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Socio-Economic Research on Fusion
SERF 1997-98

Macro Task E2: External Costs and Benefits
Task 2: Comparison of External Costs

Report R2.2

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Summary

This report is part of the SERF (Socio-Economic Research on Fusion) project, Macro Task E2, which covers External Costs and Benefits. The report is the documentation of Task 2, Comparison of External Costs.

The aim of Task 2 Comparison of External Costs, has been to compare the external costs of the fusion energy with those from other alternative energy generation technologies. In this task identification and quantification of the external costs for wind energy and photovoltaics have been performed by RISØ, while identification and quantification of the external costs for nuclear fission and fossil fuels have been discussed by VTT.

The methodology used for the assessment of the externalities of the fuel cycles selected has been the one developed within the ExternE Project. First estimates for the externalities of fusion energy have been under examination in Macrotask E2. Externalities of fossil fuels and nuclear fission have already been evaluated in the ExternE project and a vast amount of material for different sites in various countries is available. This material is used in comparison. In the case of renewables wind energy and photovoltaics are assessed separately.

The external costs related to fusion energy are assessed to be in the same range as renewables like wind and photovoltaics. However, taking into consideration the operational costs may give advantages for renewable energy sources. In the case of wind energy today the operational costs (45 mECU/kWh) are a little higher than costs based on fossil fuels, while the operational costs of PV's are about 320 mECU/kWh. A survey performed for a number of long-term forecasts for the wind power technology in general shows a decrease in production costs of 2-2.5% p.a., which implies that the cost of wind-generated electricity would be halved by the year 2030, making it competitive to conventional fossil fuel based electricity production. The PV costs are expected to decrease during the next 10-50 years. Before 2010 it is expected to be reduced by a factor of five and some time between 2010 and 2050 electricity production based on photovoltaics will be fully comparable to fossil fuels, while operational costs for fusion are expected to be somewhat higher.

Both fusion and fission have rather low external costs and it is not easy to observe the difference between these alternatives on the basis of external costs. The fission power plants with relative low costs among the studied cases are probably more commensurable cases for comparison between fusion and fission in the future around 2050. Still the costs of both alternatives could be even lower if very long-term integration of doses were not considered or if discounting were used. On the other hand externalities of the costs due to nuclear accidents are estimated to be very low in case the estimates are based on expectation values of economic damages. Therefore, the point that severe accidents will not occur in fusion power production has no remarkable impact on the external costs of fusion. The accounting of risk aversion may increase the contribution of accidents to the total external costs considerably.

Global warming impact due to carbon dioxide emissions is the dominating term in the fossil fuel cycles, when modern plants are compared. If other costs of fossil fuel cycle were almost avoided due to future technical development the external costs due to

global warming are so high for all power production technologies using fossil fuels that they dominate over fusion or fission costs. This is also otherwise evident; negotiations to restrict carbon dioxide emissions are going on. Still global warming and long-term doses have not been considered in a very commensurable way.

It seems not very relevant to compare only the monetarised external costs as it is obvious that the costs for fusion will be rather low compared to fossil fuels, especially due to the global warming costs related to fossil fuels. The external costs for fusion have been estimated to be approximately the same as for some renewables. However, it must be stated that the estimates of the external costs for fusion are rather preliminary and need to be assessed more detailed in order to get a comparable estimate.

External costs of the various alternatives may change as new technologies are developed and costs can to a high extent be avoided (e.g. acidifying impacts but also global warming due to carbon dioxide emissions). Also fusion technology can experience major progress and some important cost components probably can be avoided already by 2050.

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Contents

Abstract

This report is part of the SERF (Socio-Economic Research on Fusion) project, Macro Task E2, which covers External Costs and Benefits. The programme for Socio-Economic Research on Fusion (SERF) was started in the autumn of 1997 following an initiative from the EU-commission. The programme includes a number of different tasks and subtasks – all related to the long-term development of fusion. These tasks include the development of long term energy/economy scenarios, status and perspectives for the technical development of fusion and alternative technologies, and the evaluation of externalities related to these technologies. Finally, a number of sociology related topics are treated in the programme.

This report is part of the Macro Task E2, which covers External Costs and Benefits, and is the documentation of Task 2, Comparison of External Costs. The aim of this task is to compare the external costs of fusion energy with those from other alternative energy generation technologies. Task 2 has been prepared in the following sub-tasks.

Sub-task 2.1. Evaluation of external costs of wind and photovoltaic energy.

The work covers identification and quantification of the external costs for wind energy and photovoltaics using the ExternE methodology. The sub-task should include assessment of the long term development (mid 21st century) of these external costs, but due to lack of data this part of the task has not been carried out. The analysis in this sub-task has been carried out by RISØ National Laboratory.

Sub-task 2.2. Evaluation of external costs of nuclear fission and fossil fuels.

In this subtask the external costs for nuclear fission and fossil fuels have been evaluated by VTT using mainly the ExternE material.

Sub-task 2.3. Comparison of external costs. Renewables.

In this sub-task RISØ has performed the comparison of externalities calculated for renewable energy sources with those from fusion. In the comparison the long-term development of renewable energy has been taken into consideration.

Sub-task 2.4. Comparison of external costs. Nuclear fission and fossil fuels.

A comparison of external impacts of the fusion fuel cycle and nuclear fission and fossil fuel cycles has been carried out by VTT energy, also considering the long-term development.

The methodology used for the assessment of the externalities of the fuel cycles selected has been the one developed within the ExternE Project *(CEC, 1995 a-f)*. It is a bottom-up methodology with a site-specific approach; i.e. it considers the effect of an additional fuel cycle located in a specific place. The study is using a unified approach to ensure compatibility between results. This is being achieved through the use of the EcoSense software package, which is an integrated computer system developed at the University of Stuttgart. It assesses the environmental impacts and

resulting external costs from electricity generation systems. The system has an environment database at both a local and regional level including population, crops, building materials, and forests. The system also incorporates two air transport models, allowing local and regional scale modelling. A set of impact assessment modules, based on the dose-response relationships used in the ExternE Study, and also a database of monetary values are included for different impacts.

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Introduction and conclusion has been performed in collaboration.

1. Introduction

This report is part of the SERF (Socio-Economic Research on Fusion) project, Macro Task E2, that covers External Costs and Benefits.

The aim of Task 2 Comparison of External Costs is to compare the external costs of the fusion energy with those from other alternative energy generation technologies. Monetarised external costs for fusion will be compared to those for alternative energy sources for electricity generation. In this task identification and quantification of the external costs for wind energy and photovoltaics have been performed by RISØ using the ExternE methodology, while identification and quantification of the external costs for nuclear fission and fossil fuels have been discussed by VTT using the same methodology.

This report presents the results of these analyses and a comparison of the externalities of the respective alternative energy sources with those of fusion energy.

First estimates for the externalities of fusion energy have been under examination in Macrotask E2. Externalities of fossil fuels and nuclear fission have already been evaluated in the ExternE project and a vast amount of material for different sites in various countries is available (*Saez and Linares, 1997*). This material will be used in comparison. In the case of renewables wind energy and photovoltaics are assessed separately in the present report.

Various problems are, however, associated with comparison. One problem is the fairness of comparing technology of today with energy production technologies in the year 2050 or onwards. Material for future technologies in the field of fission, fossil fuels and renewables are not yet available and one has to use the existing material of ExternE and other sources for the present day technology. This must be understood only as a starting point for comparison of fusion. Some insight into future aspects can be obtained by studying the most important cost components in some more detail.

Another problem is, that the site of the plant has impact on the external costs. As one should make valid comparisons, reference cases should be commensurable, but this is not yet quite possible. High population density causes e.g. higher doses. On the other hand environments with low population can be sensitive to pollution, e.g. parts of Northern Europe are rather sensitive to acidification. In comparison of costs it is not possible to use similar sites, e.g. for wind energy specific sites are necessary. In ExternE 'real' sites which describe the natural, socio-economic and demographic conditions are used. For fusion only one site has been studied.

As is evident the comparison, assuming technology of today for alternatives, with fusion, gives rather low external costs for fusion and relatively high external costs for fossil fuels, especially coal (and peat). The important costs will be studied and explained in detail to make the comparison more transparent. The comparison, however, is not quite adequate as the alternatives are based on the technology of today and as present environmental conditions are assumed. On the other hand also fusion technology will proceed until 2050 and some notified important cost components might be decreased or avoided. As environmental conditions in the future probably are closer to various kind of ‘saturation’ (critical loads, concentration targets for global warming), underestimation of some impacts will occur, while some other impacts (transfer of radionuclides and health impacts due to caused doses) may not be affected by that kind of saturation. The consideration of time scales, space scales and discount rates impact costs considerably.

2. Methodology

The methodology used for the assessment of the externalities of the fuel cycles selected has been the one developed within the ExternE Project *(CEC, 1995 a-f)*. It is a bottom-up methodology, with a site-specific approach; i.e. it considers the effect of an additional fuel cycle, located in a specific place.

The ExternE Project uses the 'impact pathway' approach for the assessment of the external impacts and associated costs resulting from the supply and use of energy. The analysis proceeds sequentially through the pathway, as shown in Figure 2.1. Emissions and other types of burden such as risk of accident are quantified and followed through to impact assessment and valuation. The approach thus provides a logical and transparent way of quantifying externalities.

To allow comparison to be made between different fuel cycles, it is necessary to observe the following principles:

- Transparency, to show precisely how the work was done, the uncertainty associated with the results, and the extent to which the external costs of any fuel cycle have been fully quantified.
- Consistency, with respect to the boundaries placed on the system in question, to allow valid comparison to be made between different fuel cycles and different types of impact within a fuel cycle.
- Comprehensiveness, to consider all burdens and impacts of a fuel cycle, even though many may not be investigated in detail. For those analysed in detail, it is important that the assessment is not arbitrarily truncated.

These characteristics should be present along the stages of the methodology, namely: site and technology characterisation, identification of burdens and impacts, prioritisation of impacts, quantification, and economic valuation.

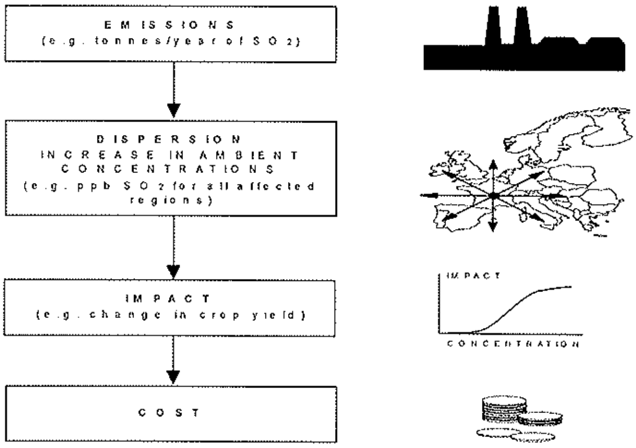

Figure 2.1 An illustration of the main steps of the impact pathway methodology applied to the consequences of pollutant emissions. Each step is analysed with detailed process models.

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, as required by the marginal approach.

The underlying principle for the economic valuation is to obtain the willingness to pay off the affected individuals to avoid a negative impact, or the willingness to accept the opposite. Several methods are available for this, which will be adopted depending on the case.

The study is using a unified approach to ensure compatibility between results. This is being achieved through the use of the EcoSense software package, which is an integrated computer system developed at the University of Stuttgart. It assesses the environmental impacts and resulting external costs from electricity generation systems. The system has an environment database at both a local and regional level including population, crops, building materials and forests. The system also incorporates two air transport models, allowing local and regional scale modelling. A set of impact assessment modules, based on the dose-response relationships used in the ExternE Study, and also a database of monetary values are included for different impacts.

3. The Wind Fuel Cycle

In 1995 about 8% of the energy production in Denmark was covered by renewable energy. Wind power produced about 5% of the total electricity production. Ultimo 1996, 825 MW wind power have been estimated to be installed *(Danish Wind Turbine Manufacturers Association, 1997).* It is the intention to extend the wind power to 1700 MW by the year 2005, of which 310 MW will be offshore.

There is a large amount of unused wind resources in Denmark as well on land as offshore. On land, however, areas with good wind conditions are limited due to the size of the country, its relatively high population density, and the disposal of areas for forestry, bird protection areas, and industry. For all these reasons Denmark constructed the world's first offshore wind farm in 1991, and today two such wind farms are in operation.

Both of the existing offshore wind farms, Vindeby wind farm close to Lolland and Tunø Knob wind farm close to the East Coast of Jutland, have been established as demonstration projects. Vindeby wind farm was established with the purpose of investigating the technical and economic conditions concerning offshore wind energy, while Tunø Knob wind farm also was intended to investigate the wind turbine effect on the environment in the area.

Taking this in consideration Tunø Knob will be the most obvious wind farm to select as a case study for the offshore wind fuel cycle in the ExternE study. At Tunø Knob investigations concerning the environment are already being made for the following areas:

- Ornithologists are investigating the lives of both birds and shells in the area.
- Archaeologists have dived after ship wrecks and Stone Age residences.
- Biologists have searched for threatened nature types on the seabed.
- Hydrologists have mapped current conditions.
- Landscape architects have visualised the offshore wind turbines.
- The electrical utility has made calculations of noise.

All these investigations concerning the environment will be important in relation to the assessment of environmental impacts of offshore wind farms.

Also a case study for an ordinary wind farm on land has been assessed. The wind farm that has been chosen as the case on land is Fjaldene wind farm located in the middle of Jutland. It has been selected because it is quite similar to the Tunø Knob system in size and type of turbines.

3.1 The fuel cycle

Wind is a natural energy source, occurring directly at the point of use. Therefore, there is no fuel cycle with fuel extraction, fuel transportation and processing in connection with a wind farm. The wind fuel cycle consists only of the presence of the wind turbines, their operation and connection to the electric grid.

Characteristic for the wind fuel cycle is the lack of pollution connected directly to the wind turbine. However, there is chemical pollution connected to the manufacturing of materials for the turbine itself and the materials used for the electrical transmission equipment. In order to include this chemical pollution the wind turbines are considered from a life cycle analysis (LCA) point of view. The life cycle has the following stages, as shown in Figure 3.1.

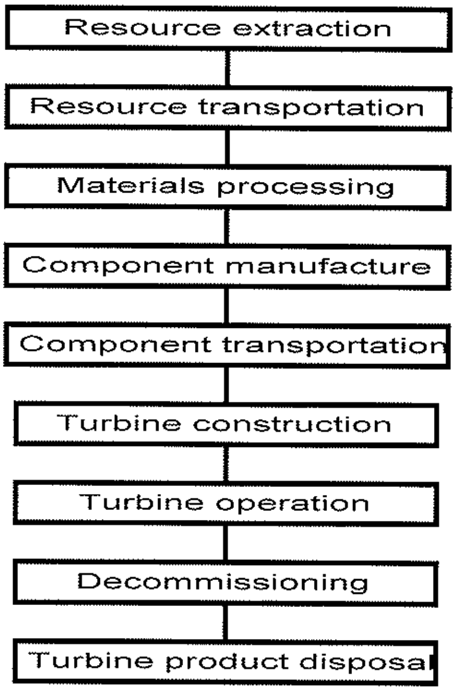

Figure 3.1 Life cycle of the wind turbine fuel cycle

3.2 Technology description

The wind farm analysed in the case study is an offshore wind farm consisting of 10 500 kW turbines with a total capacity of 5 MW. Also an ordinary wind farm on land has been analysed. The wind farm that have been chosen is a wind farm consisting of 18 500 kW turbines with a total capacity of 9 MW.

3.2.1 Tunø Knob offshore wind farm

Tunø Knob wind farm is located at a northern geographical latitude of 55.57 degrees and an eastern longitude of 10.21 degrees. The wind farm consists of 10 wind turbines. The turbines are three-bladed Vestas V39 offshore pitch-regulated machines, each with a capacity of 500-kW at a nominal wind speed of 16 m/s. The tower height is 40.5 m and the rotor diameter is 39 m.

Tunø Knob wind farm is operated by the Jutland electricity company Midtkraft, which is located in Århus; its control centre is located in the village of Hasle outside of Århus.

Each of the wind turbines in the Tunø Knob wind farm has data and transmission equipment, which communicates with the control centre at Midtkraft via radio communication. Wind speed and wind direction and also the electricity production from the wind turbines as well as other data are recorded here.

The wind turbines may be started and stopped from the operational central office at Midtkraft. The wind turbines work fully automatically via stand-alone modes. Each turbine may be operated separately without regard to the others in the farm. Twice a year, technicians for inspecting all the units visit the wind farm.

3.2.2 Fjaldene wind farm

Fjaldene wind farm is located at a northern geographical latitude of 56.9 degrees and an eastern longitude of 8.34 degrees. The wind farm consists of 18 wind turbines placed in two rows with 9 turbines in each row. The distance between the rows is 580 m, while the distance between the wind turbines in the row is 188 m. Each turbine has a capacity of 500 kW. The height of the turbines is 41.5 m. Technical details are available in appendix I.

The wind farm is connected to the high-voltage grid south of the village of Spjald via a 60/10 kV transformer. 13 of the wind turbines are owned by the electric utility company Vestkraft, while the remaining five units are privately owned. A transformer room is placed close to each turbine, transforming 10 kV to the voltage of the turbine on 690 V.

3.3 Site description

3.3.1 Tunø Knob

Tunø Knob is located south of Århus Bay. The landscape, which may be affected by the wind farm, is limited by Stavns Fjord at Samsø in the east, and the east coast of Jutland in the west. From Helgenæs in the north to Horsens Fjord, and the islands Endelave and Samsø in the south

The surrounding landscapes include moraine surfaces and unregularly open, hilly landscapes. The sea area is characterised by the islands and the many bays, inlets and forelands. South of Århus, at Helgenæs, Tunø and Samsø there are cliffs and slopes towards the sea, which are popular recreational resorts. Along the East Coast of Jutland from Århus to the beach of Saksild there are many popular beaches and areas for summer residents. In the community of Odder live 19,250 people *(Denmark Statistics, 1995).*

On the northwest side of Tunø there is a smaller area for summer residents, located at a distance of 3 km from Tunø Knob. Most of the other locations mentioned are more than 10 km away from Tunø Knob. The stretch from Hov across Saksild Beach to

Malling is less than 10 km away from Tunø Knob. Saksild Beach is located 6 km away.

The wind farm is most conspicuous from the western and northwestern part of Tunø. The wind farm is also visible from Saksild Beach and from the top of the hills in the northern part of Samsø.

3.3.2 Fjaldene

Fjaldene wind farm is located in the middle of Jutland. The wind farm occupies an area of about 200 ha.

The surrounding landscapes include plantations and irregularly open, hilly landscapes. The wind farm is located on a hill 83 m above sea level, and may therefore be visible for quite a distance compared with wind farms in flat areas. There are three smaller villages at a distance of 3-4 km from the wind farm.

3.4 Overview of burdens related to the wind fuel cycle

The impacts from the wind fuel cycle may be divided into impacts due to the use of fossil fuels for the material manufacturing and those due to the presence and operation of the turbine. It is not feasible to include all of the impacts connected to the use of fossil fuels in the assessment of the wind fuel cycle and only the most important of them will therefore be considered.

Acid emissions and greenhouse gases are believed to be the most important environmental burdens from the life cycle assessment. The impacts may be divided into three subjects:

- Impacts associated with the operation of wind turbines
- Impacts associated with the non-operational stages of the life-cycle of wind turbines
- Impacts associated with the electricity distribution systems for wind turbines

3.5 Selection of priority impacts

For the offshore wind farm in this study the following impacts have been assessed as externalities for the full life cycle of the wind turbines:

- Noise from the turbines
- Visual amenity of the wind farms
- Atmospheric emissions related to material production
- Accidents
- Impacts on birds and shells
- Impacts on fish
- Interference with electromagnetic communication systems

The same impacts are assessed as externalities for the wind farm on land except impacts on fish and interference with electromagnetic communication systems, which are considered irrelevant for the land-based wind farm.

3.5.1 Noise from the turbines

Noise from the wind farm is a burden to the residents and other people in the area close to the wind farm. As Tunø Knob wind farm is located at sea 3 km from land the noise effect is negligible. Still, as noise is the most discussed burden in relation to wind energy this burden is given high priority. Also in the case of Fjaldene wind farm the assessment of noise is quite important.

3.5.2 Visual amenity of the wind farms

Visual intrusion is a burden for residents, visitors, travellers and others near the wind farm. The region of Tunø Knob is a popular one for summer residents and visual intrusion is therefore a burden that has caused a lot of discussion. The visual burden has been given a high priority.

3.5.3 Atmospheric emissions related to material production

There are no atmospheric emissions related to power production using wind turbines. However the production of materials for the wind turbines will cause atmospheric emissions. The materials will mostly be produced by coal and natural gas causing emissions of SO_2, NO_x, CO and particulates, which will affect human health, materials, agriculture, forests, freshwater and ecosystems.

3.5.4 Accidents

Accidents in the shape of wind blades flying off may cause minor or major injuries or even death to people at a distance from the turbines. As the turbines at Tunø Knob are located at sea the only potential danger would be to sea voyages. The probability that a person in a boat would be struck by a wind blade is almost negligible, and therefore accidents to public health are given low priority.

Accidents may also happen in the road transportation of workers at the wind farm. The wind farms are operated in a remote-control mode from Midtkraft and Vestkraft, and the road transportation relates to the movement of workers from home to the site in the operation of the wind farms at Midtkraft and Vestkraft.

3.5.5 Impacts on birds and shells

The motion of the turbines may cause death, injury or disturbance of birds close to the wind farm. Tunø Knob is located in an area between two larger Ramsar areas with resting eiders at the islet and large passages of birds over the islet. Therefore the effect of the blade rotation is given a high priority.

3.5.6 Impacts on fish

The utilisation of areas at sea for the siting of Tunø Knob wind farm may affect the natural ecosystem and fishes and shells in the area. Current conditions near the wind farm may be changed and the life of shells and fishes in the area may also be changed. Threatened nature types on the seabed may disappear as a consequence of the establishment of the offshore wind farm.

Investigations have been made of the current conditions in the area around Tunø Knob based on earlier hydraulic investigations. The result of these investigations is that the existence of the offshore wind farm will not affect the current conditions. Therefore this impact is given a low priority.

3.5.7 *Interference with electromagnetic communication systems*

Scattering of electromagnetic waves may cause interference for radio and TV users in the vicinity of the wind farm. Residents in the area may not be affected, but scattering of radio waves may be a problem to sailors in the area. Scattering of radio waves is therefore given medium priority.

3.6 Quantification of impacts and damages

3.6.1 *Noise*

Only noise in connection with operation of the wind turbines will be considered in this study, as noise from the turbines during operation will affect the largest area over a much longer time than other noise sources in connection with wind turbines.

Noise level and its effect are calculated by a logarithmic formula, which includes the distance from the wind turbine *(CEC,1995f)*. The formula is adjusted for the variation between night and day sensitivity, irregular operation, noise sensitivity of people and background noise. The formula for the annual value of noise, AVN, is as follows:

$$AVN = \sum_{allpositions} (L_{year,obs} - L_{dn,back}) * N_{houses} * A(P) * NDSI$$

Where

$L_{year,\,obs}$ =	Average of noise whilst the turbines are in operation over a period of a year
$L_{dn,\,back}$ =	Expected noise without the turbines
N_{houses} =	Number of houses at that location
A(P) =	Annuitised average house price
NDSI =	Noise depreciation sensitivity index

As seen from the formula the noise is valued as long as the average of the noise whilst the turbines are in operation is higher than the expected noise without the turbines in a certain distance.

The annual value of noise is calculated to be 967 ECU for Tunø Knob wind farm or 0.004 mECU/kWh. For Fjaldene wind farm the annual value of noise is calculated to be 7,535 ECU or 0.019 mECU/kWh (appendix I).

3.6.2 *Visual amenity*

Visual amenity is a rather difficult impact to handle; for a wind turbine it is a very individual matter. Some people like the sight of a wind turbine in the nature, while others think that the sight of this same wind turbine destroys the nature.

A survey of house prices has shown a systematic tendency for houses, which are affected by wind turbines on the purchase date, to be cheaper than other houses *(Jordal-Jørgensen, 1995)*.

The effect on house prices of houses in the vicinity of a wind farm is used as monetisation value for the Fjaldene wind farm. The radius influenced by the wind farm is defined to 1500 meters. Data for monetisation of visibility are shown in Table 3.1.

Table 3.1 Monetisation of visibility for Fjaldene wind farm

Fjaldene wind farm	18 wind turbines
Yearly net electricity production	19,800 MWh
Lifetime	20 years
Number of influenced houses	7
Effect per wind turbine per house	527.50 ECU
Monetisation of visibility	0.17 mECU/kWh

The results are very uncertain. Among others the results from the survey of house prices are based on only three observations. Also the defined radius influenced by the wind farm and thereby the number of houses affected is especially important for the monetisation calculation and can vary the results quite a lot.

In the case of Tunø Knob wind farm both photo- and video-montages have been made. Based on these montages protests have been made before the establishment of Tunø Knob wind farm. The protests were based in particular on both the effects of light from the wind turbines, which could be a disturbance to the nature, as well as noise from the turbines. Today the wind farm is in operation and most of the people in the neighbouring area accept it. There have been no light effects and no noise problems from the wind farm.

Based on these observations visual amenity has been monetised to zero for Tunø Knob wind farm.

3.6.3 Impacts of atmospheric emissions

Atmospheric emissions in connection with the wind fuel cycle are especially related to the production of materials for the wind farm. The main materials used for the total wind farms are materials for the wind turbines, materials for fundaments and for the offshore wind farm sea cable materials *(Schleisner et al., 1995).*

The relevant atmospheric emissions due to the production of Tunø Knob wind farm and Fjaldene wind farm are shown in Table 3.2 - 3.3*(Fenhann, Kilde, 1994).*

Table 3.2 Emissions from the production of Tunø Knob wind farm

	SO_2 (kg)	NO_x (kg)	CO_2 (kg)	N_2O (kg)	CH_4 (kg)	CO (kg)
Wind turbines	3888	3067	1151079	35	21	513
Fundaments	6175	15229	4029797	95	200	2999
Sea cables	1174	1153	362094	11	8	207
Total	11238	19449	5542970	141	229	3718

Table 3.3 Emissions from the production of Fjaldene wind farm

	SO_2 (kg)	NO_x (kg)	CO_2 (kg)	N_2O (kg)	CH_4 (kg)	CO (kg)
Wind turbines	6999	5520	1351116	41	26	788
Fundaments	5558	13706	3722776	88	181	2724
Total	12557	19226	5331530	138	212	3551

3.6.4 CO, SO_2 and NO_x

Only the impacts associated with emissions of CO, SO_2 and NO_x will be assessed here. The emissions divided into those related to electricity, heat and transport due to material production are shown in Table 3.4 for Tunø Knob offshore wind farm and Table 3.5 for Fjaldene wind farm on land (taking the 20-year electricity production into account for both).

Table 3.4 Emissions of SO_2, NO_x and CO in g/kWh for Tunø Knob offshore wind farm

	SO_2 (g/kWh)	NO_x (g/kWh)	CO (g/kWh)
electricity emissions	0.031	0.016	0.002
heat emissions	0.003	0.028	0.003
transport emissions	0.011	0.032	0.010
Total emissions	0.045	0.076	0.015

Table 3.5 Emissions of SO_2, NO_x and CO in g/kWh for Fjaldene wind farm on land

	SO_2 (g/kWh)	NO_x (g/kWh)	CO (g/kWh)
electricity emissions	0.023	0.012	0.001
heat emissions	0.002	0.017	0.002
transport emissions	0.007	0.019	0.006
Total emissions	0.032	0.048	0.009

As noted above the above-mentioned emissions are related to production of different materials. A part of the materials are produced in other countries than Denmark, but the emissions mentioned are still based on Danish emission factors.

The damages caused by atmospheric emissions will be calculated using the EcoSense model. The emissions related to electricity production will be based on an average coal-fired plant located in Denmark. Data for the coal-fired plant Fynsværket are used together with Danish meteorological data for production of wind turbines and other materials.

Only the regional module of the EcoSense model has been run, as a part of the emissions arise from other countries. The emissions related to transportation of the material have been excluded, as these emissions are caused mostly by transportation of materials at sea, and cannot be related to energy production from a power plant.

For the emissions related to heat, results from the natural gas fuel cycle of the EcoSense runs have been scaled down to fit the heat emissions for the production of the wind farms.

The total damage in mECU/kWh related to Tunø Knob wind farm is shown in Table 3.6.

Table 3.6 Total damage in mECU/kWh related to Tunø Knob wind farm

Receptor	Pollutant	Mid damage
Crops	SO_2, nitrogen / acid deposition	2 e-4
Human health	pm10, nitrates, sulfates, SO_2, NO_x, CO	0.42
Materials	SO_2 , wet deposition	0.01
	Total	0.42

98% of the damages relate to human health. About 48% are caused by NO_x emissions, and 44% by SO_2 emissions. 50% of the damages relate to electricity production, and the other half to heat production.

The total damage in mECU/kWh related to Fjaldene wind farm is shown in Table 3.7.

Table 3.7 Total damage in mECU/kWh related to Fjaldene wind farm

Receptor	Pollutant	Mid damage
Crops	SO_2, nitrogen/ acid deposition	3 e-4
Human health	pm10, nitrates, sulfates, SO_2, NO_x	0.22
Materials	SO_2 , wet deposition	80 e-4
	Total	0.22

3.6.5 Ozone

The damages due to ozone are calculated based on the NO_x emission related to the plant. The following numbers are used for monetisation:

Table 3.8 Monetisation values for ozone

		Monetisation value
Mortality	Europe	259 ECU/t NO_x
	Outside Europe	153 ECU/t NO_x
Morbidity	Europe	460 ECU/t NO_x
	Outside Europe	272 ECU/t NO_x
Crops	Europe	200 ECU/t NO_x
	Outside Europe	150 ECU/t NO_x

The NO_x emissions related to production of materials for the wind turbines are assumed to be inside Europe. The NO_x emissions related to production of Tunø Knob are 0.076 g/kWh, while the NO_x emissions related to Fjaldene are 0.048 g/kWh. The damages due to ozone via NO_x are shown in Table 3.9.

Table 3.9 Damages due to ozone via NO_x emission

	Tunø Knob	Fjaldene
Mortality	0.03 mECU/kWh	0.02 mECU/kWh
Morbidity	0.06 mECU/kWh	0.04 mECU/kWh
Crops	0.03 mECU/kWh	0.02 mECU/kWh
Total	0.12 mECU/kWh	0.08 mECU/kWh

3.6.6 Greenhouse gases

Like the other atmospheric emissions the emission of greenhouse gases is related to energy use for production of materials for the wind turbines. The emissions from the production of Tunø Knob and Fjaldene wind farms were shown in Table 3.4 and

Table 3.5 respectively. The emissions of N_2O, CH_4 and CO are converted to CO_2 equivalents by the factors: 320, 21 and 1.4 respectively. The total emissions of greenhouse gases for Tunø Knob and for Fjaldene wind farms are shown in Table 3.10. The emissions have been divided into those related to electricity, heat and transport.

Table 3.10 Emissions of CO_2 in g/kWh for Tunø Knob offshore wind farm and Fjaldene wind farm on land

	Tunø Knob CO_2 (g/kWh)	Fjaldene CO_2 (g/kWh)
electricity emissions	8.428	6.343
heat emissions	11.872	7.127
transport emissions	1.740	1.065
Total emissions	22.040	14.535

The monetisation values used for CO_2 have been estimated using the FUND and Open Framework Models *(Schleisner, Nielsen, (Appendices) 1997).* Four different values have been used as seen in Table 3.11.

Table 3.11 Total damage due to global warming in mECU/kWh related to material production for Tunø Knob and Fjaldene wind farms

Monetary value for CO_2	Tunø Knob (mECU/kWh_{el})	Fjaldene (mECU/kWh_{heat})
ECU/t CO_2	0.08	0.06
18 ECU/t CO_2	0.40	0.26
46 ECU/t CO_2	1.01	0.67
139 ECU/t CO_2	3.06	2.02

3.6.7 Accidents

Accidents have impacts on both occupational and public health in relation to production of the wind turbines and transportation of people to and from the wind farms.

3.6.7.1 Public accidents

In the first consideration the amount of public accidents must be site-specific. These are accidents like the detachment of part of a blade, a whole blade or even the whole rotor whilst in motion. This could result in a large object being projected over a considerable distance. The worst case scenario is the runaway of a turbine at wind speeds above the “cut-off”, followed by a rapid structural failure in the blade, so that detachment occurs at very high blade speeds *(Taylor and Rand, 1991).* It has been estimated that such a sequence of events could result in a blade fragment travelling 700 to 800 metres *(UKDEn, 1985; MacQueen et al, 1983).* However, it seems to be a very unlikely occurrence and that without such runaway conditions the distance could not even approach the range of nearby houses. For the wind farm offshore the risk is even smaller. Therefore, this kind of public accident is not considered as an externality.

Another kind of accident, which here is considered as public, is the road transportation of people working at the wind farm.

The total distance related to the operation of Tunø Knob wind farm is 4030 km pr. year, while the total number of km related to operation of Fjaldene wind farm is 9030 pr. year *(Schleisner, Nielsen, (Appendices) 1997).*

Also, road transportation in relation to the whole life cycle is included in the calculation of public accidents. The total amount of km that relates to construction of Tunø Knob wind farm is 36,000 km. For Fjaldene a total distance related to construction of the wind farm is 24,000 km *(Schleisner, Nielsen, (Appendices) 1997).*

The following accident data are estimated from statistical information over the years 1990-1994: *(Vejtransporten i tal og tekst 1995, Auotomobil-importørernes sammenslutning, 1995) (Denmark Statistics, 1995)*

Accidents pr. million km of transportation: 0.15

Killed pr. million km of transportation: 0.009

Using the above-mentioned accidents and an estimate of accident damage valuation at 1,400 ECU for minor accidents, 94,000 ECU for major accidents and 3,100,000 ECU for fatal accidents the damage cost of public accidents is 0.016 mECU/kWh for Tunø Knob off shore wind farm and 0.018 mECU/kWh for Fjaldene wind farm.

3.6.7.2 Occupational accidents

The number of occupational accidents is connected to the production of wind turbines. Occupational accidents in the production of the wind turbines are reported to the responsible agency, and the number of accidents reported for 1995 was 69. The number of wind turbines produced in 1995 was 1545 with a total capacity of 577 MW *(Vindmølleindustrien, 1997)*. Only 6% of these turbines were established in Denmark corresponding to 98 MW; the rest were exported. The accidents per MW are estimated to be 0.12. Seven of the accidents are major ones, while the rest are minor. There are no fatal accidents *(Arbejdstilsynet, 1997)*.

The same estimate of accident damage valuation as for public accidents will be used. With these assumptions, the damage cost of accidents due to the production of Tunø Knob (5 MW, 0.06 major accidents, 0.54 minor accidents) are 0.022 mECU/kWh and 0.025 mECU/kWh for Fjaldene (9 MW, 0.11 major accidents, 0.97 minor accidents).

Also, during the work at sea there may be occupational accidents. Within the establishment of the fundaments at Tunø Knob one diver had an accident. He had encountered physical permanent injuries, and will never be able to dive again.

3.6.8 Impacts on birds and shells

The motion of the turbines may cause death, injury or disturbance to birds near the offshore wind farm. The wind farm is located in an area between two larger Ramsar areas with resting eiders at the islet and large passages of birds over the islet. Therefore the motion of turbines is given a high priority.

Many of the birds in the area, especially eiders, use the low water at the islet to find feed and rest. Since February 1994 biologists therefore have examined the life of birds in the area. The investigations are made from two towers for bird counting, one at Tunø Knob, and the other at Samsø. In the small tower at Tunø Knob one or two biologists have been working for some days at a time, registering the number of birds, the dispersion and the behaviour before the establishment of the wind turbines *(Midtkraft, 1995)*.

After establishment of the wind farm the same investigations are made. In this way it is possible to register the change in the bird population at the site, caused by the establishment of the wind farm. Also shells, which are the eiders preferred feed, are observed. One eider may eat one or two kilos of shells a day, and in this way intrusions in the number and behaviour of birds will also influence the amount of shells.

According to these investigations the number of eiders has decreased in the area. However, it is believed that the wind farm not has caused the decrease, as the amount of food for the eiders also has decreased, possibly because of changes in weather conditions.

In relation to birds killed by wind turbines Dutch ornithologists have reported an investigation in the area surrounding five turbines every two days for a year *(Musters et al., 1996)*. There were five turbines and they were in an apparently particularly vulnerable area for the birds - an estuary area with large numbers of bird movements. They found only 26 bodies of which only six were definitely killed by the turbines, three may have been and for eight the cause of death could not be determined. The turbines did definitely not kill the last nine.

Based on the above-mentioned investigation the damage of birds due to wind turbines has been monetised to zero.

3.6.9 Impacts on fish

Impacts on fish is an impact, that is related only to an offshore wind farm and not to an ordinary wind farm. In connection with the other Danish offshore wind farm, Vindeby, studies have been made about the fish life before and after the wind farm had been sited. The conclusion of the investigations is that the establishment of an offshore wind farm has not had any negative effect on fishing in the area. The function of the area as a spawn growth area has not been reduced. On the other hand, the number of codfish around the fundaments has increased.

Fauna and flora have been re-established in the plant area. The fundaments of the turbines function now as reef, resulting in an increase of feed for the codfish. There have been no observations of noise or other physical influences from the wind turbines as having an influence on fish in the area.

In this way offshore wind farms have mostly a positive impact on fish, but only very locally, and its impact has therefore been monetised to zero.

3.6.10 Interference with electromagnetic communication systems

Scattering of electromagnetic waves may cause burdens for radio and TV users in the area near the wind farm. Residents in the area may not be affected, as they are located at a distance of more than 3 km from the wind farm, but especially for an offshore wind farm scattering of radio waves may be a problem to sailors in the area.

In the ExternE project the interference with electromagnetic communication systems is considered not to be an externality. There may be some smaller problems in connection with microwaves and aviation communication, but these can be avoided by taking care of them in the construction phase of the wind farm. For local television consumers the problem may be solved in a very inexpensive way and is not to be considered as an externality.

However, in the case of an offshore wind farm, the interference with electromagnetic communication systems may affect the communication and navigation systems at sea. It is therefore important to register if the operation of the offshore wind farm will cause any problems. Until now, however, 1½ years after the establishment of Tunø Knob wind farm no effects on the navigation systems have been registered, and the interference with electromagnetic communication systems has therefore been monetised to zero.

3.7 Interpretation of the results and sensitivity analyses

The total impacts and damages which have been assessed in relation to Tunø Knob offshore wind farm and Fjaldene wind farm on land are shown in Table 3.12.

In the table the geometric standard deviations σ_g for each damage are shown. The labels are:
A = high confidence, corresponding to $\sigma_g = 2.5$ to 4;
B = medium confidence, corresponding to $\sigma_g = 4$ to 6;
C = low confidence, corresponding to $\sigma_g = 6$ to 12;

The numbers stated in the table for mortality are based on the years of life lost (YOLL) approach, while the numbers in brackets are based on the value of statistical life (VSL) approach.

The value of statistical life (VSL) is essentially a measure of willingness to pay (WTP) for reducing the risk of premature death. The value derived for the VSL is 2.6 MECU. In earlier phases of the ExternE project a number of questions were raised regarding the use of the VSL for every case of mortality considered. These originally related to the fact that many people whose deaths were linked to air pollution were suspected of having only a short life expectancy even in the absence of air pollution. Was it logical to ascribe the same value to someone with a day to live as someone with tens of years of remaining life expectancy? Furthermore, is it logical to ascribe the full VSL to cases where air pollution is only one factor of perhaps several that determines the time of death, with air pollution playing perhaps only a minor role in the timing of mortality? In view of this the ExternE project team explored valuation on the basis of life years lost. For quantification of the value of a life year (YOLL) it was necessary to adapt the estimate of the VSL. This is not ideal by any means (to derive a robust estimate primary research is required), but it does provide a first estimate for the YOLL.

Table 3.12 Damages in relation to Tunø Knob offshore farm and Fjaldene wind farm on land

	Tunø Knob mECU/kWh	Fjaldene mECU/kWh	σ_g
POWER GENERATION			
Public health (accidents)	16 e-3	18 e-3	A
Occupational health	ng	ng	A
Noise	4 e-3	0.02	B
Visual impacts	0	0.17	A
Impacts on birds	0	0	A
Impacts on fish	0	-	A
Interference with electromagnetic communication systems	0	nq	A
OTHER FUEL CYCLE STAGES			
Material production and manufacture			
Public health			
Mortality*- YOLL *(VSL)*	0.39 (2.59)	0.17 (1.36)	B
Of which PM_{10}	*6 e-3 (0.02)*	*4.8 e-3 (0.02)*	
SO_2	*0.12 (0.61)*	*0.09 (0.46)*	
NO_x	*0.24 (0.89)*	*0.05 (0.17)*	
NO_x (via ozone)	*0.03(1.07)*	*0.02 (0.71)*	
Morbidity	0.15	0.12	B
Of which PM10, SO_2, NO_x	*0.05*	*0.08*	
NO_x (via ozone)	*0.06*	*0.04*	
Accidents	7.1 e-3	2.3 e-3	A
Occupational health	0.02	0.03	A
Crops	0.03	0.02	B
Of which SO_2	*2 e-4*	*3 e-4*	
NO_x (via ozone)	*0.03*	*0.02*	
Ecosystems	Ng	iq	
Materials	0.01	8 e-3	B
Global warming			C
Low	*0.08*	*0.06*	
Mid 3%	*0.40*	*0.26*	
Mid 1%	*1.01*	*0.67*	
High	*3.06*	*2.02*	

*Yoll= mortality impacts based on 'years of life lost' approach, VSL= impacts evaluated based on 'value of statistical life' approach.

ng: negligible; nq: not quantified; iq: only impact quantified; - : not relevant

In Table 3.12 the mortality impacts are calculated by using the years of life lost approach. In the case of Tunø Knob global warming accounts for 13% of the damages using the low estimate and as much as 85% using the high estimate. It must be pointed out that these damages are not related to the power production phase, but to the production of materials for the wind turbines.

In the case of Fjaldene mortality accounts for 13% of the damages, and global warming accounts for 58% of the damages using the mid 1% value. In this case, Fjaldene being a wind farm on land visual impacts are important, accounting for 15% of the damages.

Table 3.13 Total damages of Tunø Knob and Fjaldene wind fuel cycles

	Tunø Knob mECU/kWh	Fjaldene mECU/kWh	σ_g
Power generation	0.02	0.21	A-B
Other fuel cycle stages	0.66-3.64	0.40-2.36	B-C
Subtotal	0.68-3.66	0.61-2.57	B-C

Table 3.13 shows that nearly all the damages from an offshore wind farm are related to the production of the materials for the wind farm. The damages are mostly related to the emissions of CO_2 and to some extent NO_x and SO_2. For Fjaldene wind farm on land 35% of the damages are damages related to the power generation stage using the low value for CO_2.

Figure 3.2 shows the difference in monetised non-global damages for the Tunø Knob offshore wind farm and Fjaldene land-based wind farm. As seen from the figure the damages related to noise and especially visual amenity are much larger for a land-based wind farm than for a sea-based one. For the former noise and visual amenity account for about 39% of the total damages excluding global warming, while these two impacts for the latter account for less than 1% of the total damages.

The damages related to atmospheric emissions are larger for the offshore wind farm than for the other, as the emissions per kWh are larger for the offshore wind farm than for the ordinary wind farm. The reason for this is especially the amount of materials used for foundation and also the material used for the sea cables.

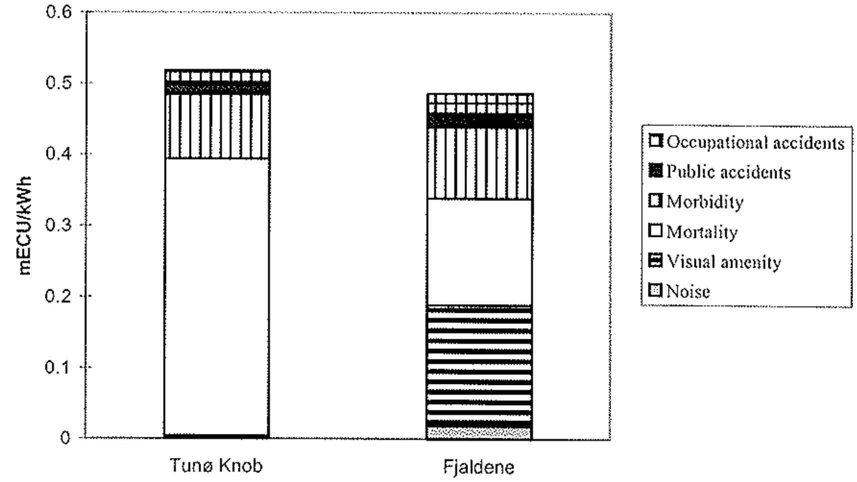

Figure 3.2 Monetised non-global damages for Tunø Knob and Fjaldene wind farm

However, for Tunø Knob as well as Fjaldene the damages related to atmospheric emissions are dominant (mortality and morbidity) even though the atmospheric emissions are related only to the production phase of the wind turbines.

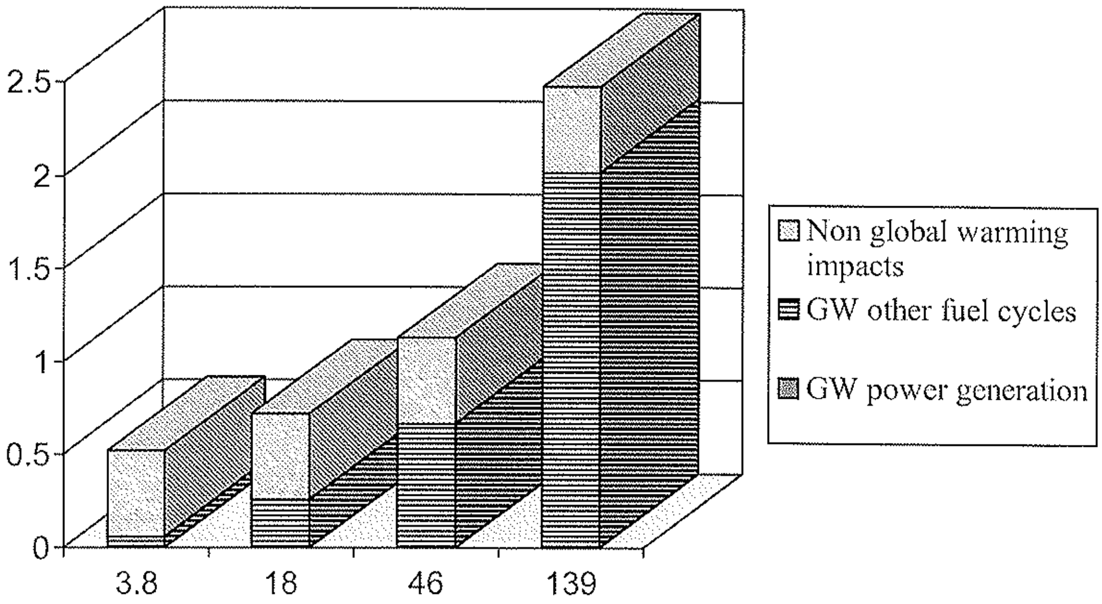

Figure 3.3 Monetised externalities related to Fjaldene wind farm depending on the values used for monetisation of CO_2

Figure 3.3 shows the total monetised externalities related to Fjaldene wind farm on land depending on the monetisation values used for CO_2. Using the two lowest values for CO_2 monetisation the non-global impacts are still dominants, while global warming becomes dominant using the upper values for CO_2.

4. The Photovoltaic Fuel Cycle

In the future in Denmark photovoltaics will mostly be installed as integrated systems in buildings or at the top of the buildings. Today in total 5 photovoltaics plants connected to the electricity net have been installed at larger buildings with a total PV area of 300 m^2 corresponding to the electricity consumption of about 10 families. In another PV project called "the 30 roofs project" 30 family houses in a joint area have had PV's integrated in the houses, corresponding to a PV area of about 600 m^2. The PV plants cover around half of the electricity consumption of the 30 families.

Beside these projects about 1000 m2 PV's have been installed at the residential property Solgården. This project is classified as the only PV centre in Denmark today and will be used to assess the external costs.

4.1 Technology description

The selected photovoltaic plant is one of the latest developed plants in Denmark. The plant has been established in connection with restoration of a residential property with the purpose of demonstrating different kinds of utilisation of photovoltaics .

The residential property, named Solgården, is located in Kolding in the south of Jutland. The photovoltaic plant consists of two systems, a 757 m^2 PV system at the top of the roof , and a 175 m^2 system which is integrated in the balconies at the southern front of the building.

The PV plant on the roof consists of four through strings of semi transparent, mono crystalline PV panels placed on a steal stand. The plant consists of 846 PV panels with a total peak capacity of 89.5 kWp. The PV's in the balconies consist of 80 PV panels with a total peak capacity of 16.5 kWp (*the Municipality of Kolding and the Ministry of Housing, 1996*).

The total plant is divided into 16 sections, which through a converter deliver 230 V AC to the local electricity network. The electricity is primarily used in the residential property, but surplus energy is sold to a power station.

The electricity production from the total PV plant is expected to be 106,000 kWh per year, of which the roof system will deliver 89,500 kWh. The total electricity consumption in Solgården is expected to be 175,000 kWh (*the Municipality of Kolding and the Ministry of Housing, 1996*).

The PV systems are assumed to have a total lifetime of 20 years.

4.2 Overview of burdens related to the PV fuel cycle

As for the wind fuel cycle there are no atmospheric pollutants related to the energy production from the photovoltaics. However, there are chemical pollutants connected to the manufacturing of materials for the PV's, and the PV's are therefore in the same way as the wind turbines considered from a life cycle analysis point of view.

The burdens related to photovoltaics may in this way be divided into three subjects:

- Impacts associated with operation of the PV's
- Impacts associated with the non-operational stages of the life cycle of the PV's
- Impacts associated with the electricity distribution systems for PV's

4.3 Selection of priority impacts

The following impacts will be assessed as the most important externalities related to the full life cycle of photovoltaics:

- Visual amenity
- Land use
- Atmospheric emissions related to material production
- Accidents

4.3.1 Visual amenity

The visual effects of photovoltaics will depend upon, if the PV's are stand alone panels or if they are integrated systems in the buildings. Being stand alone systems the PV's may have visual effects, while it may be reasonable to assume that there are no visual effects if the PV's are integrated into the buildings.

4.3.2 Land use

Photovoltaic systems have low energy density and require large amounts of land in order to produce a fair amount of electricity. The use of land may result in damages to natural ecosystems.

4.3.3 Atmospheric emissions related to material production

There are no atmospheric emissions related to power production from photovoltaics. However, the production of materials for the PV's will cause atmospheric emissions. The materials will mostly be produced by coal and natural gas causing emissions of SO_2, NO_x, CO and particulate, which will affect human health, materials, agriculture, forests, freshwater, and ecosystems.

4.3.4 Accidents

Accidents may happen during the work effort required for production and installation of the PV plant. Also traffic accidents may happen during transport of materials and workers to the plant. Accidents may also happen during inspection of the plant in operation.

4.4 Quantification of impacts and damages

4.4.1 Visual amenity

The PV's at the top of the roof of the residential property in Solgården are placed on a 5 floor building. The PV system is visible for passers-by in a certain distance from the building, as it is located in an open area. However, the PV-system is not visible for the residents and people walking around the building. The PV system, which is integrated in the balconies at the southern front of the building, are integrated in a way that there is no significant difference to the rest of the facade. The whole facade is restored, the integrated PV system in the balconies being a part of it.

Based on the above mentioned conditions visual amenity has been estimated to zero in external costs.

4.4.2 *Land use*

The PV plant connected to Solgården is placed on top of the roof and is not taking up any land. Therefore no external costs result from the use of land connected with this kind of application.

4.4.3 *Impacts of atmospheric emissions*

The emission data for the photovoltaics are based on a detailed life cycle analysis made in the German part of the ExternE National Implementation Project. The emissions of SO_2, NO_x, CO_2, CH_4, N_2O and particles are summarised in Table 4.1. Beside these emissions a wide range of substances and materials are released into the environment during the production of the PV modules. These substances have not been included in this study, but have been quantified in another study (*Hagedorn and Hellriegel, 1992).*

Table 4.1 Atmospheric emissions related to production of photovoltaics

	PV system on roof		PV facade system		Total
	(g/kWp)	(g/kWh)	(g/kWp)	(g/kWh)	(g/kWh)
SO_2	1894.6	0.095	1793.0	0.090	0.185
NO_x	1801.3	0.090	1287.7	0.064	0.154
CO_2	970800	49.00	777200	39.00	88.00
CH_4	1602.0	0.080	1025.3	0.051	0.131
N_2O	3.1	0.0002	2.4	0.0001	0.0003
Particles	110.3	0.006	-	-	0.006

4.4.4 *SO_2, NO_x and particles*

The damages caused by atmospheric emissions of SO_2 and NO_x will be calculated using the EcoSense model. All the emissions are assumed to be related to electricity production and will be based on an average coal-fired plant located in Denmark, although the emissions in Table 4.1 are based on emission factors from German energy production technologies. Data for the coal-fired plant Fynsværket are used for production of the photovoltaics and other materials together with Danish meteorological data. Only the regional module of the EcoSense model has been run, as a part of the emissions arise from other countries.

The total damage in mECU/kWh related to the photvoltaics at Solgården is shown in Table 4.2.

Table 4.2 Total damage in mECU/kWh related to Solgården PV

Receptor	Pollutant	Mid damage
Crops	SO_2, nitrogen / acid deposition	0.0012
Human health	pm10, nitrates, sulfates, SO_2, NO_x, CO	1.53
Materials	SO_2 , wet deposition	0.05
	Total	1.58

96 % of the damages are related to human health.

4.4.5 *Ozone*

The damages due to ozone are calculated based on the NO_x emissions related to the plant. The following numbers are used for monetisation:

Table 4.3 Monetisation values for ozone

		Monetisation value
Mortality	Europe	259 ECU/t NO_x
	Outside Europe	153 ECU/t NO_x
Morbidity	Europe	460 ECU/t NO_x
	Outside Europe	272 ECU/t NO_x
Crops	Europe	200 ECU/t NO_x
	Outside Europe	150 ECU/t NO_x

The NO_x emissions related to production of materials for the PV's are assumed to be inside Europe. The NO_x emissions related to the production of the PV's at Solgården are 0.154 g/kWh. The damages due to ozone via NO_x are shown in Table 4.4.

Table 4.4 Damages due to ozone via NO_x emission

	Solgården PV
Mortality	0.04 mECU/kWh
Morbidity	0.07 mECU/kWh
Crops	0.03 mECU/kWh
Total	0.14 mECU/kWh

4.4.6 *Greenhouse gases*

Like the other atmospheric emissions the emission of greenhouse gases is related to energy use for production of materials for the PV's. The emissions from the production of the PV's were shown in Table 4.1. The emissions of N_2O, CH_4 and CO are converted to CO_2 equivalents by the factors: 320, 21 and 1.4 respectively. This results in a total amount of emissions of greenhouse gases for the residential property Solgården of 90.85 g/kWh.

The monetisation values used for CO_2 have been estimated using the FUND and Open Framework Models *(Schleisner, Nielsen, (Appendices) 1997)*. Four different values have been used as seen in Table 4.5.

Table 4.5 Total damage due to global warming in mECU/kWh related to material production for PV's at the residential property Solgården

Monetary value for CO_2	Solgården PV (mECU/kWh)
3.8 ECU/t CO_2	0.35
18 ECU/t CO_2	1.64
46 ECU/t CO_2	4.18
139 ECU/t CO_2	12.63

4.4.7 *Accidents*

Accidents are considered in relation to occupational health impacts and also as public accidents in relation to road transportation of people working with the PV plant.

As no data have been available regarding working hours related to photovoltaics the person hours per kWh for production of materials and construction of the technologies have been assumed to be the same for PV's as for a natural gas power plant *(Schleisner, Nielsen, (Appendices) 1997)*. Using UK engineering sector figures fatal accidents are 0.162% of all accidents, major accidents are 12.9%, and minor accidents are 87% of the total number of accidents.

Regarding accidents in relation to road transportation the same assumptions concerning transportation distance and data for accidents per km transportation have been used as in the case of the wind farm on land, assuming that a PV plant needs the same amount of supervision as the wind farm per kWh produced.

Values used for monetisation are 3,100,000 ECU for fatal accidents, 94,000 ECU for major and 1,400 ECU for minor accidents. These values result in external costs for occupational health of 0.17 mECU/kWh and 0.018 mECU/kWh for public accidents.

4.5 Interpretation of the results and sensitivity analyses

The total impacts and damages which have been assessed in relation to the photovoltaic plants at the residential property Solgården are shown in Table 4.7.

In the table the geometric standard deviations σ_g for each damage are shown. The labels are:

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

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

C = low confidence, corresponding to $\sigma_g = 6$ to 12;

The numbers stated in the table for mortality are based on the years of life lost (YOLL) approach, while the numbers in brackets are based on the value of statistical life (VSL) approach.

Table 4.6 Damages in relation to the photovoltaic plant at Solgården

	Solgården PV mECU/kWh	σ_g
POWER GENERATION		
Public accidents	0.018	A
Land use	0	A
Visual impacts	0	A
OTHER FUEL CYCLE STAGES		
Material production and manufacture		
Public health		
Mortality*- YOLL *(VSL)*	1.34 (7.45)	B
Of which PM10	*0.04 (0.13)*	
SO_2	*0.73 (3.71)*	
NO_x	*0.59 (2.19)*	
NO_x *(via ozone)*	*0.04 (1.42)*	
Morbidity	0.26	B
Of which PM10, SO_2, NO_x	*0.19*	
NO_x (via ozone)	*0.07*	
Occupational health	0.17	A
Crops	0.0312	B
Of which SO_2	*0.0012*	
NO_x *(via ozone)*	*0.03*	
Materials	0.05	B
Global warming		C
Low	*0.35*	
Mid 3%	*1.64*	
Mid 1%	*4.18*	
High	*12.63*	

*Yoll= mortality impacts based on 'years of life lost' approach, VSL= impacts evaluated based on 'value of statistical life' approach.

ng: negligible; nq: not quantified; iq: only impact quantified; - : not relevant

Table 4.7 shows that nearly all the damages from photovoltaics are related to the production of the materials for the PV's. The damages are mostly related to the emissions of CO_2 and to some extent NO_x and SO_2. 15% of the damages are related to CO_2 using the low value for CO_2, while 87% of the damages are related to CO_2 using the high value for CO_2.

Table 4.7 Total damages of the photovoltaic fuel cycle

	Solgården PV mECU/kWh	σ_g
Power generation	0.018	A-B
Other fuel cycle stages	2.20-14.48	B-C
Subtotal	2.22-14.50	B-C

5. External Costs for Fossil Fuels

In the assessment of external costs related to fossil fuels the evaluation of costs due to global warming is a very important factor. For national implementations in the ExternE values for the CO_2 emissions in the range of 3.8-139 ECU/ tCO_2 have been recommended. This gives the 95% confidence interval. A restricted range of emission costs 18-46 ECU/ tCO_2 has also been given. These values would cause that generation of electricity by fossil fuels, which gives emissions in the range of about 0.3-1 kg CO_2 /kWh_e would result in rather high external costs of about 5-46 mECU/kWh.

Especially after the Kyoto Protocol global warming and CO_2 emissions are considered to be extremely important environmental issues. Negotiations to restrict emissions causing global warming will be continued. The present CO_2 concentration is about 360 ppm (1995). Stabilisation at the level 550 ppm (double the pre-industrial concentration) has been one proposed target. If environmental costs of carbon dioxide were considered so high as considered in the ExternE it would be relatively easy to argue that other power production and energy production alternatives than coal (or also other fossil fuels) should be chosen.

Important factors in the evaluation of global warming costs are time scales (including discount rates) and space scales. Global warming, for example, is a global scale phenomenon having different local impacts. Emissions remain in air some hundred years. Integration over these relatively long periods of time gives relatively high time integrals. If discount rates are applied, the future damages are considered to be of less value than the more present ones. Future emissions can also be considered to have lower impact if fixed integration periods are used and future emissions therefore have smaller impact. Another point is that due to stabilisation targets future emissions can be considered to be actually more expensive than emissions of today due to the fact that targets will almost be reached, and also that gases (CO_2) have no time (regarding to e.g. stabilisation in 2100) to be transferred effectively from the air. The valuation of the CO_2 emissions in the range of 3.8-139 ECU/ tCO_2 includes a 5% discount rate for the lower range and a 1% discount rate for the upper range. So even the upper range includes discounting.

The chosen context has impact on the costs. The scenario used for the evaluation of carbon dioxide costs (*Eyre et al. 1997*) is based on the IPCC scenario IS92a, which is a basic scenario assuming no measures. The emissions of carbon dioxide during 1990-2100 are 1500 Gt C. Also scenario IS92d for 1995-2004 carbon dioxide emissions has been studied; the costs have been estimated to be little lower (*Eyre et al. 1997*). Actually one would expect that costs were more dependent on the chosen scenario

Global warming impacts also differ in that respect from most other environmental impacts (also e.g. global scale collective doses have similar impacts) that global warming costs e.g. due to electricity generation in EU countries is mainly paid by people in other countries. Therefore, apart from economic arguments other arguments are required, too. The contribution of EU countries to the carbon dioxide concentration development has been calculated to be about 13 ppm in 1990, when the total concentration increase due to use of fossil fuels was estimated to be 65 ppm, which is about as much as the contribution of developing countries, namely 14 ppm.

New technologies will be developed to decrease global warming. The exact evaluation of the new technologies should of course include the evaluation of the externalities of the whole technology, e.g. the environmental costs of CO_2 capture and disposal, and not only the avoided emissions.

5.1 Coal

A coal plant near Lauffen has already been analysed in the ExternE project. As the site of the fusion plant to be analysed is also in Lauffen the externalities for coal at that site are in that respect very useful. In order to have the ranges of externalities for coal, also material from other studies has to be used.

The externalities for coal are rather high compared to fission or renewables. They are evaluated to be 17-138 mECU/kWh for the plant in Lauffen, restricted range 30-55 mECU/kWh. For the Finnish Meri-Pori coal plant values about 8–124 mECU/kWh have been given, restricted range 20-44 mECU/kWh (*Pingoud et al.1997*).

For the Finnish case the global warming has been considered to be the most important impact causing external costs. For the plant in Lauffen other impacts such as human health impacts, and other impacts than those caused by global warming are about 14 mECU/kWh. Apart from Meri-Pori a Swedish coal power plant in Västerås has rather low other impacts (about 3-4 mECU/kWh). One reason for this is probably the low population density. If the global warming costs by some means could be essentially lowered the external costs could for some considered plants be in the range of costs of fission or renewables. The estimated costs of fusion (1.3 - 2.7 mECU/kWh) (Model plants 1 and 2) are about of that order.

Possibilities for lower costs might be that the global warming costs are overestimated. Still it is probable that even when somewhat overestimated, CO_2 emissions will cause high costs in future decades. In future carbon dioxide emissions to air might be avoided e.g. by disposal of CO_2 to ocean. Other emissions due to coal may also be lower in the future, but probably more weight will be given to the pricing of ecosystems, causing that external costs e.g. due to acidification will not be lower.

For national implementations in the ExternE project values for the CO_2 emissions in the range of 3.8 - 139 ECU/ t CO_2 have been recommended, giving the 95% confidence interval. A restricted range of emission costs 18-46 ECU/t CO_2 has also been given. These values would cause that generation of electricity by coal, which gives emissions of about 1 kg CO_2 /kWh_e or less would result in rather high external costs (somewhat less than 18-46 ECU/kWh_e for the restricted range of emission costs).

5.2 Other fossil fuels

From other fossil fuels analysed in the ExternE oil and peat give about similar costs as coal. The Finnish peat fuel cycle case Rauhalahti 87 MW has been studied in the ExternE project (*Pingoud et al. 1997*). The study gave a value of about 15-150 mECU/kWh, restricted range 23-51 mECU/kWh. Due to cogeneration the external costs were not much higher than for coal. Natural gas gives then considerably lower external costs than other fossil fuels. External costs for oil and gas have also been evaluated for the site Lauffen. For a 780 MW gas power plant in Lauffen external costs of 6-60 mECU/kWh has been given, restricted range 12-23 mECU/kWh. For the plant in Lauffen other impacts than those caused by global warming are about 3.4 mECU/kWh. These impacts have been estimated to be relatively small also for most other studied gas power plants.

If global warming impacts in the future could be lowered very much gas power plants could have relatively low external costs, in the range of nuclear fission and renewables.

For a 156 MW gas turbine plant (oil and orimulsion chains) in Lauffen external costs 38-166 mECU/kWh have been evaluated, restricted range 51-78 mECU/kWh. Human health impacts are rather high, 26 mECU/kWh, and about double the value given for the coal power plant in Lauffen and about ten-fold the value for gas power plant.

6. External costs for nuclear fission

The nuclear fission technologies have many similarities with the fusion technologies. For example, massive plant buildings are necessary, rather complicated equipments are used, radioactive releases are caused, and disposal of radioactive wastes is necessary. Important external costs may be caused by doses calculated as population exposure expressed in manSv in both cases. Due to analogous features it is useful to be able to compare the external costs of the various stages, e.g. of the waste disposal.

External costs of nuclear fission 2.5-7 mECU/kWh (*Saez and Linares, 1997*) are about at the level of some renewables (e.g. wind, chapter 3 in this report). Biomass seems to give higher external costs. The Finnish case study for biomass (the plant in the Finnish town Forssa) gave somewhat higher external costs, 15 - 25 mECU/kWh (*Pingoud et al., 1997*). The costs of fission are considerably lower than for fossil fuels.

Only two case studies are studied in some more detail in the following. The first one is the French ExternE case (*Anon, 1995*), the other a Finnish case not included in ExternE (*Hongisto et al., 1998*). The costs of these cases are in the lower range of costs due to nuclear fuel cycle. Also fission plants having relative high external costs are included in the ExternE study. Especially a fictional PWR nuclear power plant of 450 MW in the Netherlands have been estimated to have public health impacts of 7.1 mECU/kWh due to other fuel cycle stages than power generation (*Dorland et al., 1998).*

Even more than in the case of fossil fuel technologies time scales, space scales and discount rates have impact on the results. Especially in the case of waste disposal but also in the cases of reprocessing, normal operation and mining and milling these factors have an essential role. In both the French ExternE case and also in the UNSCEAR studies (*UNSCEAR, 1982, 1988, 1993*) reprocessing and nuclides C-14 and I-129 are important. The half-life times of these nuclides are 5700 years and 17 million years. If instead of reprocessing, direct final disposal of spent fuel is used, the caused doses might be lower when collective doses are integrated without time limit, if uranium in the original fuel is not considered (*INFCE, 1980*). If also uranium is considered and no integration limit is used doses will be higher.

Time scales considered were 100000 years in the case of reprocessing and I -129 in the French study (*Anon, 1995*). As C-14 is the most important nuclide a time scale of about 10000 years has importance. This has actually been used in other studies. Regarding space scales global scale seems to dominate in doses (French ExternE study).

In the case of direct disposal of spent fuel time scales of millions of years are often used. It is assumed that releases to the biosphere occur in the very far future and that the integration periods may be very long. If global scale is considered it will dominate in collective doses.

It can be argued that the methodology is not very fair for radioactive waste disposal. This has also been discussed in the other E2 report (*Korhonen, 1998*) where the external costs due to disposal of fusion waste are estimated.

Radon due to mill tailings has also been considered to have a remarkable contribution to external costs of fission energy. Long-term population doses are caused by emissions of Rn-222 from mill tailings, as these are considered to emit radon for very long time periods. UNSCEAR data (*UNSCEAR, 1993*) has been used to give 1-1000 man Sv/GWa (for the duration 10000 years), which would give external costs in the range of 0.02-20 mECU/kWh. The best estimated value 150 manSv/GWa would give 3.3 mECU/kWh. This value has been criticised and a much lower value of about 1 manSv/GWa has been given (*Uranium institute, 1998*), resulting in 0.022 mECU/kWh. In ExternE mill tailings are assumed to be disposed of and therefore a low external value for mining and milling is used.

Reprocessing of nuclear waste is considered to cause C-14 emissions, resulting in external costs of about 2 mECU/kWh for the French case study (*Anon, 1995*). The value is about equivalent to the UNSCEAR 1993 results. The total external costs without discounting were estimated to be 2.5 mECU/kWh. Due to disposal rather small dose estimates have been given about 0.02 mECU/kWh due to disposal of high level waste, when only local scale is considered (*Anon, 1995*). Amounts of C-14 are rather low in fission waste. Doses would be higher if also global scale were considered but to be considerably higher very long time spans had to be considered. On the other hand, C-14 emissions due to normal operation in fission plants can still cause higher costs than emissions due to disposal.

For the Finnish Lovisa nuclear power plant (two PWR plants in Lovisa) 2.09 manSv/TWh for the fuel cycle has been given (*Hongisto et al., 1998*). This would result in external costs of only 0.4 mECU/kWh. The main reason for the low value is that mining and milling is estimated to cause very low costs, which is generally the case in ExternE, and reprocessing is not considered to take place. The estimated Finnish case study is presented in Table 6.1 and Table 6.2. Releases from normal operation are estimated to cause the main part of costs of about 0.3 mECU/kWh. (In the French study this component was estimated to be 0.4 mECU/kWh.) Manufacturing of materials and construction has not been included in costs. Materials have not been considered in the French study either. Relatively low values of 0.4E-02 mECU/kWh have been evaluated for construction in the French case.

Discounting will result in very low costs.

Table 6.1. Estimated global public collective doses originated from different stages of nuclear fuel cycle in normal operation for two nuclear power plants (Lovisa /Hongisto et al. 1998).

Process of fuel cycle	Collective dose, manSv/TWh		
	low	mid	high
Mining and milling A (UNSCEAR -93)	1.14E-01	1.71E+01	1.14E+02
Mining and milling B (ExternE)		1.77E-01	
Conv.+enrich.+fuel fabr.		3.20E-04	
Operation	1.06E+00	1.77E+00	2.24E+00
Low and medium level waste disposal	1.43E-04	2.86E-04	1.14E-02
Decommissioning waste disposal	2.29E-06	1.17E-03	1.43E-02
Spent fuel disposal	0.00E+00	1.36E-01	
Spent fuel transportation	9.76E-04	1.21E-03	
Sub total (B)		2.09E+00	

Table 6.2. Estimated external costs from different stages of nuclear fuel cycle in normal operation for two nuclear power plants in Lovisa, monetarization of Table 6.1 collective doses.

Process of fuel cycle	External costs mECU/kWh		
	low	mid	high
Mining and milling A (UNSCEAR -93)	2.2E-02	3.3E+00	2.2E+01
Mining and milling B (ExternE)		3.5E-02	
Conv.+enrich.+fuel fabr.		6.2E-05	
Operation	2.1E-01	3.5E-01	4.4E-01
Low and medium level waste disposal	2.8E-05	5.6E-05	2.2E-03
Decommissioning waste disposal	4.5E-05	2.0E-04	2.8E-03
Spent fuel disposal	0.0E+00	2.7E-02	
Spent fuel transportation	1.9E-04	2.4E-04	
Sub total (B)		4.2E-01	

7. Comparison of externalities for renewable energy, fossil fuels and nuclear fission with the externalities for fusion

7.1 External costs of fusion

Two conceptual power plant designs, producing 1000 MW of electricity, were considered. Model 1 applies helium cooling and vanadium alloy structures for the components near the plasma, thus emphasising the use of low-activation materials. Model 2 is based on reduced activation martensitic steel for the structures and uses water-cooling. The plants are assumed to be situated in Lauffen near the River Neckar in the south-western part of Germany.

On the basis of the preliminary studies performed in the sub-task, external costs of fusion have been evaluated to be very low for the Model plant 1 (0.3-4.6 mECU/kWh) and also relatively low for the Model plant 2 (0.6-11.3 mECU/kWh).

In the environmental costs of fusion, some cost components seem dominant. Material manufacturing, construction and decommissioning of the plant give rise to relatively high cost components (about 0.3 mECU/kWh each). These costs are the same for both model plants. Of course, these components are absolutely very small. The global warming impact due to greenhouse gas emissions is important in material manufacturing. These global warming costs might also be avoided if future energy systems do not emit large amounts of greenhouse gases. However, the alternative energy production technologies then have lowered environmental costs, too. (Another possibility is to consider that the necessary electricity for material production is produced by fusion power and not by the average energy system.)

Other important emissions are C-14 emissions due to normal operation (Model 2) and due to waste disposal in decommissioning. These cause doses.

Occupational accidents in construction and decommissioning of the plant are estimated to give 0.5 mECU/kWh totally. This gives a relative high percentage of the estimated total costs. These costs originate mainly from the occupational accidents in industries involved in construction. As the estimated total costs are very low this kind of occupational costs are important.

A relatively high amount of C-14 has been evaluated to be produced in shield materials in the SEAFP project. If the effects of this C-14 inventory are estimated taking long-term global impacts into account, the C-14 cost component can become very important. Using the ExternE methodology, disposal can cause relatively high extra contributions to external costs. A best estimate value of 0.2 mECU/kWh (integration time 10000 years) has been chosen (*Korhonen, 1998*). If C-14 releases due to normal operation can be avoided in commercial fusion plants, the disposal component is even more important. A conclusion is that shield materials should be further studied in order to avoid a large activation of C-14. Another possibility would be to perform disposal employing appropriate repository design so that very small doses are caused, as has been assumed in this study.

Important cost components are due to global impacts. Local impacts are in many cost components (manufacturing of materials, operational phase) considered to be lower by some orders of magnitude than the global impacts. Occupational external costs are important in construction and decommissioning where costs are caused by accidents and diseases. These are mainly estimated on the basis of accidents in industries involved and are therefore not local. Global environmental impacts (global doses and greenhouse warming) are important in other cost components of fusion. Therefore, it could be concluded, that the site of the fusion power plant is not very important in environmental considerations. On the other hand, the site for the waste disposal has still to be chosen rather carefully.

However, it is still necessary to study the importance of local impacts in some more detail to be sure that local costs especially due to local doses in relatively high populated areas are as low as estimated in this stage of the present study.

It seems that it is not very relevant to compare only the monetarised external costs, as it is obvious that the costs for fusion will be rather low and e.g. the costs for coal are high, especially due to global warming costs. External costs of the various alternatives may change as new technologies are developed and to a high extent costs can be avoided (e.g. acidifying impacts but also global warming due to carbon dioxide emissions). Also fusion technology can experience major progress and some relative important cost components probably can be avoided already by 2050.

7.2 Comparisons between renewable energy and fusion

Characteristic for renewable energy sources is that there is no atmospheric pollution during operation, however, there is chemical pollution connected to the manufacturing of materials and the materials used for the electrical transmission equipment. In order to include this chemical pollution the renewable energy sources are considered from a life cycle analysis (LCA) point of view. Compared to other energy sources the emissions from material production and manufacturing are rather high per kWh produced.

The renewable energy sources, which have been analysed in this report, are wind farms off shore and on land and a photovoltaic plant. For the wind farms the external costs related to operation of the plants are rather low (0.01 mECU/kWh for the off shore wind farm and 0.19 mECU/kWh for the wind farm on land). For the PV plant the external costs related to operation have been assessed to zero, as the PV's are installed in a residential property. However, in the case of photovoltaics there may be external costs related to stand alone PV plants.

The dominating external costs related to the wind fuel cycle and the PV fuel cycle are the costs connected to other fuel cycle stages, especially being the external costs related to emissions during material production and manufacturing. For the wind fuel cycle these costs are in the range of 0.6-3.6 mECU/kWh, while in the case of photovoltaics costs are as much as 2.2-14.5 mECU/kWh. The reason for those high costs is the amount of fossil fuels used for the production and manufacturing of materials. The range indicates the large uncertainty in calculating the CO_2 damages. The low value is based on a CO_2 price of 3.8 ECU/ton CO_2, while the high value is based on a CO_2 value of 139 ECU/ton CO_2.

The external costs related to renewable energy sources may decrease in the future for several reasons. First of all the most energy and emission heavy materials used for the renewable technologies may be replaced by other materials with lower energy demand. Another point may be that in the future the emissions from fossil fuels used for material production may decrease, either caused by better efficiency, use of new technologies or by the use of cleaner fuels. Finally, in the future when renewables contribute to a large extent of the energy demand, the materials for the renewables may be produced and manufactured based on renewable energy itself instead of fossil fuels.

The external costs related to fusion energy are assessed to be in the same range as renewables like wind and photovoltaics. However, taking into consideration the operational costs may give advantages for renewable energy sources. In the case of wind energy today the operational costs (45 mECU/kWh) are a little higher than costs based on fossil fuels, while the operational costs of PV's are about 320 mECU/kWh. A survey performed for a number of long-term forecasts for the wind power technology in general shows a decrease in production costs of 2-2.5% p.a., which implies that the cost of wind-generated electricity would be halved by the year 2030, making it competitive to conventional fossil fuel based electricity production. The PV costs are expected to decrease during the next 10-50 years. Before 2010 it is expected to be reduced by a factor of five and some time between 2010 and 2050 electricity production based on photovoltaics will be fully comparable to fossil fuels, while operational costs for fusion are expected to be somewhat higher.

7.3 Comparisons between fusion and fission

The costs due to material production, construction, transportation and decommissioning are more dependent on the development of other technologies and are not so dependent on the development of fusion or fission power technology. These costs are somewhat higher for fusion than for fission due to higher amounts of materials and more specific requirements. These costs are still rather low. An important part of these costs is caused by the global warming impact. The occupational accidental costs are also important. It may be argued that these costs are not environmental costs, but associated with occupational activities.

The health effects due to long term doses from emissions during normal operation and from waste disposal are important cost components for both fusion and nuclear fission if long term impacts from global scales are taken into account (1000-1000 000 years). Obviously C-14 is the dominating radionuclide causing doses and costs. Reprocessing, if used, can cause relatively high external costs for nuclear fission due to C-14 emissions (about 2mECU/kWh). Also mining and milling, if calculated using UNSCEAR's estimate gives relatively high cost components for nuclear fission (about 3mECU/kWh).

Both fusion and fission have rather low external costs and it is not easy to observe the difference between these alternatives on the basis of external costs. The fission power plants with relative low costs among the studied cases (*Saez and Linares, 1997*) are probably more commensurable cases for comparison between fusion and fission in the future around 2050. Still the costs of both alternatives could be even lower if very long-term integration of doses were not considered or if discounting were used. On the other hand externalities of the costs due to nuclear accidents are estimated to be very low in case the estimates are based on expectation values of economic damages. Therefore, the point that severe accidents will not occur in fusion power production has no remarkable impact on the external costs of fusion. The accounting of risk aversion may increase the contribution of accidents to the total external costs considerably.

7.4 Comparison between fusion and fossil fuels

Global warming impact due to carbon dioxide emissions is the dominating term in the fossil fuel cycles, when modern plants are compared. If other costs of fossil fuel cycle were almost avoided due to future technical development the external costs due to global warming are so high for all power production technologies using fossil fuels that they dominate over fusion or fission costs. This is also otherwise evident; negotiations to restrict carbon dioxide emissions are going on.

Still global warming and long-term doses have not been considered in a very commensurable way. By using ExternE implementation recommendations 1 man-mSv might correspond to an emission of 4-11 t CO_2, if the restricted range used in ExternE for CO_2 costs is applied. The price for statistical life has been rather high (about 3 MECU) also in the case of global scale doses. In the case of disposal the doses are often integrated over long time periods. Also when costs of e.g. C-14 emissions due to normal operation are estimated long time periods are evaluated. Especially the reasons for rather different integration of impacts due to circulation of carbon in the case of radioactive isotope C-14 or in the case of stable carbon (carbon dioxide emissions to air) causing greenhouse warming should be discussed more.

In comparison same underlying assumptions are necessary also for discount rates. If discount rates are applied for carbon dioxide emissions, it can be argued that they should also be applied to waste disposal. This would give that external costs from long living radionuclides would be minimal. However, there is quite a general world-wide agreement that future generations should be given equally cautious protection as the present generation.

On the other hand, in the comparison of external costs of fusion to the external costs of fossil fuels these methodological questions are not very important when external costs of fossil fuels have dominating costs. In future, when fossil fuel technologies will cause lower emissions, it will be more important that impacts are calculated in a commensurable way.

8. Conclusion

In the report the external costs have been assessed for renewables, specified in details by two wind farms and a photovoltaic plant. In all cases the production of materials for the renewable plants has proven to be the most important issue, when considering external costs. The external costs for biomass and biogas have been estimated in different studies in the ExternE National Implementation project. The external costs are given in the following for wind and photovoltaics, and for the biogas case in Denmark and the biomass case in Finland using the restricted range for CO_2.

Wind farm on land:	0.8-1.2 mECU/kWh
Wind farm off shore:	1.0-1.6 mECU/kWh
Integrated PV's:	3.5-6.0 mECU/kWh
Biogas:	16-19 mECU/kWh
Biomass:	15-25 mECU/kWh

The reason for the relative high values for biogas and biomass are emissions from the combustion process and predominantly the release of CH_4. A smaller part of the emissions is related to transportation of biomass.

For fossil fuels external costs have been estimated based on different fuel cycles carried out in the ExternE project. In general the most important factor in the assessment of external costs related to fossil fuels is shown to be the costs in relation to global warming. The external costs for different fossil fuels have been estimated to the following values using the restricted range for CO_2. The estimates are the results of different studies in different countries from the ExternE project.

Natural gas:	12-23 mECU/kWh
Peat:	23-51 mECU/kWh
Coal:	20-55 mECU/kWh
Oil and orimulsion:	51-78 mECU/kWh

The external costs of nuclear fission have been estimated to be at the same level as some renewables as e.g. photovoltaics. The range for nuclear fission is as follows:

Nuclear fission:	2.5-7 mECU/kWh

Even more than in the case of fossil fuel technologies, time scales, space scales and discount rates have impact on the results. Especially in the case of waste disposal but also in the cases of reprocessing, normal operation and mining and milling these factors have an essential role. Reprocessing and also mining and milling can cause relatively high external cost components about 2-3 mECU/kWh both.

The nuclear fission technology has many similarities with the fusion technology. For example, massive plant buildings are necessary, rather complicated equipment is used, radioactive releases are caused and disposal of radioactive wastes is necessary. Important external costs might be caused by doses calculated as population exposure expressed in manSv for as well fusion as fission. On the basis of the preliminary studies performed in this sub-task, external costs of fusion have been evaluated to be very low.

Fusion, Model plant 1:	0.3-4.6 mECU/kWh
Fusion, Model plant 2:	0.6-11.3 mECU/kWh.

It seems not very relevant to compare only the monetarised external costs as it is obvious that the costs for fusion will be rather low compared to fossil fuels, especially due to the global warming costs related to fossil fuels. The external costs for fusion have been estimated to be approximately the same as for some renewables. However, it must be stated that the estimates of the external costs for fusion are rather preliminary and need to be assessed more detailed in order to get a comparable estimate.

External costs of the various alternatives may change as new technologies are developed and costs can to a high extent be avoided (e.g. acidifying impacts but also global warming due to carbon dioxide emissions). Also fusion technology can experience major progress and some important cost components probably can be avoided already by 2050.

The assessment of external costs for different energy technologies is in principle useful as it gives a common measure for comparison. However, some aspects are often left out from the monetarisation, and some aspects may be difficult to monetarise. Human impacts are often prioritised and less attention is given to ecosystems and social factors.

Also in the case of fusion only health impacts have been considered of importance. For Model 1 the best estimate is about 100 death cases (or equivalents). The main part occurs during the production and decommissioning phase and around thirty percent later in the very far future. For Model 2 about 200 death cases are estimated, the main part in the future (100 years after 2050). It is quite possible that some important valuation aspects have been excluded in the evaluations.

Another possible approach would be to use some sociological measures for disadvantages. E.g. the concept Index of Environmental Friendliness gives indices on the basis of valuation of various environmental concerns. This kind of statistical approach can relatively easy value environmental issues, however, it has no specific scientific basis. The valuation represents the view of some expert groups, and might change rather easily under different conditions.

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