description of additional plant models with silicon carbide structure. EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, UK. SEAFP-99/S2.1/UKAEA/1 (Rev. 1) April 1999.

Taylor, N.P. and J-Ch. Sublet. 1999. Description of additional plant models with silicon carbide structure. SEAFP99/S2.1/UKAEA/1(Rev. 1).

THTR experience: waste management, off gas systems, management of aerial effluents, decommissioning**.** Personal communication.

Titley, T. Cabiana, G. Lawson, S. F. Mobbs and J. Simmonds 1995. Improved global dispersion models for iodine-129 and carbon-14. EUR 15880 EN. Luxembourg, Office for Official Publications of the European Communities. ISBN 92-827-0090-9. 151 p.

Trends in nuclear fuel cycle: Economic, Environmental and Social Aspects**,** NEA, 2002.

UKAEA 2001. Ward, David. Technical inputs on additional models of conceptual fusion power plants. November 2001.

UKAEA, 2000. Inventories of model plants for SERF2 Model plants.

UKAEA, 2002. Inventories of model plants for SERF2 Model plants. David Ward, personal communication.

UNSCEAR 2000. Sources and effects of ionizing radiation. United Nations Scientific Committee on the Effects of Atomic Radiation UNSCEAR 2000. Report to the General Assembly, with Scientific Annexes. Vol. I: Sources. New York, NY: United Nations, 2000. ISBN 92-1-142238-8. 654 p.

Vieno, Timo; Mészáros, Ferenc; Nordman, Henrik; Taivassalo, Veikko 1993a. Safety analysis ofdisposal of decommissioning waste from the Olkiluoto nuclear power plant PURKU-93. Nuclear Waste Commission of Finnish Power Companies YJT, Helsinki. 112 p. Report /YJT : 93-27

Vieno, Timo; Nordman, Henrik 1991. Safety analysis of the VLJ repository. Nuclear Waste Commission of Finnish Power Companies YJT, Helsinki. 200 p. Report / YJT : 91-12

Vieno, Timo; Nordman, Henrik 1996. Interim report on safety assessment of spent fuel disposal TILA-96. POSIVA, Helsinki . 176 p. POSIVA : 96-17 ISBN 951-652-016-2

Vieno, Timo; Nordman, Henrik; Taivassalo, Veikko; Nykyri, Mikko 1993b. Post-closure safety analysis of a rock cavern repository for low and medium level waste. Radioactive Waste Management and the Nuclear Fuel Cycle. Vol. 17 (1993) No: 2, pp.139 - 159.

Vuori, Seppo 1996. Radiation and environmental safety of spent nuclear fuel management options based on direct disposal or reprocessing and disposal of high-level waste (in Finnish). Ministry of Trade and Industry, Helsinki, 68 p. KTM, Studies and Reports 8/1996.

Ward, D. (2001) Technical inputs on additional models of conceptual fusion power plants. SERF3/UKAEA/EFCA2.1.

Ward, D. 2002. Personal communication.

Wirendal, B., Studsvik RadWaste AB, personal communication, 1998.