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ES EXECUTIVE SUMMARY

ES 1 Introduction

ES 1.1 Background and objectives

The use of energy causes damage to a wide range of receptors, including human health, natural ecosystems, and the built environment. Such damages are referred to as external costs, as they are not reflected in the market price of energy. These externalities have been traditionally ignored.

However, there is a growing interest towards the internalisation of externalities to assist policy and decision making. Several European and international organisms have expressed their interest in this issue, as may be seen in the 5th Environmental Action Programme, in the White Paper on Growth, competitiveness and employment, or the White Paper on Energy, all from the European Commission. This interest has led to the development of internationally agreed tools for the evaluation of externalities, and to its application to different energy sources.

Within the European Commission R&D Programme Joule II, the ExternE Project developed and demonstrated a unified methodology for the quantification of the externalities of different power generation technologies. Under Joule III, this project has been continued with three distinguished major tasks: ExternE Core for the further development and updating of the methodology, ExternE National Implementation to create an EU-wide data set and ExternE-Transport for the application of the ExternE methodology to energy related impacts from transport. The current report is the result of the ExternE National implementation project for Germany.

The objective of the ExternE National Implementation project is to establish a comprehensive and comparable set of data on externalities of power generation for all EU member states and Norway. The tasks include the application of the ExternE methodology to the most important fuel cycles for each country as well as to update the already existing results; to aggregate these site- and technology-specific results to more general figures. For countries already involved in Joule II, these data have been applied to concrete policy questions, to indicate how these data could feed into decision and policy making processes. Other objectives were the dissemination of results in the different countries, and the creation of a network of scientific institutes familiar with the ExternE methodology, data, and their application.

The ExternE National Implementation project has generated a large set of comparable and validated results, covering more than 60 cases, for 15 countries and 11 fuel cycles. A wide range of technologies have been analysed, including fossil fuels, nuclear and renewables. Fuel cycle analyses have been carried out, determining the environmental burdens and impacts of all stages. Therefore, besides from the externalities estimated, the project offers a large database of environmental aspects of the fuel cycles studied. An aggregation exercise has also been carried out, to extend the analysis to the whole electricity system of each of the participant countries. The usefulness of the current results has been demonstrated through application in a wide range of energy policy related case studies, including e.g. the analysis of costs and benefits of the introduction of emission abatement technologies.

Further work is needed, however, to remove existing uncertainties if externality values are to be used directly for policy measures, not only as background information. The acceptability of these measures will depend on the credibility of the externality values.

The present report is to be seen as part of a larger set of ExternE publications. It summarises the results of the national implementation of the ExternE methodology in Germany. More detailed information on the approach and the application in Germany is given in a set of reports that have been published under JOULE II.

ES 1.2 The German National Implementation

In Germany, about 50 % of the electricity is generated from coal and lignite, with a large fraction of hard coal used in the western part, and a large fraction of lignite used in the eastern part of the country (former GDR). Nuclear energy accounts for nearly 30 % of the total electricity production. While the contribution from coal and lignite was slightly decreasing over the last years, there was an increase in electricity generation from natural gas, which however still accounts for less than 10 % of the power generation.

Taking into account this composition of the German power sector, our analysis was primarily focused on the fossil and nuclear fuel cycles. In addition, external costs from renewable fuel cycles (PV, wind and biomass) were estimated to give an indication of the environmental performance of potential alternative fuel sources.

ES 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 (European Commission, 1995). It is a bottom-up methodology, with a site-specific approach, that is, it considers the effect of an additional fuel cycle, located in a specific place.

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 to the results, and the extent to which the external cost 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 be not 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 characterization, identification of burdens and impacts, prioritization of impacts, quantification, and economic valuation.
- 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 of 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.

ES 3 Overview of the fuel cycles assessed

ES 3.1 Fossil fuel cycles

The following fuel cycles were analysed:

- Coal fired power plant burning domestic coal (underground coal mining), equipped with electrostatic dust precipitators, flue gas desulphurisation and DENOX. Capacity: 600 MW, thermal efficiency: 43.0 %. 6500 full load hours per year. Hypothetical site at Lauffen.
- Lignite fired power plant, open pit mining, equipped with electrostatic dust precipitators, flue gas desulphurisation and DENOX. Capacity: 800 MW, thermal efficiency: 40.1 %. 6500 full load hours per year. Hypothetical site at Grevenbroich.
- Oil fired power plant with gas turbine. Capacity: 156 MW, thermal efficiency: 31.1 %, 6500 full load hours per year. Hypothetical site at Lauffen.
- Combined cycle natural gas fired power plant, Capacity: 778 MW, thermal efficiency: 57.6 %, 6500 full load hours per year. Hypothetical site at Lauffen.

The priority impacts considered are impacts from airborne pollutants on human health, crops, building materials, and natural ecosystems, global warming, occupational health impacts, impacts from mining activities on groundwater quality, resettlement due to open pit mining, and effects of oil spills on aquatic systems.

The major damage costs from the fossil fuel cycles result from impacts on human health and global warming - in particular the latter impact category is subject of major uncertainties. The external costs from the oil fired gas turbine reference plant with a rather low thermal efficiency are the highest from all the fossil fuel cycles analysed, and are close to the level of private costs of electricity generation. Not surprisingly, the operation of a modern combined cycle gas fired power plant leads to the lowest external costs of the fossil fuels, which are significantly lower than the private costs.

ES 3.2 Nuclear fuel cycle

The power plant analysed is a hypothetical PWR with a capacity of 1375 MW (Wehowsky et al., 1994), operated at a hypothetical site in the Southwest of Germany. The major sources of exposure are radon emissions from abandoned mill tailing piles, which together with globally dispersed H-3, Kr-85 and C-14 from the power generation and reprocessing stages accounts for about 98% of the calculated collective dose integrated over 10 000 years. However, the average individual dose is very small and the dose-response function is considered to be very uncertain as it is interpolated from the results of studies for high individual dose levels. Because of the long time horizon of the radiological effects, the discounted damage is much lower and dominated by the non-radiological impacts due to emissions of non-radioactive pollutants from the life cycle. Based on the expected value of risk, the damage from beyond design accidents are small compared to the external costs from the whole fuel cycle.

ES 3.3 PV fuel cycle

Two different PV applications were analysed: a PV home application, consisting of 96 polycrystalline modules with a total peak power of 4.8 kWp, and a facade application consisting of 200 modules with a total peak power of 13 kWp. The modules are integrated into the facade of an office building. Both plants are existing plants in operation, and we have used measurement data on the annual electricity production.

Atmospheric emissions released during the production phase (SO_2, NO_x, particulates, CO_2, CH_4, N_2O) have been determined and the related external costs have been quantified, including impacts on public health, agriculture, forests, materials and the global climatic system. Potential impacts from other substances which are released into the environment during the production phase are discussed but not quantified. Occupational net-risks have been calculated, that is the difference between the risks of average industrial activities and the specific activities related to the life cycle. In the case of photovoltaics this leads to negative damage costs in some areas.

The external costs presented in Figure ES.1 and ES.2 are calculated based on the assumption that in the production phase fossil fuels are used and the required electrical energy is taken from the grid. The emissions therefore represent average values for heat processes and power plants in Germany. The external costs are mainly caused by the present use of fossil plants. External costs are much lower when it is assumed that electrical energy required for the production is not taken from the grid but is produced by the PV technology itself.

ES 3.4 Wind fuel cycle

The "Nordfriesland Windpark" is located in the coastal area of Friedrich-Wilhelm-Lübke-Koog in the federal state Schleswig-Holstein. The park includes 51 wind energy converters of the type HSW-250. The rated power of one WEC is about 250 kW.

Quantities of atmospheric emissions released in the production phase (SO_2, NO_x, particulates, CO_2, CH_4, N_2O) have been calculated. The related external costs have been quantified, including impacts on public health, agriculture, forests, materials and the global climatic system. Noise propagation has been calculated according to the VDI-guideline 2714. Willingness to pay figures for noise reduction have been used to valuate an increase in noise level. The quantification of damage due to visual intrusion remains difficult because no valuation studies exist which directly refer to typical wind park sites. Willingness to pay for intact countryside during holidays has been used to valuate the impacts. Impacts on animals and risks of epileptic fits have been discussed but seem to be negligible.

Occupational health impacts caused by accidents and diseases are assessed using statistical information from the relevant industrial sectors. Construction, transport, operation and dismantling of the WEC have been considered.

Like in the case of PV, the external costs are calculated based on the assumption that in the production phase fossil fuels are used and the required electrical energy is taken from the grid. The external costs are mainly caused by the use of fossil fuels. External costs are lower when it is assumed that electrical energy required for the production is not taken from the grid but is produced by the wind technology itself.

ES 3.5 Biomass fuel cycle

From the multitude of possible fuel cycles to produce electricity and/or heat from biomass the combustion of residual wood (Norway spruce) in a combined heat and power (CHP) plant with a generator capacity of 20 MW is taken as reference technology as this is already in the short-term an economically sensible option in Germany. The technology of the reference plant is a circulating atmospheric fluidised bed combustor. Especially the NO_x emissions of the CHP plant are high if compared to the fossil power plants but this is mostly due to the smaller plant size, less to the fuel. The CHP plant is located in Tübingen, south of Stuttgart.

The fuel cycle consists of the six major process steps: conveying in forest, storage and drying, hacking, transport, generation, and waste disposal. In comparison to normal tree stands no additional cultivation measures are necessary. There are no alternative usages for the residual wood and no market price. Thus, the process step cultivation does not have to be taken into account in this analysis. The combustion of the residual wood contributes above all to the total air-borne emissions – with the notable exception of CO_2. There is no net atmospheric CO_2 build-up from the burning of biomass grown sustainably because CO_2 released in combustion is compensated for by that withdrawn from the atmosphere during growth.

The effects of the air-borne emissions on human health, terrestrial ecosystems and buildings, occupational health effects and global warming are quantified. Other impacts like e.g. ash disposal effects or fertiliser runoff effects either do not apply to this specific biomass technology or do not cause significant effects. Increased mortality, mostly due to the NO_x emissions of the generation stage. contribute the most to the total quantified damage costs. For global warming only low damage costs are quantified.

ES 3.6 Aggregation

We have demonstrated the applicability of the detailed bottom-up impact pathway approach to the whole electricity sector in Germany by using an extended *multi-source* version of the EcoSense software. One of the main findings concerning the aggregation methodology is that damage costs per tonne of pollutant emitted might differ significantly even within a country. The main reason for such differences is the spatial variation in SO_2, NO_x, and NH_3 emissions. As ammonia is mainly emitted from agricultural activities, and the availability of free ammonia in the atmosphere also depends on the level of SO_2 and NO_x emissions from other sources, the damage costs we refer to as ‘energy’ externalities in fact strongly depend on emissions from various industrial activities.

In Germany, we have to take into account the specific situation in the former GDR (‘neue Länder’) with very high emissions from the power sector, leading to external costs which are much higher than the private costs of electricity generation. The damage costs from electricity generation in Germany excluding global warming are estimated to result in about $30 \cdot 10^9$ ECU, which is more than 1 % of the 1990 GDP. Estimates of global warming damage costs are very uncertain, they are estimated to be within a range of 1.5 to 55 billion ECU/a. There was a drastic reduction of emissions in the ‘neue Länder’, leading to a reduction of the overall damage costs of about 25 % since 1990. As soon as data from CORINAIR 1990 are available, the results will be updated to reflect these changes. The quantified damage costs from nuclear power generation are relatively low compared to the fossil fuels. Although nuclear energy contributes to nearly 30 % of power production in 1990, the share of damage costs from nuclear electricity is only about 1.5 %.

ES 3.7 Policy case studies

IER has applied the ExternE methodology together with ETSU in two policy oriented case studies on the assessment of benefits of an acidification strategy for the European Union, and on the costs and benefits of pollution abatement options for large combustion plants.

The case study on the benefits of a European acidification strategy demonstrates that the ExternE methodology and the multi-source EcoSense model can be applied to provide sophisticated and detailed analysis of pan-European emission scenarios. A major advantage of this approach is that it is able to take account of geographical variation in damages with respect to the source of emissions and the location of damage receptors. An overall comparison of costs and benefits indicates that estimated benefits of moving to scenarios implementing more stringent abatement measures, substantially exceed costs at the European level. However, under some scenarios some countries are predicted to experience a net cost.

This case study on costs and benefits of pollution abatement applies ExternE results for pollution damage assessment using impact pathway analysis to consider the costs and benefits of measures to reduce the emission of air pollutants from large combustion plant. The conclusion of this case study is that strict emissions controls for SO_2, NO_x and particulates from Large Combustion Plant are justified, in many cases even without consideration of mortality effects.

ES 4 Conclusions

The results presented in this report provide a comprehensive set of external cost data for a wide range of technologies operated in Germany. External cost estimates are calculated following a standardised methodology that is widely accepted now on the international level, and similar data sets are produced in all member states of the European Union. Although there are significant remaining uncertainties in some areas, our results indicate that external costs of some fuel cycles are high enough to affect energy policy decisions.

A preliminary ‘multi-source’ version of the EcoSense model was used to calculate aggregated damage costs from the German power sector, and to estimate environmental benefits resulting from the implementation of European emission reduction strategies. The possibility of carrying out this type of cost-benefit analysis for environmental policy measures is certainly a promising field of application for the ExternE methodology, and first results created an increasing interest of policy makers.

Although further research is required to reduce the existing uncertainties, this report provides a comprehensive analysis of environmental impacts and resulting external costs from electricity generation in Germany, and we believe that results give helpful support to the integration of environmental aspects into energy policy and for a more rational environmental policy.

CONTENTS

1. INTRODUCTION

Economic development of the industrialised nations of the world has been founded on continuing growth in energy demand. The use of energy clearly provides enormous benefits to society. However, it is also linked to numerous environmental and social problems, such as the health effects of pollution of air, water and soil, ecological disturbance and species loss, and landscape damage. Such damages are referred to as external costs, as they have typically not been reflected in the market price of energy, or considered by energy planners, and consequently have tended to be ignored. Effective control of these ‘externalities’ whilst pursuing further growth in the use of energy services poses a serious and difficult problem. The European Commission has expressed its intent to respond to this challenge on several occasions; in the 5th Environmental Action Programme; the White Paper on Growth, Competitiveness and Employment; and the White Paper on Energy.

A variety of options are available for reducing externalities, ranging from the development of new technologies to the use of fiscal instruments, or the imposition of emission limits. The purpose of externalities research is to quantify damages in order to allow rational decisions to be made that weigh the benefits of actions to reduce externalities against the costs of doing so.

Within the European Commission R&D Programme Joule II, the ExternE Project developed and demonstrated a unified methodology for the quantification of the externalities of different power generation technologies. It was launched as the EC-US Fuel Cycles Study in 1991 as a collaborative project with the US Department of Energy. From 1993 to 1995 it continued as the ExternE project, involving more then 40 European institutes from 9 countries, as well as scientists from the US. This resulted in the first comprehensive attempt to use a consistent ‘bottom-up’ methodology to evaluate the external costs associated with a wide range of different fuel chains. The result was identified by both the European and American experts in this field as currently the most advanced project world-wide for the evaluation of external costs of power generation (EC/OECD/IEA, 1995).

Under the European Commission’s Joule III Programme, this project has continued with three major tasks: ExternE Core for the further development and updating of the methodology, ExternE National Implementation to create an EU-wide data set and ExternE-Transport for the application of the ExternE methodology to energy related impacts from transport. The current report is the result of the ExternE National implementation project for ***country x.***

1.1 Objectives of the project

The objective of the ExternE National Implementation project is to establish a comprehensive and comparable set of data on externalities of power generation for all EU member states and Norway. The tasks include;

- the application of the ExternE methodology to the most important fuel chains for each country
- updating existing results as new data become available for refinement of methods
- aggregation of site- and technology-specific results to the national level
- for countries already involved in Joule II, data have been applied to policy questions, to indicate how these data could feed into decision and policy making processes
- dissemination of results
- creation of a network of scientific institutes familiar with the ExternE methodology and data, and their application
- compilation of results in an EU-wide information system for the study.

The data in this report results from the application of ExternE-methodology as developed under Joule II. However, because our understanding of the impacts of environmental burdens on humans and nature is improving continuously, this methodology (or more precise, the scientific inputs into the accounting framework) has been updated and further developed.

The National Implementation project has generated a large set of comparable and validated results, covering more than 60 cases, for 15 countries and 12 fuel chains. A wide range of generating options have been analysed, including fossil, nuclear and renewable technologies. Analysis takes account of all stages of the fuel chain, from (e.g.) extraction of fuel to disposal of waste material from the generating plant. In addition to the estimates of externalities made in the study, the project also offers a large database of physical and social data on the burdens and impacts of energy systems.

The ExternE results form the most extensive externality dataset currently available. They can now be used to look at a range of issues, including;

- internalisation of the external costs of energy
- optimisation of site selection processes
- cost benefit analysis of pollution abatement measures
- comparative assessment of energy systems

Such applications are illustrated by the case studies presented later in this report, and in other national implementation reports.

1.2 Publications from the project

The current report is to be seen as part of a larger set of publications, which commenced with the series of volumes published in 1995 (European Commission, 1995a-f). A further series of reports has been generated under the present study.

First, the current report covers the results of the national implementation for Germany and is published by the Institut für Energiewirtschaft und Rationelle Energieanwendung (IER). It contains all the details of the application of the methodology to the coal, lignite, oil natural gas, nuclear PV and wind fuel cycle, aggregation, and the application of the methodology in two policy oriented case studies. Brief details of the methodology are provided in Chapter 2 of this report and the Appendices; a more detailed review is provided in a separate report (European Commission, 1998a). A further report covers the development of estimates of global warming damages (European Commission, 1998b). The series of National Implementation Reports for the 15 countries involved are published in a third report (European Commission, 1998c).

In addition, further reports are to be published on the biomass and waste fuel chains, and on the application and further development of the ExternE methodology for the transport sector.

This information can also be accessed through the ExternE website. It is held at the Institute for Prospective Technological Studies, and is accessible through the Internet (*http://externe.jrc.es*). This website is the focal point for the latest news on the project, and hence will provide updates on the continuation of the ExternE project.

1.3 Structure of this report

The structure of this report reflects that it is part of a wider set of publications. In order to ease comparison of results, all ExternE National Implementation reports have the same structure and use the same way of presentation of fuel cycles, technologies and results of the analysis.

The common structure is especially important for the description of the methodology. Chapter 2 describes the general framework of the selected bottom-up methodology. The major inputs from different scientific disciplines into that framework (e.g. information on dose-response functions) are summarised in the methodological annexes to this report and are discussed at full length in the separate ExternE methodology report. Because the methodological issues are similar for the different fuel cycles studied, and for the application in different countries, they are described in the annexes, which are the same for all National Implementation reports. This structure allows easy comparison between the different fuel cycles, technologies and countries and it clearly reflects that all data have been calculated using the same methodology. Nevertheless, some country specific situations or data problems have resulted in a few country specific methodological issues, which are discussed in separate methodological annex.

In order to ease readability, the main text of the chapters dealing with the application to the different fuel cycles provide the overview of technology, fuel cycles, environmental burdens and the related externalities. More detailed information (e.g. results for a specific type of impact) is provided in the annexes.

Most of the fuel cycles relevant for Germany were analysed in the first phase of the German National Implementation project and are described in detail in a set of reports (see below). For these fuel cycles, the present report briefly summarises the reference technologies and the major methodological issues. Results are updated, taking into account new exposure-response functions and monetary values that are recommended now by the ExternE Core group, so that results are comparable across fuel cycles, and comparable with results from the other country studies. Work in the second phase of the German Implementation project under JOULE III was focused on the further development of the EcoSense model, the implementation of the biomass fuel cycle, aggregation and on policy oriented case studies; these results are covered in more detail in the present report. For a detailed discussion of the work carried out in the first phase of the project, the reader should refer to the following reports:

Jochen Diekmann, Barbara Praetorius: Economics of Energy Externalities. ExternE - Implementation of the Accounting Framework in Germany. Final report prepared for the Commission of the European Union, DG XII. Deutsches Institut für Wirtschaftsforschung (DIW), May 1995.

Klaus Rennings: Economic Valuation of Fuel Cycle Externalities. ExternE - Implementation of the Accounting Framework in Germany. Final report prepared for the Commission of the European Union, DG XII. Institut für Verkehrswissenschaften an der Universität Münster (IVM)/Zentrum für Europäische Wirtschaftsforschung (ZEW), June 1995.

Wolfram Krewitt, Petra Mayerhofer, Alfred Trukenmüller, Rainer Friedrich: External Costs of the Fossil Fuel Cycles. ExternE - Implementation of the Accounting Framework in Germany. Final report prepared for the Commission of the European Union, DG XII. Institut für Energiewirtschaft und Rationelle Energieanwendung (IER), August 1995.

Fotis Raptis, Frank Kaspar, Jürgen Sachau: Assessment of the External Costs of the Photovoltaic and Wind Energy Life Cycle. ExternE - Implementation of the Accounting Framework in Germany. Final report prepared for the Commission of the European Union, DG XII. Institut für Solare Energieversorgungstechnik (ISET). August 1995.

The results of the German National Implementation Study are described in detail also in

Rainer Friedrich, Wolfram Krewitt (Eds.): Umwelt- und Gesundheitsschäden durch die Stromerzeugung - Externe Kosten von Stromerzeugungssystemen. Springer Verlag Berlin. 1997.

2. METHODOLOGY

2.1 Approaches Used for Externality Analysis

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.

However, this style of analysis has only recently become possible, through developments in environmental science and economics, and improvements in computing power has. Early externalities work used a ‘top-down’ approach (the impact pathway approach being ‘bottom-up’ in comparison). Such analysis is highly aggregated, being carried out at a regional or national level, using estimates of the total quantities of pollutants emitted or present and estimates of the total damage that they cause. Although the work of Hohmeyer (1988) and others advanced the debate on externalities research considerably, the style of analysis was too simplistic for adoption for policy analysis. In particular, no account could be taken of the dependence of damage with the location of emission, beyond minor corrections for variation of income at the valuation stage.

An alternative approach was the ‘control cost’ method, which substitutes the cost of reducing emissions of a pollutant (which are determined from engineering data) for the cost of damages due to these emissions. Proponents of this approach argued that when elected representatives decide to adopt a particular level of emissions control they express the collective ‘willingness-to-pay’ of the society that they represent to avoid the damage. However, the method is entirely self-referencing - if the theory was correct, whatever level of pollution abatement is agreed would by definition equal the economic optimum. Although knowledge of control costs is an important element in formulating prescriptive regulations, presenting them as if they were damage costs is to be avoided.

Life cycle analysis (OECD, 1992; Heijungs *et al*, 1992; Lindfors *et al*, 1995) is a flourishing discipline whose roots go back to the net energy analyses that were popular twenty years ago. While there are several variations, all life cycle analysis is in theory based on a careful and holistic accounting of all energy and material flows associated with a system or process. The approach has typically been used to compare the environmental impacts associated with different products that perform similar functions, such as plastic and glass bottles. Restriction of the assessment to material and energy flows means that some types of externality (such as the fiscal externalities arising from energy security) are completely outside the scope of LCA.

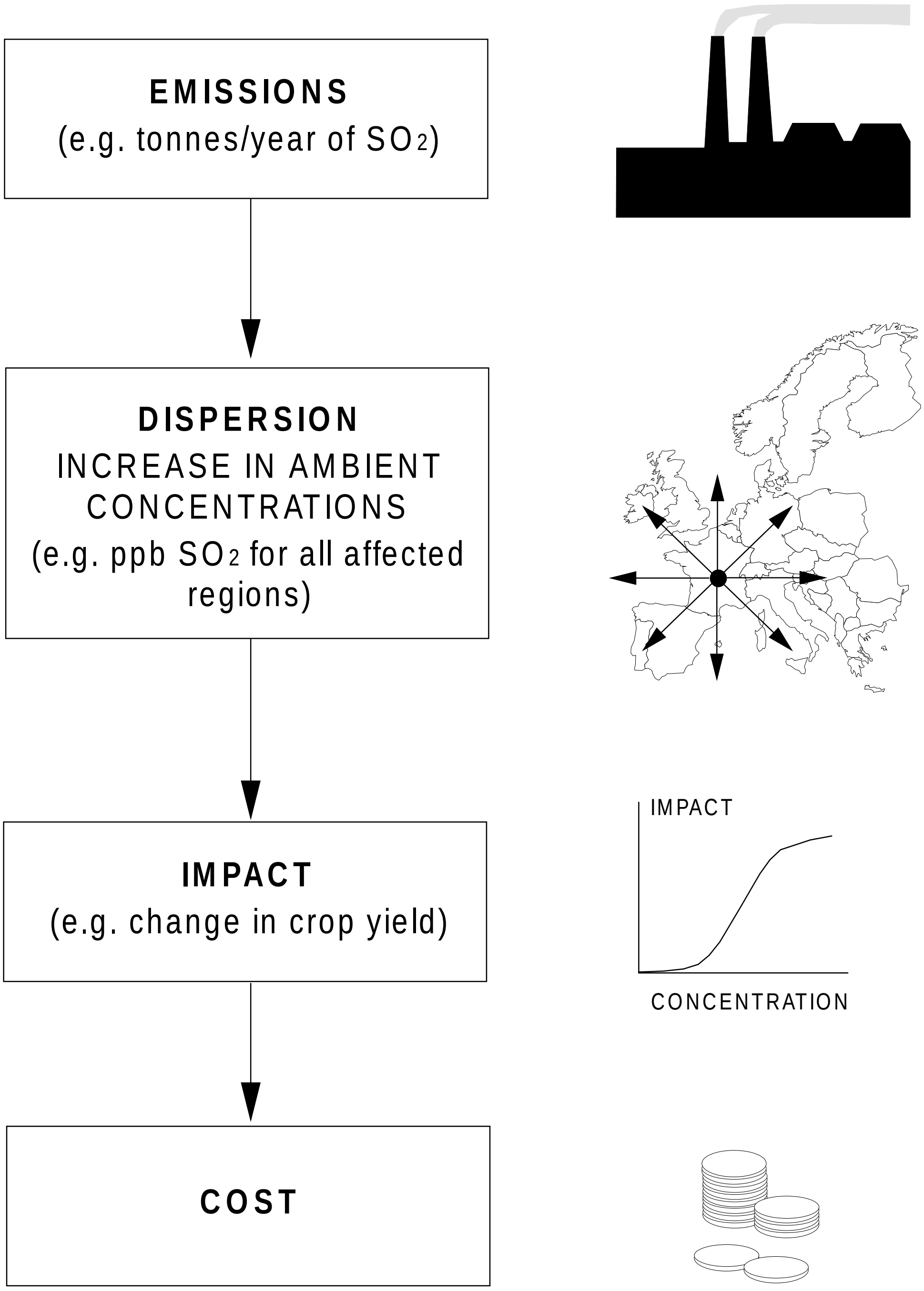


Figure 2.1 An illustration of the main steps of the impact pathways methodology applied to the consequences of pollutant emissions. Each step is analysed with detailed process models.

The ExternE method has numerous links to LCA. The concept of fuel cycle or fuel chain analysis, in which all components of a given system are analysed 'from cradle to grave', corresponds with the LCA framework. Hence for electric power fuel chains the analysis undertaken within the ExternE Project covers (so far as possible); fuel extraction, transportation and preparation of fuels and other inputs; plant construction, plant operation (power generation), waste disposal and plant decommissioning.

There are, however, some significant differences between externalities analysis as presented in this study and typical LCA analysis. Life cycle analyses tend not to be specific on the calculation of impacts, if they have attempted to quantify impacts at all. For example, the 'classification factors' identified by Heijungs *et al* (1992) for each pollutant are independent of the site of release. For air pollution these factors were calculated with the assumption of uniform mixing in the earth's atmosphere. While this can be justified for greenhouse gases and other pollutants with long residence times, it is unrealistic for particulate matter, NO_x, SO_2 and ozone (O_3). The reason for this radical approximation lies in the choice of emphasis in LCA: accounting for all material flows, direct and induced. Since induced flows occur at many geographically different points under a variety of different conditions, it is simply not practicable to model the fate of all emissions. In this sense, ExternE is much more ambitious and precise in its estimates than LCA.

A second difference is that most LCA studies have a much more stringent view on system boundaries and do not prioritise between different impacts. The ExternE analysts have to a large extent decided themselves if certain stages of the fuel cycle, such as plant construction or fuel transportation, can be excluded. Such decisions are made from experience of the likely magnitude of damages, and a knowledge of whether a given type of impact is *perceived* to be serious. [Note that it is recommended to quantify damages for any impact perceived to be serious whether or not earlier analysis has suggested that associated damages will be negligible]. What might be referred to as analytical 'looseness' is a consequence of the remit of the ExternE project, which has as a final objective quantification of the externalities of energy systems. As such the main emphasis of the study is quite properly on the impacts that are likely (given current knowledge) to dominate the results. Externalities assessments based on the ExternE methodology but conducted for other purposes may need to take a more truly holistic perspective than has been attempted here.

The analysis presented in this report places its emphasis on the quantification of impacts and cost because people care more about impacts than emissions. The quantification of emissions is merely a step in the analysis. From this perspective the choice between externalities assessment and conventional LCA is a matter of accuracy; uncertainties increase the further the analysis is continued. In general terms, however, it is our view that the fuel chain analyses of the ExternE Project can be considered a particular example of life cycle analysis.

2.2 Guiding Principles in the Development of the ExternE Methodology

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

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

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

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

In order to comply with these principles, much of the analysis described in this report looks at the effects of individual power projects which are closely specified with respect to:
- The technologies used;
- The location of the power generation plant;
- The location of supporting activities;
- The type of fuel used;
- The source and composition of the fuel used.

Each of these factors is important in determining the magnitude of impacts and hence associated externalities.

2.3 Defining the Boundaries of the Analysis

The starting point for fuel chain analysis is the definition of the temporal and spatial boundaries of the system under investigation, and the range of burdens and impacts to be addressed. The boundaries used in the ExternE Project are very broad. This is essential in order to ensure consistency in the application of the methodology for different fuel chains.

Certain impacts brought within these boundaries cannot be quantified at the present time, and hence the analysis is incomplete. However, this is not a problem peculiar to this style of analysis; it simply reflects the existence of gaps in available knowledge. Our rule here is that no impact that is known or suspected to exist, but cannot be quantified, should be ignored for convenience. Instead it should be retained for consideration alongside whatever analysis has been possible. Further work is needed so that unquantified effects can be better integrated into decision making processes.

2.3.1 Stages of the fuel chain

For any project associated with electricity generation the system is centred on the generation plant itself. However, the system boundaries should be drawn so as to account for all potential effects of a fuel chain. The exact list of stages is clearly dependent on the fuel chain in question, but would include activities linked to the manufacture of materials for plant, construction, demolition and site restoration as well as power generation. Other stages may need to be considered, such as, exploration, extraction, processing and transport of fuel, and the generation of wastes and by-products, and their treatment prior to disposal.

In practice, a complete analysis of each stage of a fuel chain is often not necessary in order to meet the objectives of the analysis (see below). However, the onus is on the analyst to demonstrate that this is the case - it cannot simply be assumed. Worth noting is the fact that variation in laws and other local conditions will lead to major differences between the importance of different stages in different parts of the world.

A further complication arises because of the linkage between fuel chains and other activities, upstream and downstream. For example, in theory we should account for the externalities associated with (e.g.) the production of materials for the construction of the plant used to make the steel that is used to make turbines, coal wagons, etc. The benefit of doing so is, however, extremely limited. Fortunately this can be demonstrated through order-of-magnitude calculations on emissions, without the need for detailed analysis.

The treatment of waste matter and by-products deserves special mention. Impacts associated with waste sent for disposal are part of the system under analysis. However, impacts associated with waste utilised elsewhere (which are here referred to not a waste but as by-products) should be considered as part of the system to which they are transferred from the moment that they are removed from the boundaries of the fuel chain. It is of course important to be sure that a market exists for any such by-products. The capacity of, for example, the building industry to utilise gypsum from flue gas desulphurisation systems is clearly finite. If it is probable that markets for particular by-products are already saturated, the ‘by-product’ must be considered as waste instead. A further difficulty lies in the uncertainties about future management of waste storage sites. For example, if solid residues from a power plant are disposed in a well engineered and managed landfill there is no impact (other than land use) as long as the landfill is correctly managed; however, for the more distant future such management is not certain.

2.3.2 Location of fuel chain activities

One of the distinguishing features of the ExternE study is the inclusion of site dependence. For each stage of each fuel chain we have therefore identified specific locations for the power plant and all of the other activities drawn within the system boundaries. In some cases this has gone so far as to identify routes for the transport of fuel to power stations. The reason for defining our analysis to this level of detail is simply that location is important in determining the size of impacts. There are several elements to this, the most important of which are:

- Variation in technology arising from differing legal requirements (e.g. concerning the use of pollution abatement techniques, occupational safety standards, etc.);
- Variation in fuel quality;
- Variations in atmospheric dispersion;
- Differences in the sensitivity of the human and natural environment upon which fuel chain burdens impact.

The alternative to this would be to describe a ‘representative’ site for each activity. It was agreed at an early stage of the study that such a concept is untenable. Also, recent developments elsewhere, such as use of critical loads analysis in the revision of the Sulphur Protocol within the United Nations Economic Commission for Europe’s (UN ECE) Convention on Long Range Transboundary Air Pollution, demonstrate the importance attached to site dependence by decision makers.

However, the selection of a particular series of sites for a particular fuel chain is not altogether realistic, particularly in relation to upstream impacts. For example, although some coal fired power stations use coal from the local area, an increasing number use coal imported from a number of different countries. This has now been taken into account.

2.3.3 Identification of fuel chain technologies

The main objective of this project was to quantify the external costs of power generation technologies built in the 1990s. For the most part it was not concerned with future technologies that are as yet unavailable, nor with older technologies which are gradually being decommissioned.

Over recent years an increasingly prescriptive approach has been taken to the regulation of new power projects. The concept of Best Available Techniques (BAT), coupled with emission limits and environmental quality standards defined by both national and international legislation, restrict the range of alternative plant designs and rates of emission. This has made it relatively easy to select technologies for each fuel chain on a basis that is consistent across fuel chains. However, care is still needed to ensure that a particular set of assumptions are valid for any given country. Across the broader ExternE National Implementation Project particular variation has for example been found with respect to the control of NO_x in different EU Member States.

As stated above, the present report deals mainly with closely specified technology options. Results have also been aggregated for the whole electricity generating sector, providing first estimates of damages at the national level.

2.3.4 Identification of fuel chain burdens

For the purposes of this project the term ‘burden’ relates to anything that is, or could be, capable of causing an impact of whatever type. The following broad categories of ‘burden’ have been identified:

- Solid wastes;
- Liquid wastes;
- Gaseous and particulate air pollutants;
- Risk of accidents;
- Occupational exposure to hazardous substances;
- Noise;
- Others (e.g. exposure to electro-magnetic fields, emissions of heat).

During the identification of burdens no account has been taken of the likelihood of any particular burden actually causing an impact, whether serious or not. For example, in spite of the concern that has been voiced in recent years there is no definitive evidence that exposure to electro-magnetic fields associated with the transmission of electricity is capable of causing harm. The purpose of the exercise is simply to catalogue everything to provide a basis for the analysis of different fuel chains to be conducted in a consistent and transparent manner, and to provide a firm basis for revision of the analysis as more information on the effects of different burdens becomes available in the future.

The need to describe burdens comprehensively is highlighted by the fact that it is only recently that the effects of long range transport of acidic pollutants, and the release of CFCs and other greenhouse gases have been appreciated. Ecosystem acidification, global warming and depletion of the ozone layer are now regarded as among the most important environmental concerns facing the world. The possibility of other apparently innocuous burdens causing risks to health and the environment should not be ignored.

2.3.5 Identification of impacts

The next part of the work involves identification of the potential impacts of these burdens. At this stage it is irrelevant whether a given burden will actually cause an appreciable impact; all potential impacts of the identified burdens should be reported. The emphasis here is on making analysts demonstrate that certain impacts are of little or no concern, according to current knowledge. The conclusion that the externalities associated with a particular burden or impact, when normalised to fuel chain output, are likely to be negligible is an important result that should not be passed over without comment. It will not inevitably follow that action to reduce the burden is unnecessary, as the impacts associated with it may have a serious effect on a small number of people. From a policy perspective it might imply, however, that the use of fiscal instruments might not be appropriate for dealing with the burden efficiently.

The first series of ExternE reports (European Commission, 1995a-f) provided comprehensive listings of burdens and impacts for most of the fuel chains considered. The tasks outlined in this section and the previous one are therefore not as onerous as they seem, and will become easier with the development of appropriate databases.

2.3.6 Valuation criteria

Many receptors that may be affected by fuel chain activities are valued in a number of different ways. For example, forests are valued not just for the timber that they produce, but also for providing recreational resources, habitats for wildlife, their interactions (direct and indirect) with climate and the hydrological cycle, protection of buildings and people in areas subject to avalanche, etc. Externalities analysis should include all such aspects in its valuation. Again, the fact that a full quantitative valuation along these lines is rarely possible is besides the point when seeking to define what a study should seek to address: the analyst has the responsibility of gathering information on behalf of decision makers and should not make arbitrary decisions as to what may be worthy of further debate.

2.3.7 Spatial limits of the impact analysis

The system boundary also has spatial and temporal dimensions. Both should be designed to capture impacts as fully as possible.

This has major implications for the analysis of the effects of air pollution in particular. It necessitates extension of the analysis to a distance of hundreds of kilometres for many air pollutants operating at the 'regional' scale, such as ozone, secondary particles, and SO_2. For greenhouse gases the appropriate range for the analysis is obviously global. Consideration of these ranges is in marked contrast to the standard procedure employed in environmental impact assessment which considers pollutant transport over a distance of only a few kilometres and is further restricted to primary pollutants. The importance of this issue in externalities analysis is that in many cases in the ExternE Project it has been found that regional effects of air pollutants like SO_2, NO_x and associated secondary pollutants are far greater than effects on the local scale (for examples see European Commission, 1995c). In some locations, for example close to large cities, this pattern is reversed, and accordingly the framework for assessing air pollution effects developed within the EcoSense model allows specific account to be taken of local range dispersion.

It is frequently necessary to truncate the analysis at some point, because of limits on the availability of data. Under these circumstances it is recommended that an estimate be provided of the extent to which the analysis has been restricted. For example, one could quantify the proportion of emissions of a given pollutant that have been accounted for, and the proportion left unaccounted.

2.3.8 Temporal limits of the impact analysis

In keeping with the previous section, impacts should be assessed over their full time course. This clearly introduces a good deal of uncertainty for long term impacts, such as those of global warming or high level radioactive waste disposal, as it requires a view to be taken on the structure of future society. There are a number of facets to this, such as global population and economic growth, technological developments, the sustainability of fossil fuel consumption and the sensitivity of the climate system to anthropogenic emissions.

The approach adopted here is that discounting should only be applied after costs are quantified. The application of any discount rate above zero can reduce the cost of major events in the distant future to a negligible figure. This perhaps brings into question the logic of a simplistic approach to discounting over time scales running far beyond the experience of recorded history. There is clear conflict here between some of the concepts that underlie traditional economic analysis and ideas on sustainability over timescales that are meaningful in the context of the history of the planet. For further information, the discounting of global warming damages is discussed further in Appendix V.

The assessment of future costs is of course not simply a discounting issue. A scenario based approach is also necessary in some cases in order to describe the possible range of outcomes. This is illustrated by the following examples;

- A richer world would be better placed to take action against the impacts of global warming than a poorer one;
- The damages attributable to the nuclear fuel chain could be greatly reduced if more effective treatments for cancer are discovered.

Despite the uncertainties involved it is informative to conduct analysis of impacts that take effect over periods of many years. By doing so it is at least possible to gain some idea of how important these effects might be in comparison to effects experienced over shorter time scales. The chief methodological and ethical issues that need to be addressed can also be identified. To ignore them would suggest that they are unlikely to be of any importance.

2.4 Analysis of Impact Pathways

Having identified the range of burdens and impacts that result from a fuel chain, and defined the technologies under investigation, the analysis typically proceeds as follows:

- Prioritisation of impacts;
- Description of priority impact pathways;
- Quantification of burdens;
- Description of the receiving environment;
- Quantification of impacts;
- Economic valuation;
- Description of uncertainties.

2.4.1 Prioritisation of impacts

It is possible to produce a list of several hundred burdens and impacts for many fuel chains (see European Commission, 1995c, pp. 49-58). A comprehensive analysis of all of these is clearly beyond the scope of externality analysis. In the context of this study, it is important to be sure that the analysis covers those effects that (according to present knowledge) will provide the greatest externalities (see the discussion on life cycle analysis in section 2.1). Accordingly, the analysis presented here is limited, though only after due consideration of the potential magnitude of all impacts that were identified for the fuel chains that were assessed. It is necessary to ask whether the decision to assess only a selection of impacts in detail reduces the value of the project as a whole. We believe that it does not, as it can be shown that many impacts (particularly those operating locally around any given fuel chain activity) will be negligible compared to the overall damages associated with the technology under examination.

There are good reasons for believing that local impacts will tend to be of less importance than regional and global effects. The first is that they tend to affect only a small number of people. Even though it is possible that some individuals may suffer very significant damages these will not amount to a significant effect when normalised against a fuel chain output in the order of several Tera-Watt (10^{12} Watt) hours per year. It is likely that the most appropriate means of controlling such effects is through local planning systems, which be better able than policy developed using externalities analysis to deal flexibly with the wide range of concerns that may exist locally. A second reason for believing that local impacts will tend to be less significant is that it is typically easier to ascribe cause and effect for impacts effective over a short range than for those that operate at longer ranges. Accordingly there is a longer history of legislation to combat local effects. It is only in recent years that the international dimension of pollution of the atmosphere and water systems has been realised, and action has started to be taken to deal with them.

There are obvious exceptions to the assertion that in many cases local impacts are of less importance than others;

- Within OECD states one of the most important exceptions concerns occupational disease, and accidents that affect workers and members of the public. Given the high value attached to human life and well-being there is clear potential for associated externalities to be large.
- Other cases mainly concern renewable technologies, at least in countries in which there is a substantial body of environmental legislation governing the design and siting of nuclear and fossil-fired plant. For example, most concern over the development of wind farms typically relates to visual intrusion in natural landscapes and to noise emissions.
- There is the possibility that a set of conditions - meteorology, geography, plant design, proximity of major centres of population, etc. - can combine to create local air quality problems.

The analysis of certain upstream impacts appears to create difficulties for the consistency of the analysis. For example, if we treat emissions of SO_2 from a power station as a priority burden, why not include emissions of SO_2 from other parts of the fuel chain, for example from the production of the steel and concrete required for the construction of the power plant? Calculations made in the early stages of ExternE using databases, such as GEMIS (Fritsche *et al*, 1992), showed that the emissions associated with material inputs to fossil power plants are 2 or 3 orders of magnitude lower than those from the power generation stage. It is thus logical to expect that the impacts of such emissions are trivial in comparison, and can safely be excluded from the analysis - if they were to be included the quantified effects would be secondary to the uncertainties of the analysis of the main source of emissions. However, this does not hold across all fuel chains. In the reports on both the wind fuel chain (European Commission, 1995f) and the photovoltaic fuel chain (ISET, 1995), for example, it was found that emissions associated with the manufacture of plant are capable of causing significant externalities, relative to the others that were quantified.

The selection of priorities partly depends on whether one wants to evaluate damages or externalities. In quite a few cases the externalities are small in spite of significant damages. For example, if a power plant has been in place for a long time, much of the externality associated with visual and noise impacts will have been internalised through adjustments in the price of housing. It has been argued that occupational health effects are also likely to be internalised.

For example, if coal miners are rational and well informed their work contracts should offer benefits that internalise the incremental risk that they are exposed to. However, this is a very controversial assumption, as it depends precisely upon people being both rational and well informed and also upon the existence of perfect mobility in labour markets. For the present time we have quantified occupational health effects in full, leaving the assessment of the degree to which they are internalised to a later date.

It is again stressed that it would be wrong to assume that those impacts given low priority in this study are always of so little value from the perspective of energy planning that it is never worth considering them in the assessment of external costs. Each case has to be assessed individually. Differences in the local human and natural environment, and legislation need to be considered.

2.4.2 Description of priority impact pathways

Some impact pathways analysed in the present study are extremely simple in form. For example, the construction of a wind farm will affect the appearance of a landscape, leading to a change in visual amenity. In other cases the link between 'burden' (defined here simply as something that causes an 'impact') and monetary cost is far more complex. To clearly define the linkages involved in such cases we have drawn a series of diagrams. One of these is shown in Figure 2.2, illustrating the series of processes that need to be accounted for from emission of acidifying pollutants to valuation of impacts on agricultural crops. It is clearly far more complex than the pathway suggested by Figure 2.1.

A number of points should be made about Figure 2.2. It (and others like it) do not show what has been carried out within the project. Instead they illustrate an ideal - what one would like to do if there was no constraint on data availability. They can thus be used both in the development of the methodology and also as a check once analysis has been completed, to gain an impression of the extent to which the full externality has been quantified. This last point is important because much of the analysis presented in this report is incomplete. This reflects on the current state of knowledge of the impacts addressed. The analysis can easily be extended once further data becomes available. Also, for legibility, numerous feedbacks and interactions are not explicitly shown in the diagrammatic representation of the pathway.

2.4.3 Quantification of burdens

The data used to quantify burdens must be both *current* and *relevant* to the situation under analysis. Emission standards, regulation of safety in the workplace and other factors vary significantly over time and between and within different countries. It is true that the need to meet these demands creates difficulties for data collection. However, given that the objective of this work is to provide as far as possible an accurate account of the environmental and social burdens imposed by energy supply and use, these issues should not be ignored. It is notable that data for new technologies can change rapidly following their introduction. In addition to the inevitable refinement of technologies over time, manufacturers of novel equipment may be cautious in their assessment of plant performance. As an example of this latter point, NO_x emission factors for combined cycle gas turbine plant currently coming on stream in several countries are far lower than was suggested by Environmental Statements written for the same plant less than five years ago.

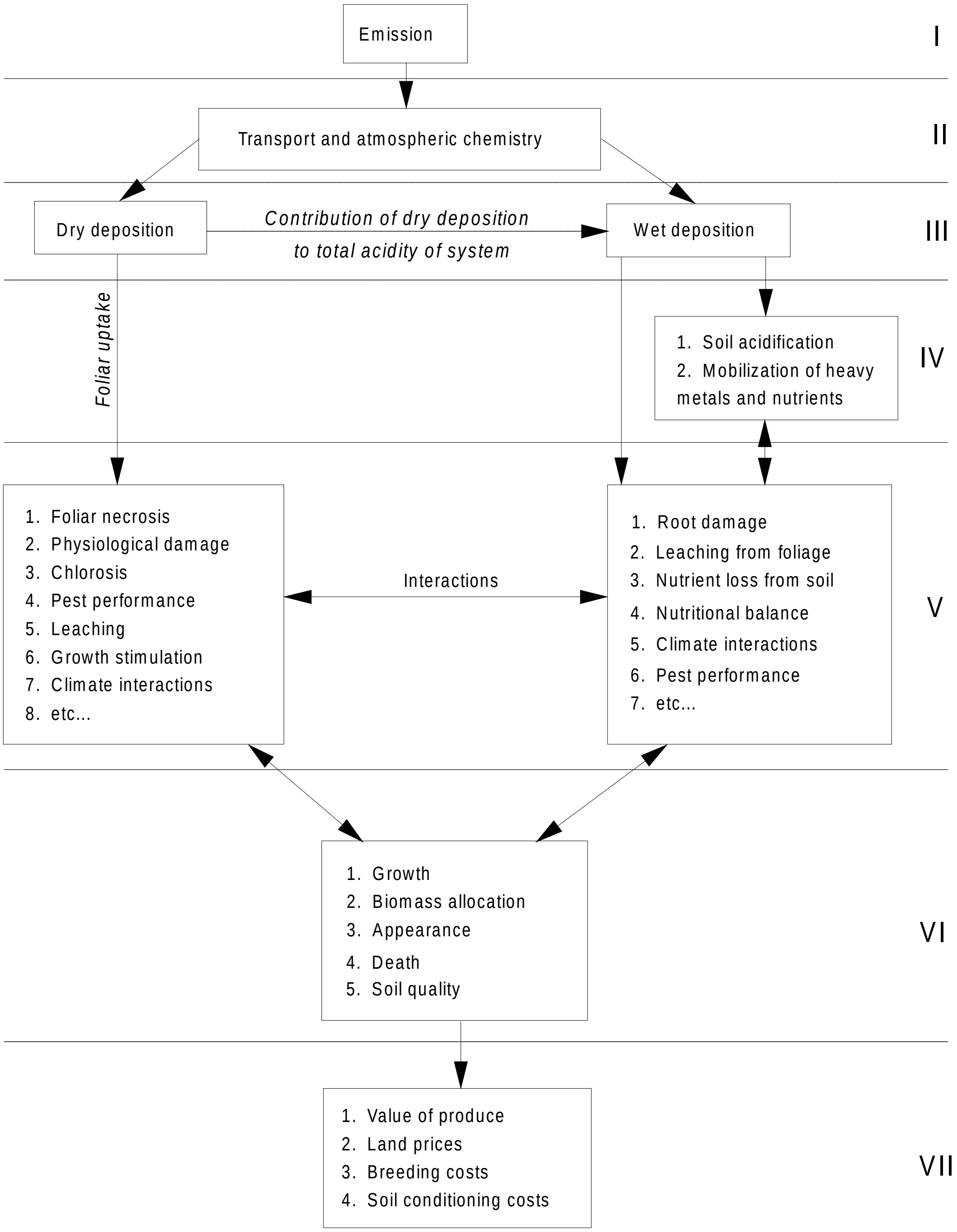


Figure 2.2 The impact pathway showing the series of linkages between emission of acidifying pollutants and ozone precursors and valuation of impacts on agricultural systems.

All impacts associated with pollution of some kind require the quantification of emissions. Emission rates of the ‘classical’ air pollutants (CO_2, SO_2, NO_x, CO, volatile organic compounds and particulate matter) are quite well known. Especially well determined is the rate of CO_2 emission for fuel using equipment; it depends only on the efficiency of the equipment and the carbon/hydrogen ratio of the fuel - uncertainty is negligible. Emissions of the other classical air pollutants are somewhat less certain, particularly as they can vary with operating conditions, and maintenance routines. The sulphur content of different grades of oil and coal can vary by an order of magnitude, and hence, likewise, will emissions unless this is compensated for through varying the performance of abatement technologies. The general assumption made in this study is that unless otherwise specified, the technology used is the best available according to the regulations in the country of implementation, and that performance will not degrade. We have sought to limit the uncertainty associated with emissions of these pollutants by close identification of the source and quality of fuel inputs within the study.

The situation is less clear with respect to trace pollutants such as lead and mercury, since the content of these in fuel can vary by much more than an order of magnitude. Furthermore, some of these pollutants are emitted in such small quantities that even their measurement is difficult. The dirtier the fuel, the greater the uncertainty in the emission estimate. There is also the need to account for emissions to more than one media, as pollutants may be passed to air, water or land. The last category is the subject of major uncertainty, as waste has historically been sent for disposal to facilities of varying quality, ranging from simple holes in the ground to well-engineered landfills. Increasing regulation relating to the disposal of material and management of landfills should reduce uncertainty in this area greatly for analysis within the European Union, particularly given the concept of self-sufficiency enshrined in Regulation 259/93 on the supervision and control of shipments of waste into, out of and within the European Community. The same will not apply in many other parts of the world.

The problem becomes more difficult for the upstream and downstream stages of the fuel chain because of the variety of technologies that may be involved. Particularly important may be some stages of fuel chains such as biomass, where the fuel chain is potentially so diverse that it is possible that certain activities are escaping stringent environmental regulation.

The burdens discussed so far relate only to routine emissions. Burdens resulting from accidents also need to be considered. These might result in emissions (e.g. of oil) or an incremental increase in the risk of injury or death to workers or members of the public. Either way it is normally necessary to rely upon historical data to quantify accident rates. Clearly the data should be as recent as possible so that the rates used reflect current risks. Major uncertainty however is bound to be present when extreme events need to be considered, such as the disasters at Chernobyl and on the Piper Alpha oil rig in the North Sea. To some extent it is to be expected that accident rates will fall over time, drawing on experience gained. However, structural changes in industries, for example through privatisation or a decrease in union representation, may reverse such a trend.

Wherever possible data should be relevant to the country where a particular fuel chain activity takes place. Major differences in burdens may arise due to different standards covering occupational health, extension of the distance over which fuel needs to be transported, etc.

2.4.4 Description of the receiving environment

The use of the impact pathway approach requires a detailed definition of the scenario under analysis with respect to both time and space. This includes:

- Meteorological conditions affecting dispersion and chemistry of atmospheric pollutants;
- Location, age and health of human populations relative to the source of emissions;
- The status of ecological resources;
- The value systems of individuals.

The range of the reference environment for any impact requires expert assessment of the area influenced by the burden under investigation. As stated above, arbitrary truncation of the reference environment is methodologically wrong and will produce results that are incorrect. It is to be avoided as far as possible.

Clearly the need to describe the sensitivity of the receiving environment over a vast area (extending to the whole planet for some impacts) creates a major demand on the analyst. This is simplified by the large scale of the present study - which has been able to draw on data held in many different countries. Further to this it has been possible to draw on numerous databases that are being compiled as part of other work, for example on critical loads mapping. Databases covering the whole of Europe, describing the distribution of the key receptors affected by SO_2, NO_x, NH_3 and fine particles have been derived or obtained for use in the EcoSense software developed by the study team.

In order to take account of future damages, some assumption is required on the evolution of the stock at risk. In a few cases it is reasonable to assume that conditions will remain roughly constant, and that direct extrapolation from the present day is as good an approximation as any. In other cases, involving for example the emission of acidifying gases or the atmospheric concentration of greenhouse gases this assumption is untenable, and scenarios need to be developed. Confidence in these scenarios clearly declines as they extend further into the future.

2.4.5 Quantification of impacts

The methods used to quantify various types of impact are discussed in depth in the report on the study methodology (European Commission, 1998). The functions and other data that we have used are summarised at the back of this report in Appendices I (describing the EcoSense software), II (health), III (materials), IV (ecological receptors), V (global warming effects) and VI (other impacts), VII (economic issues) and VIII (uncertainty). The complexity of the analysis varies greatly between impacts. In some cases externalities can be calculated by multiplying together as few as 3 or 4 parameters. In others it is necessary to use a series of sophisticated models linked to large databases.

Common to all of the analysis conducted on the impacts of pollutants emitted from fuel chains is the need for modelling the dispersion of pollutants and the use of a dose-response function of some kind. Again, there is much variation in the complexity of the models used (see Appendix I). The most important pollutant transport models used within ExternE relate to the atmospheric dispersion of pollutants. They need to account not only for the physical transport of pollutants by the winds but also for chemical transformation. The dispersion of pollutants that are in effect chemically stable in the region of the emission can be predicted using Gaussian plume models. These models assume source emissions are carried in a straight line by the wind, mixing with the surrounding air both horizontally and vertically to produce pollutant concentrations with a normal (or Gaussian) spatial distribution. The use of these models is typically constrained to within a distance of 100 km of the source.

Air-borne pollutant transport of course extends over much greater distances than 100 km. A different approach is needed for assessing regional transport as chemical reactions in the atmosphere become increasingly important. This is particularly so for the acidifying pollutants. For this analysis we have used receptor-orientated Lagrangian trajectory models. The outputs from the trajectory models include atmospheric concentrations and deposition of both the emitted species and secondary pollutants formed in the atmosphere.

A major problem has so far been the lack of a regional model of ozone formation and transport within fossil-fuel power station plumes that is applicable to the European situation. In consequence a simplified approach has been adopted for assessment of ozone effects (European Commission, 1998).

The term ‘dose-response’ is used somewhat loosely in much of this work, as what we are really talking about is the response to a given *exposure* of a pollutant in terms of atmospheric concentration, rather than an ingested *dose*. Hence the terms ‘dose-response’ and ‘exposure-response’ should be considered interchangeable. A major issue with the application of such functions concerns the assumption that they are transferable from one context to another. For example, some of the functions for health effects of air pollutants are still derived from studies in the USA. Is it valid to assume that these can be used in Europe? The answer to this question is to a certain degree unknown - there is good reason to suspect that there will be some variation, resulting from the affluence of the affected population, the exact composition of the cocktail of pollutants that the study group was exposed to, etc. Indeed, such variation has been noted in the results of different epidemiological studies. However, in most cases the view of our experts has been that transference of functions is to be preferred to ignoring particular types of impact altogether - neither option is free from uncertainty.

Dose-response functions come in a variety of functional forms, some of which are illustrated in Figure 2.3. They may be linear or non-linear and contain thresholds (e.g. critical loads) or not. Those describing effects of various air pollutants on agriculture have proved to be particularly complex, incorporating both positive and negative effects, because of the potential for certain pollutants, e.g. those containing sulphur and nitrogen, to act as fertilisers.

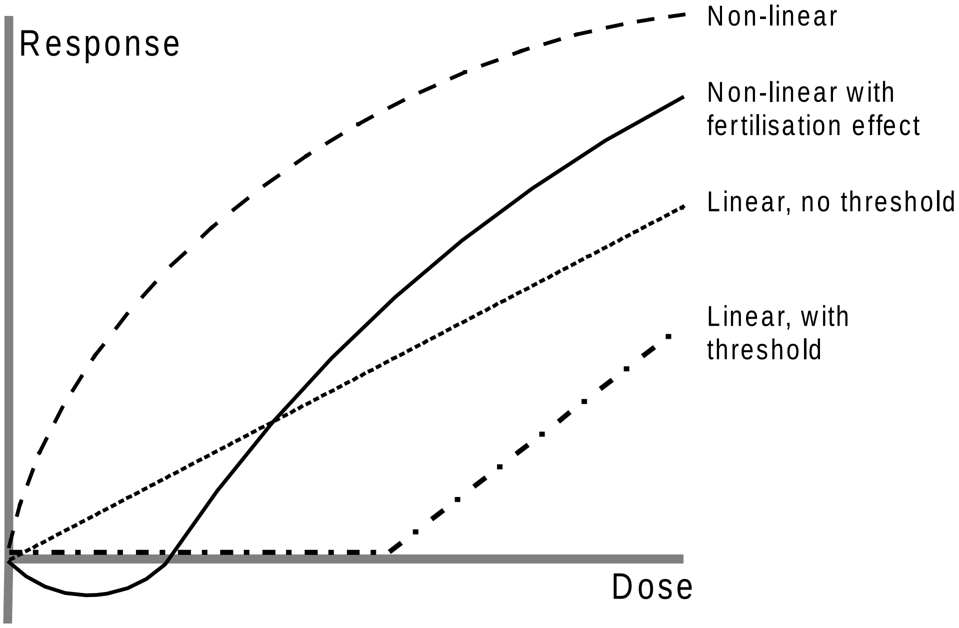


Figure 2.3 A variety of possible forms for dose-response functions.

Ideally these functions and other models are derived from studies that are epidemiological - assessing the effects of pollutants on real populations of people, crops, etc. This type of work has the advantage of studying response under realistic conditions. However, results are much more difficult to interpret than when working under laboratory conditions, where the environment can be closely controlled. Although laboratory studies provide invaluable data on response mechanisms, they often suffer from the need to expose study populations to extremely high levels of pollutants, often significantly greater than they would be exposed to in the field. Extrapolation to lower, more realistic levels may introduce significant uncertainties, particularly in cases where there is reason to suspect that a threshold may exist.

The description and implementation of exposure-response relationships is fundamental to the entire ExternE Project. Much of the report on methodology (European Commission, 1998) is, accordingly, devoted to assessment of the availability and reliability of these functions.

2.4.6 Economic valuation

The rationale and procedures underlying the economic valuation applied within the ExternE Project are discussed in Appendix VII and in more detail in the methodology report (European Commission, 1998). The approach followed is based on the quantification of individual ‘willingness to pay’ (WTP) for environmental benefit.

A limited number of goods of interest to this study - crops, timber, building materials, etc. - are directly marketed, and for these valuation data are easy to obtain. However, many of the more important goods of concern are not directly marketed, including human health, ecological systems and non-timber benefits of forests. Alternative techniques have been developed for valuation of such goods, the main ones being hedonic pricing, travel cost methods and contingent valuation (Appendix VII). All of these techniques involve uncertainties, though they have been considerably refined over the years.

The base year for the valuation described in this report is 1995, and all values are referenced to that year. The unit of currency used is the ECU. The exchange rate was approximately 1 ECU to US$1.25 in 1995.

The central discount rate used for the study is 3%, with upper and lower rates of 0% and 10% also used to show sensitivity to discount rate. The rationale for the selection of this range and best estimate, and a broader description of issues relating to discounting, was given in an earlier report (European Commission, 1995b).

2.4.7 Assessment of uncertainty

Uncertainty in externality estimates arises in several ways, including:

- The variability inherent in any set of data;
- Extrapolation of data from the laboratory to the field;
- Extrapolation of exposure-response data from one geographical location to another;
- Assumptions regarding threshold conditions;
- Lack of detailed information with respect to human behaviour and tastes;
- Political and ethical issues, such as the selection of discount rate;
- The need to assume some scenario of the future for any long term impacts;
- The fact that some types of damage cannot be quantified at all.

It is important to note that some of the most important uncertainties listed here are not associated with technical or scientific issues, instead they relate to political and ethical issues, and questions relating to the development of world society. It is also worth noting that, in general, the largest uncertainties are those associated with impact assessment and valuation, rather than quantification of emissions and other burdens.

Traditional statistical techniques would ideally be used to describe the uncertainties associated with each of our estimates, to enable us to report a median estimate of damage with an associated probability distribution. Unfortunately this is rarely possible without excluding some significant aspect of error, or without making some bold assumption about the shape of the probability distribution. Alternative methods are therefore required, such as sensitivity analysis, expert judgement and decision analysis. In this phase of the study a more clearly quantified description of uncertainty has been attempted than previously. Further discussion is provided in Appendix VIII, though it is worth mentioning that in this area of work uncertainties tend to be so large that additive confidence intervals usually do not make sense; instead one should specify multiplicative confidence intervals. The uncertainties of each stage of an impact pathway need to be assessed and associated errors quantified. The individual deviations for each stage are then combined to give an overall indication of confidence limits for the impact under investigation.

2.5 Priority Impacts Assessed in the ExternE Project

2.5.1 Fossil technologies

The following list of priority impacts was derived for the fossil fuel chains considered in the earlier phases of ExternE. It is necessary to repeat that this list is compiled for the specific fuel chains considered by the present study, and should be reassessed for any new cases. The first group of impacts are common to all fossil fuel chains:

1. Effects of atmospheric pollution on human health;
2. Accidents affecting workers and/or the public;
3. Effects of atmospheric pollution on materials;
4. Effects of atmospheric pollution on crops;
5. Effects of atmospheric pollution on forests;
6. Effects of atmospheric pollution on freshwater fisheries;
7. Effects of atmospheric pollution on unmanaged ecosystems;
8. Impacts of global warming;
9. Impacts of noise.

To these can be added a number of impacts that are fuel chain dependent:

10. Impacts of coal and lignite mining on ground and surface waters;
11. Impacts of coal mining on building and construction;
12. Resettlement necessary through lignite extraction;
13. Effects of accidental oil spills on marine life;
14. Effects of routine emissions from exploration, development and extraction from oil and gas wells.

2.5.2 Nuclear technologies

The priority impacts of the nuclear fuel chain to the general public are radiological and non-radiological health impacts due to routine and accidental releases to the environment. The source of these impacts are the releases of materials through atmospheric, liquid and solid waste pathways.

Occupational health impacts, from both radiological and non-radiological causes, were the next priority. These are mostly due to work accidents and radiation exposures. In most cases, statistics were used for the facility or type of technology in question. When this was not possible, estimations were taken from similar type of work or extrapolated from existing information.

Impacts on the environment of increased levels of natural background radiation due to the routine releases of radionuclides have not been considered as a priority impact pathway, except partially in the analysis of major accidental releases.

2.5.3 Renewable technologies

The priority impacts for renewables vary considerably from case to case. Each case is dependent upon the local conditions around the implementation of each fuel chain. For the wind fuel chain (European Commission, 1995f) the following were considered:

1. Accidents affecting the public and/or workers;
2. Effects on visual amenity;
3. Effects of noise emissions on amenity;
4. Effects of atmospheric emissions related to the manufacture of turbines and construction and servicing of the site.

Whilst for the hydro fuel chain (European Commission, 1995f) another group was considered:

1. Occupational health effects;
2. Employment benefits and local economic effects;
3. Impacts of transmission lines on bird populations;
4. Damages to private goods (forestry, agriculture, water supply, ferry traffic);
5. Damages to environmental goods and cultural objects.

2.5.4 Related issues

It is necessary to ask whether the study fulfils its objective of consistency between fuel chains, when some impacts common to a number of fuel chains have only been considered in a select number of cases. In part this is due to the level of impact to be expected in each case - if the impact is likely to be large it should be considered in the externality assessment. If it is likely to be small it may be legitimate to ignore it, depending on the objectives of the analysis. In general we have sought to quantify the largest impacts because these are the ones that are likely to be of most relevance to questions to which external costs assessment is appropriate.

2.6 Summary

This Chapter has introduced the ‘impact pathway’ methodology of the ExternE Project. The authors believe that it provides the most appropriate way of quantifying externalities because it enables the use of the latest scientific and economic data.

Critical to the analysis is the definition of fuel chain boundaries, relating not only to the different stages considered for each fuel chain, but also to the:

- Location of each stage;
- Technologies selected for each stage;
- Identified burdens;
- Identified impacts;
- Valuation criteria;
- Spatial and temporal limits of impacts.

In order to achieve consistency it is necessary to draw very wide boundaries around the analysis. The difficulty with successfully achieving an assessment on these terms is slowly being resolved through the development of software and databases that greatly simplify the analysis.

The definition of ‘system boundary’ is thus broader than is typically used for LCA. This is necessary because our analysis goes into more detail with respect to the quantification and valuation of impacts. In doing so it is necessary to pay attention to the site of emission sources and the technologies used. We are also considering a wider range of burdens than is typical of LCA work, including, for example, occupational health effects and noise.

The analysis requires the use of numerous models and databases, allowing a logical path to be followed through the impact pathways. The functions and other data originally used by ExternE were described in an earlier report (European Commission, 1995b). In the present phase of the study this information has been reassessed and many aspects of it have been updated (see European Commission, 1998). It is to be anticipated that further methodological changes will be needed in the future, as further information becomes available particularly regarding the health effects of air pollution and global warming impacts, which together provide some of the most serious impacts quantified under the study.

3. THE FOSSIL FUEL CYCLES

3.1 Description of the fuel cycles, quantification of burdens

Besides of the lignite plant, all reference power stations are located at a hypothetical site near the city of Lauffen, which has been identified as a suitable site for a thermal power plant in a planning procedure to make provision for future power plant sites in 1976 by the Baden-Württemberg state authorities. Although this site plan has been repealed later and there is currently no plan to build a new power plant, the Lauffen site is considered to be sufficiently representative to be used as a reference location in the present analysis. The lignite plant is located near Grevenbroich (Nordrhein-Westfalen), next to the river Erft, 40 km Northwest of Köln (Cologne).

The following technologies were analysed:

- Coal fired power plant burning domestic coal (underground coal mining), equipped with electrostatic dust precipitators, flue gas desulphurisation and DENOX.
- Lignite fired power plant, open pit mining, equipped with electrostatic dust precipitators, flue gas desulphurisation and DENOX.
- Oil fired power plant with gas turbine.
- Combined cycle natural gas fired power plant.

The technical characteristics of the power plants are summarised in Table 3.1.

3.1.1 Up- and downstream process steps of the fossil fuel cycles

Coal

The analysis of the coal fuel cycle takes into account the process steps coal extraction and transport, lime extraction and transport, construction, operation and dismantling of the power plant as well as the disposal of wastes. All hard coal in Germany is extracted from underground mines. Coal for the Lauffen power plant is obtained from the Ruhrgebiet and the Saarland fields. It is assumed that two thirds of the coal is transported by barge and one third by rail from the coal mines to the power plant. The transport follows the rivers Ruhr, Rhein, and Neckar.

Lignite

Because of the low calorific value of lignite, the generation of electricity from lignite makes only sense when the power plant is located close to the extraction area to avoid long transport ways. There are several lignite mining districts in Germany which are all opencast-mined. The reference power plant is located in the Rhenish lignite mining district. In the long term the

Table 3.1 Technical data of the reference power plants

Characteristics	Coal	Lignite	Oil	Gas
Plant type	Pulverised coal power plant with FGD, DENOX and dedusting	Pulverised lignite power plant with FGD and dedusting	Gas-turbine peak load power plant	Combined cycle
Generator capacity	652.2 MW	887.9 MW	157.2 MW	790.8
Electricity sent out	600.0 MW	800.0 MW	155.9 MW	777.5
Net efficiency	43 %	40.1 %	31.1 %	57.6
Full load hours per year	6500 h	6500 h	675 h	6500 h
Annual generation	3900.0 GWh	5200.0 GWh	105.2 GWh	5053.8 GWh
Projected lifetime	35 a	35 a	35 a	35 a
Data relevant for atmospheric transport modelling				
Stack height	240 m	200 m	170 m	250
Stack diameter	10 m	10 m	6 m	10
Flue gas volume stream (full load)	1 720 738 Nm^3/h	3 286 113 Nm^3/h	1425185 Nm^3/h	3233754 Nm^3/h
Flue gas temperature	130 °C	130 °C	160 °C	91 °C
Excess air	1.25	1.15	2.8	2.6
Fuel specification				
Calorific value H_u	29.2 MJ/kg	8.45 MJ/kg	42.7 MJ/kg	43.6 MJ/kg
Sulfur content	0.9 %	0.3 %	0.2 %	0 %
Emissions				
SO_2	288 mg/kWh	411 mg/kWh	1088 mg/kWh	0 mg/kWh
	100 mg/Nm^3	100 mg/Nm^3	132 mg/Nm^3	0 mg/Nm^3
NO_x	516 mg/kWh	739 mg/kWh	814 g/kWh	208 g/kWh
	180 mg/Nm^3	180 mg/Nm^3	89 mg/Nm^3	50 mg/Nm^3
Particulates	57 mg/kWh	82 mg/kWh	18 mg/kWh	0 mg/kWh
	20 mg/Nm^3	20 mg/Nm^3	2 mg/Nm^3	0 mg/Nm^3
CO_2	781 g/kWh	1015 g/kWh	858 g/kWh	348 g/kWh
CH_4	42 mg/kWh	14 mg/kWh	35 mg/kWh	27 mg/kWh
N_2O	42 mg/kWh	45 mg/kWh	60 mg/MWh	1 mg/MWh
Bulk materials and wastes				
Cooling water	1928 g/kWh	1952 g/kWh	/	/
$CaCO_3$	8 g/kWh	10 g/kWh	/	/
FGD-water	145 g/kWh	255 g/kWh	/	/
NH_3	780 mg/kWh	/	/	/
Ashes	20.1 g/kWh	63.6 g/kWh	20 mg/kWh	/
FGD-gypsum	12.3 g/kWh	17.2 g/kWh	/	/
Waste water	718 g/kWh	/	/	/

extraction in the Rheinland will be limited to three opencast-mines: Inden, Hambach and Garzweiler. The mines Garzweiler I and II are selected as reference mines. Constant draining is necessary to keep the mine free of water. For this purpose draining well galleries are operated. The lowering of the ground water level is effective far beyond the mine.

The lignite is transported by electrically-driven conveyor belts from the mine to the power plant. The limestone is transported by truck from the quarry to the power plant. Solid waste as ashes and gypsum of the power plant are deposited in cleared opencast-mines.

Oil

For the estimation of emissions an average German oil supply has been assumed. Most of the oil used in Germany comes from the OPEC countries, other important supply countries are Norway and Great Britain as well as eastern Europe.

Only part of the oil used in Germany, the oil from the OPEC, but about half of the worldwide produced crude oil is transported by sea . This crude oil is transported via pipeline from the coastal storage facility at Wilhelmshaven, to the reference refinery located at Wesseling near Köln. The crude oil from Eastern Europe, from the North Sea and from Germany is directly transported via pipeline to the refinery. The description of the reference refinery is based on data of a hypothetical 'German standard refinery'. The refined oil is transported by barge to the power plant.

Natural Gas

The analysis of emissions from upstream processes is based on the German standard gas composition according to the gas supply in 1991. In 1991 about 26.5 % of the natural gas used in Germany was extracted at home. The rest has been imported from the Netherlands (28.1 %), Norway (12.1 %), the GUS (32.0 %) and Denmark (1.2 %).

The extracted natural gas contains water vapour and sulfur as H_2S (hydrogen sulfide) or in organic form. About 50 to 60 % of the German gas reserves is so-called acid gas (H_2S-content > 1 Vol.-%), the rest is lean gas. The gas from the Netherlands and Norway is 100 % lean gas while the acid/acid gas split of gas from the GUS is 20/80 %.

Natural gas is transported by pipelines. It is assumed that the power plant is directly connected to the regional distribution network. The pressure in pipelines drops over long-distances because of the inner friction and the friction at the pipeline walls. Hence, compressor station are needed in intervals of 100 to 200 km. Further technical installations are control, measure and mixing devices. Storages are needed to level daily fluctuations (high pressure and low pressure gas containers) and seasonal differences (underground storages in emptied gas fields or salt caverns).

3.1.2 Emissions from Up- and Downstream Process Steps

For the quantification of emissions from up- and downstream process steps generic emission factors are used. Due to the use of electricity and heat in the up- and downstream process steps air pollutants and greenhouse gases are emitted. In addition, in some processes pollutants are emitted directly. Coal mining leads to a considerable release of CH_4. Recent sources give 21 m^3/t as emission factor. The mining of lignite sets CH_4 free, too, but much less as coal mining. During the extraction and transport by pipelines of oil and gas significant amounts of CH_4 are emitted. Especially for the pipelines in the GUS high CH_4 emission factors are given in the literature.

Due to loading and unloading 0.2 kg dust per ton coal or lignite handles are emitted (UBA, 1989).

Table 3.2 summarises the emissions of the German fossil reference energy systems. With some exceptions the highest percentage of the emissions is due to the process step generation. These exceptions are

- the emissions of particulates by loading and unloading of coal and lignite. These emissions have only a very local impact and are not taken into account in the impact assessment;
- the high CH_4 emissions in the upstream processes of all reference energy systems.

3.2 Selection of priority impacts

The impacts considered as most relevant are those caused by atmospheric emissions from the power genration stage on human health, materials, crops and ecosystems, and global warming. In addition, impacts on occupational health are analysed, which are most important for unerground coal mining. Discharges of effluents from mining activities might have a significant impacts on groundwater systems, but these effects are very difficult to quantify.

3.3 Quantification of impacts and damages

3.3.1 Public Health Effects

The general public is affected by an increased level of air pollution from activities on all process steps of the fossil fuel cycles. Both acute and chronic health impacts on the general public are estimated for particulate matter, ozone and acid aerosols resulting from emissions of SO_2 and NO_x. Although uncertainties in this field are high, an important finding of this study is that acid aerosols are a major source of health effects, so that damages from the oil and even from the gas fuel cycles are higher than previously expected.

Table 3.2 SO_2, NO_x, particulates, CH_4, and N_2O emission factors in mg/kWh and CO_2 emission factors in g/kWh for the process steps of the reference energy systems

	SO_2	NO_x	Particulates	CO_2	CH_4	N_2O
Extraction						
Coal	35.1	20.6	2.9	31.1	$0.1^{c} + 3267.7^{e}$	0.7
Lignite	12.3	22.1	2.5	30.4	$0.4^{c} + 11.4^{e}$	1.3
Oil	224.0	74.6	13.5	$10.2^{e} + 20.1^{d}$	$1.4^{c} + 89.5^{e}$	0.8
Gas	3.2	30.1	17.4	8.1	$6.9^{c} + 1294.0^{e}$	0.3
Transport Processes						
Coal	3.0	23.8	$115^{a} + 0.6^{d}$	2.9	3.4	0.0
Lignite	1.5	28.5	$425^{a} + 0.6^{d}$	1.5	0.1	0.0
Oil	88.4	69.2	34.0	8.3	9.7	0.2
Gas	0.05	39.2	0.5	6.7	$0.9^{d} + 336.2^{e}$	0.3
Refinery						
Oil	91.9	26.6	1.4	28.4	$11.5^{b} + 6.8^{e}$	0.5
Electricity Generation						
Coal	288	516	57	781	42	42
Lignite	411	739	82	1015	14	45
Oil	1207	814	18	858	35	23
Gas	0	208	0	348	27	1
Total						
Coal	326	560	182	815	3313	43
Lignite	425	790	511	1047	26	46
Oil	1611	985	67	935	145	25
Gas	3	277	18	362	1700	2

a: loading and unloading, b: thermal energy demand, c: electricity demand; d: energy demand, e: direct

3.3.2 Occupational Health Effects

Health impacts from occupational accidents and occupational diseases are assessed using a statistical approach. We have quantified the 'net'-risks, i.e. only the difference between the risks of average industrial activities and the specific activity related to the fuel cycle of concern, in order to better reflect the marginal effects. Occupational health effects are the highest from the hard coal fuel cycle, with underground mining as the major source of impacts. The net effects from the lignite and gas fuel cycles are close to zero, i.e. occupational impacts from fuel cycle specific activities are very similar to average industrial activities.

3.3.3 Agriculture

Crops can be directly or indirectly injured by air pollutants. Of these pollutants SO_2 and NO_x are quantitatively the most important which are directly emitted from the different facilities of the fossil fuel cycles. Secondary pollutants which derive from these are O_3 and acid deposition (SO_4^{2-} and NO_3^{-}). Again, as emissions from the power plants are the most important, only effects related to the operation of the power plants are calculated.

The effects which have been covered in the assessment are yield changes due to O_3 and SO_2, liming measures additionally required due to acid deposition and fertiliser *less* required due to nitrogen deposition. The last effect is a benefit of electricity generation from fossil fuels. Crop losses due to O_3 are assessed using a simplified approach because site-specific ozone models are not available at the moment.

3.3.4 Forests and natural ecosystems

In the fossil fuel cycles SO_2 and NO_x are emitted which can directly or indirectly (via O_3 or deposition of acidity of nitrogen) damage forest ecosystems. At the moment there are no relationships or models for the impact of these air pollutants on forests available. Therefore, the assessment has to fall back on the critical levels/loads concept developed by the UN-ECE. So far, critical load maps for nutrient nitrogen in natural ecosystems are and critical load maps for acidity in German forests available. The additional exceedance heights due to the fossil power plant emissions in the areas where the critical loads are already exceeded have been quantified. These indicators are called potential impact weighted exceedance areas (PIWEA). However, damages are not directly proportional to exceedances of critical loads of acidity or nutrient nitrogen. Therefore, it is not possible to derive physical impacts or even damage costs only using the critical loads. Further criteria are needed for a monetary assessment.

Applying the PIWEA indicators the fossil plants can be ranked according to their potential eutrophication impact on natural ecosystems in Europe and according to their potential acidification impact on German forest ecosystems. In both cases the oil power plant has the highest potential impact followed by coal, lignite and gas. The lignite power plant, which is located in Grevenbroich, has a lower potential impact than expected when compared to coal and oil located in Lauffen. This is caused by the difference in the distributions of the ecosystem areas and pollutant levels for the background scenario around the two sites.

3.3.5 Materials

Material surfaces are mostly endangered by SO_2 or wet acid deposition. Increased maintenance costs on natural stone, mortar, rendering, zinc and galvanised steel surfaces on European dwelling houses have been evaluated. The material inventory is derived by extrapolating building identikits based on building or population data across Europe. Building identikits for six European cities are available, none of them in Southern Europe. Thus, differences between city and countryside, and different regions are neglected. The dose-response functions for mortar and rendering are extrapolated from that of natural stone. The dose-response function for paint was derived for different paint systems as used nowadays. Critical thickness losses are partially derived from expert opinions and not from behavioural data. For other objects or materials, like historic and industrial buildings, inventories cannot be compiled or exposure-response relationships are not available.

3.3.6 Global warming

The fossil reference energy systems emit greenhouse gases, which contribute to global warming. Although the knowledge about the climate system of the earth has improved considerably during the last years, major uncertainties remain. As part of the EXTERNE project damage factors for CO_2 have been assessed, which are applied here. However, major uncertainties concerning the potential impacts of climate change and its costs remain.

3.3.7 Effects of oil spills on marine ecosystems

The operational discharge of hydrocarbons from oil tankers to the sea is characterised by a high level of non-compliance to existing regulations. Looking at tanker accidents with major oil spills, the probability of an accident is estimated from world-wide statistics and damage costs from the AMOCO CADIZ and the EXXON VALDEZ accidents are used to derive a first estimate of externalities, resulting in 0.031 mECU/kWh (AMOCO CADIZ) and 0.33 mECU/kWh (EXXON VALDEZ).

3.3.8 Further impacts considered

The negative effects of coal mining on aquatic ecosystems are draining and leaching from refuse piles and the impacts of pit water on surface water. When ferric sulfide is oxidised in the refuse pile, the pH can decrease further because this process produces sulfur acid and therefore trace elements can be mobilised. Damage resulting from this impacts will cover a long time period. The costs caused by leaching of chemicals have not been considered in German mining law until now. This may be because groundwater resources in the Ruhrgebiet have not been considered for use as drinking water.

In the mining area of the Ruhrgebiet 150 Mill. m^3/year of mine water is introduced into the receiving streams, 50 % coming from pits having been already shut down. The river Ruhr itself receives 50 Mill. m^3/year, containing an average concentration of 900 g/m^3 sulfate and 900 g/m^3 chloride. The pit water causes 67 % of the chloride and 42 % of the sulfate in the river Ruhr near Essen. Surface waters may be used as drinking water. They have to concur with the German Drinking Water Standards. Therefore, expensive water treatment is necessary in most cases.

Underground mining causes ground subsidence. This subsidence leads to damages to buildings, to the infrastructure, and to disturbances of the river system. According to the German Mining Law the mining companies have to pay for the damages caused by coal mining. It is not possible to check whether these reimbursements cover the full costs of the impaired. For the regulation of the river system the operators of the mines have to pay a contribution to co-operative managing of the water system.

7600 people have to resettle over forty years to allow the mining of Garzweiler II, the reference mine. A resettlement procedure has been established over the last decades which especially compensate material losses of the resettlers in case they are owners and not tenants in the old village. In an expert opinion started in 1987 and finished in 1990 the social acceptability of the present resettlement process has been studied. Weak points of the present procedure are lack of transparency and participation possibilities, the neglect of tenants and the undermining of solidarity of the resettlers. But even when these points are taken into account in the future the loss of home, of cultural and historical identity and a structural change of the region cannot be avoided.

3.4 Summary and interpretation of results

From the large number of burdens associated with the electricity generation from fossil fuels, a set of priority impact pathways which are expected to cause major environmental damage were analysed. The major fraction of the quantified external costs results from impacts on human health and from global warming effects - in particular the latter impact category is subject of large uncertainties. Nitrate and sulfate aerosols are the main source of human health effects, so that damages from the oil and even the gas fuel cycles are higher than previously expected. Results summarised in Table 3.3 show that external costs from the oil fired gas turbine plant with relatively low thermal efficiency are close to the private costs of electricity generation, while the external costs from a modern combined cycle gas fired power plant are small compared to the internal costs.

Table 3.3 Damages of the fossil fuel cycles

	mECU/kWh				σ_g
	Coal	**Lignite**	**Oil**	**Gas**	
POWER GENERATION					
Public health					
Mortality*- YOLL *(VSL)*	10.4 *(39.0)*	13.2 *(50.1)*	22.6 *(89.1)*	2.4 *(8.9)*	B
of which TSP	*1.1(3.3)*	*1.7 (5.6)*	*0.35 (1.1)*	-	
SO_2	*2.9 (12.9)*	*4.2 (18.6)*	*12.9 (54.7)*	-	
NO_x	*6.3 (19.7)*	*7.1 (21.9)*	*9.2 (28.4)*	*2.4 (7.7)*	
NO_x (via ozone)	*0.12 (3.1)*	*0.17 (4.0)*	*0.18 (4.9)*	*0.046 (1.2)*	
Morbidity	1.5	2.0	3.1	0.39	
of which TSP, SO_2, NO_x	*1.3*	*1.7*	*2.8*	*0.31*	A
NO_x (via ozone)	*0.21*	*0.30*	*0.32*	*0.082*	B
Accidents	ng				A
Occupational health					A
Crops	0.01	0.02	0.02	0.004	B
of which SO_2	*0.001*	*0.002*	*0.005*	*0*	
NO_x (via acid and N dep.)	*-0.0004*	*-0.0006*	*-0.0007*	*-0.0002*	
NO_x (via ozone)	*0.010*	*0.014*	*0.015*	*0.004*	
Ecosystems	iq				B
Materials	0.14	0.19	0.42	0.03	B
Monuments	nq	nq	nq	nq	
Noise	ng	ng	ng	ng	
Visual impacts	ng	ng	ng	ng	
Aquatic systems	-	-	0.18	-	
Global warming					C
low	3.0	3.9	3.3	1.3	
mid 3%	14.3	18.5	15.6	6.3	
mid 1%	36.6	47.3	39.8	16.0	
High	110.5	143.1	120.4	48.5	
OTHER FUEL CYCLE STAGES					
Public health	1.3 *(3.5)*	0.77 *(2.4)*	7.8 *(26.8)*	1.5 *(3.5)*	
Occupational health (including power generation stage)	0.19	0	0.052	0.0040	A
Crops	ng	ng	ng	ng	B
Materials	0.015	0.015	0.13	0.01	B
Monuments	nq	nq	nq	nq	
Global warming					C
low	0.4	0.1	0.3	0.2	
mid 3%	1.9	0.6	1.4	0.9	
mid 1%	4.7	1.5	3.7	2.3	
High	14.3	4.5	11.1	7.0	

*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 3.4 Sub-total damages of the fossil fuel cycle

		mECU/kWh			
		Coal	Lignite	Oil	Gas
YOLL *(VSL)*	low	17.0 *(47.8)*	20.2 *(58.8)*	37.9 *(123.4)*	5.9 *(14.4)*
	mid 3%	29.7 *(60.5)*	35.3 *(73.8)*	51.3 *(136.8)*	11.5 *(20.0)*
	mid 1%	54.9 *(85.7)*	65.0 *(103.6)*	77.8 *(163.3)*	22.7 *(31.2)*
	upper	138.4 *(169.2)*	163.8 *(202.3)*	165.8 *(251.3)*	59.8 *(68.3)*

Table 3.5 Damages by pollutant

		ECU / t of pollutant			
		Coal	Lignite	Oil	Gas
SO_2 *	YOLL	11 710	11 832	13 688	-
	(VSL)	*(46 432)*	*(46 869)*	*(52 107)*	
NO_x *	YOLL	13 898	10 945	12 773	13 148
	(VSL)	*(40 274)*	*(30 973)*	*(36 360)*	*(38 629)*
NO_x (via ozone)		1 500	1 500	1 500	1 500
PM_{10} *	YOLL	21 579	23 415	21 944	-
	(VSL)	*(60 175)*	*(70 976)*	*(63 611)*	
CO_2		3.8 - 139	3.8 - 139	3.8 - 139	3.8 - 139

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

4. THE NUCLEAR FUEL CYCLE

4.1 Description of the nuclear fuel cycle, quantification of burdens

The German nuclear fuel cycle is broken down into the process steps shown in Figure 4.4. Reference sites and technologies are defined for each of these stages as listed in Table 4.6.

The reference site for uranium mining, milling and transformation is Key Lake in Canada. Emission data for this site are taken from (UNSCEAR, 1993). As shown in Table 4.7, a major release of activity results from Radon-222 emission from abandoned mill tailing piles. According to UNSCEAR, we assume an exhalation rate of 3 Bq/m^2/s from reasonably covered mill tailings that is expected to remain unchanged over at least 10 000 years.

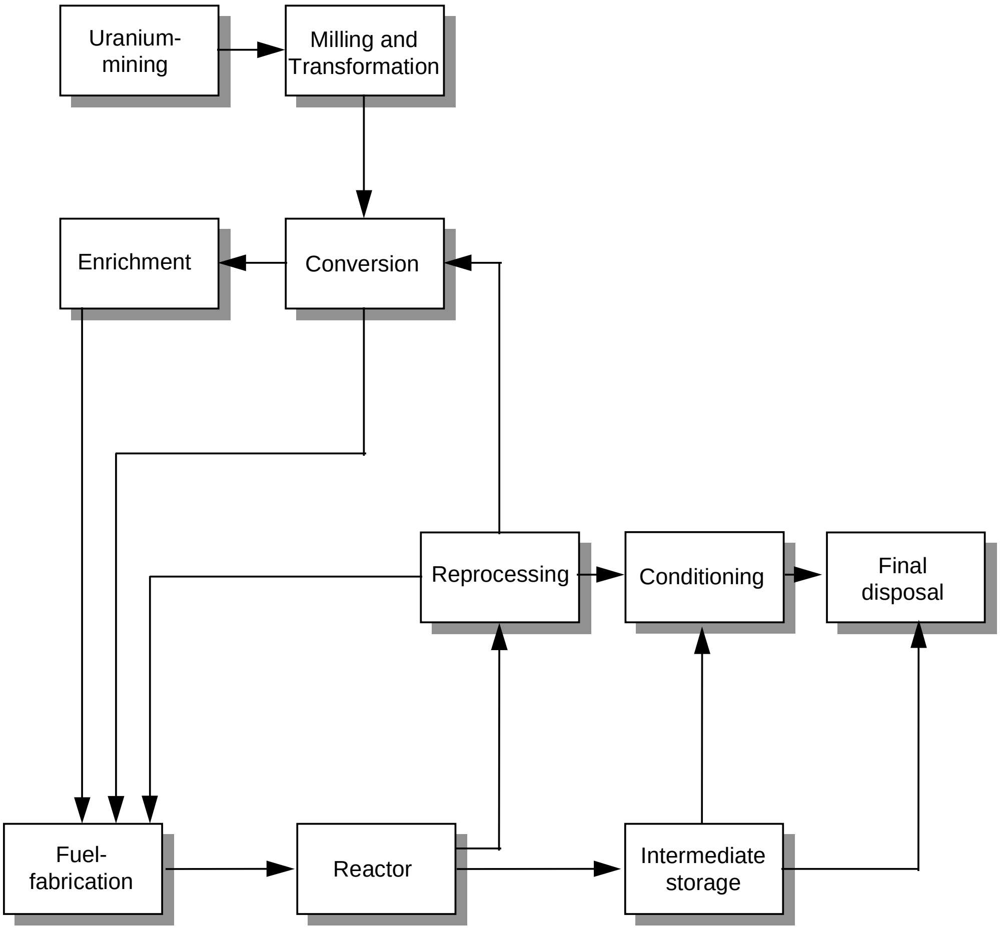


Figure 4.4 Process steps of the German nuclear fuel cycle

Table 4.6 Reference sites and technologies

Stage	Site	Technology
Uranium mining	Key Lake	Open pit
Milling a. transformation	Key Lake	
Conversion	France	
Enrichment	France	Gaseous diffusion
Fuel Fabrication	France	
Electricity generation	Southwest of Germany	PWR
Intermediate storage	Germany	Dry storage
Reprocessing	France, Le Hague	
Final disposal	Germany, Gorleben	Salt rock formation

Table 4.7 Radioactive emissions from the nuclear fuel cycle (TBq/TWh)

	Mining	Milling (operation)	Milling nill tailings in operation	milling abandoned mill tailings	Conversion	Enrichment	Fuel fabrication	Electricity generation	Reprocessing
H-3								7.9 E-2	2.4 E-2
C-14							1.8 E-9	7.3 E-3	3.8 E-2
Aerosols							1.3 E-10	3.5 E-7	
Noblegases							4.4 E-10	1.5	381
I-129									2.7 E-5
I-131								9.5 E-7	3.8 E-7
I-133									1.7 E-7
Rn-222	18.8	0.11	1.1	1.1 E+3					
U-234					3.4 E-7	1.7 E-7			
U-235					1.5 E-8	8.9 E-9			
U-238					3.2 E-7	1.3 E-10			
Pu-238									5.4 E-12
Pu-239									1.2 E-11

To quantify the environmental burden from the conversion, enrichment and fuel fabrication processes we have used data from the French ExternE study (CEPN, 1995), as no appropriate data have been available for Germany. Data are adjusted to take into account the difference in fuel requirement of the German reference reactor.

The power plant analysed is a hypothetical PWR with a capacity of 1375 MW (Wehowsky et al., 1994), operated at a hypothetical site in the Southwest of Germany. The annual electricity generation is 10.725 TWh over a lifetime of 40 years. The expected burn-up is 50 MWd/kg.

For reprocessing we again use data from the French study (CEPN, 1995) for Le Hague, adjusting the release per unit electricity by taking into account the different fuel requirement. Exposure from final disposal of low and medium level radioactive waste in salt rock formation is estimated by using data from a study by (Hirsekorn et al. 1991). The study provides a detailed analysis of potential exposure pathways for different intrusion scenarios, but does not give any probability of event, so that it is difficult to achieve a reliable estimate of impacts per TWh. Although the concepts for final disposal of high level radioactive wastes followed in France and Germany show substantial differences, in the absence of appropriate data for Germany we use results from the French study to get an indication of the order of magnitude of potential impacts from this stage of the fuel cycle.

The release of activity to the air from all stages of the fuel cycle is summarised in Table 4.7. To assess the consequences from a beyond design accident at the power plant a set of source terms calculated for different accident scenarios by (GRS, 1989) is used. Estimates of accident frequencies are taken from (Keßler, 1994) (Table 4.8).

Although the analysis of impacts from the nuclear fuel cycle is primarily focused on radiological effects, the various process steps of the fuel cycle emit a considerable amount of ‘classical’ pollutants which have to be considered for impact assessment. Table 4.9 summarises the emissions of SO_2, NO_x, particles and CO_2 cumulated over the full life cycle.

Table 4.8 Fraction of core inventory released for several beyond design accident categories according to German Reactor Safety Study (GRS, 1989). Frequency of occurrence estimated based on (Keßler, 1994).

Accident category	fraction of core inventory released							Frequency of occurrence per year
	Noble gases	Iodines	Alkali metals	Tellurium group	Alkaline earth metals	Noble metals	Metal oxides	
DRSB 1	1		(0.5 - 0.9)		3.6 E-1	1.0 E-5	3.4 E-2	10^{-7}
DRSB 2	1	3.7 E-1	3.7 E-1	2.3 E-1	1.4 E-1	2.5 E-6	1.2 E-2	10^{-7}
DRSB 3	1.7 E-1	1.5 E-1	1.5 E-1	5.0 E-2	6.4 E-4	8.8 E-8	2.1 E-9	10^{-8}
DRSB 4	1.7 E-1	2.5 E-2	2.5 E-2	1.5 E-2	1.2 E-4	1.7 E-8	3.8 E-10	10^{-8}
DRSB 5	1	7.8 E-3	7.8 E-3	2.1 E-3	1.4 E-4	3.6 E-7	1.1 E-5	10^{-6}
DRSB6	9 E-1	2.0 E-3	2.0 E-3	3.5 E-6	1.9 E-7	6.4 E-10	3.3 E-8	10^{-6}

Table 4.9 Cumulated non-radioactive emissions from the nuclear life cycle

SO_2	NO_x	Particles	CO_2
32	70	7	19 700

4.2 Selection of priority impacts

The assessment of impacts is primarily focused on radiological impacts on both workers and the general public, including fatal and non-fatal cancers and hereditary effects. In addition, occupational accidents leading to deaths, major and minor injuries are assessed. For the non-radioactive pollutants emitted from the nuclear fuel cycle, the set of priority pathways identified for the fossil fuels are analysed, including effects on public health, crops, materials, ecosystems and global warming.

4.3 Quantification of impacts and damages

The collective dose resulting from increased levels of ionising radiation due to activities on the various stages of the fuel cycle are calculated by using ‘collective dose per unit release’ factors provided by UNSCAER (1993). These factors are derived from detailed modelling at representative sites in northern Europe and give the collective dose resulting from a unit activity released for different nuclides from different source categories. While the French study (CEPN, 1995) assumes a complete sealing of the abandoned uranium mill tailings, data from UNSCEAR seems to be more realistic, assuming that some reasonably impermeable cover would be used and that the radon exhalation rate from abandoned tailing piles would be 3 $Bq/m^2/s$, which will remain unchanged over the next 10 000 years. These long-term emissions clearly dominate the exposure from the whole fuel cycle. Because of the efficient mixing in the environment and/or long lifetime of the released nuclides, a full global assessment has been included for all process steps, leading to an estimate of a global collective dose integrated over 10 000 years. The global and long term dose resulting from Rn-222, H-3, Kr-85 and C-14 emissions cause the major fraction of the total collective dose. Resulting health effects are estimated using the extensively reviewed dose-response functions of the International Commission on Radiological Protection (ICRP, 1991).

Consequences from beyond design accidents are analysed by using the COSYMA code (Jones et al., 1993). Source terms quantified for six accident categories of a 1300 MW PWR in the German Reactor Safety Study Phase B (GRS, 1989) are linked to an estimated probability of accident (Keßler, 1994) (Table 4.8). Using the linear ICRP risk factors for impact assessment, results indicate that a single event might lead to several tenthousand fatal cancers occurring within an exposed population of about 335 Mill. over 200 years after the accident. Based on the expected value of risk, the external costs normalised to a unit electricity output however contribute to a small fraction of the total external costs of the fuel cycle only.

4.4 Summary and interpretation of results

External costs from the nuclear fuel cycle are summarised in Table 4.10. As discussed before, the major source of exposure are radon emissions from abandoned mill tailing piles, which together with globally dispersed H-3, Kr-85 and C-14 from the power generation and reprocessing stages accounts for about 98% of the calculated collective dose integrated over 10 000 years. However, the average individual dose is very small and the dose-response function is considered to be very uncertain as it is interpolated from the results of studies for high individual dose levels. Because of the long time horizon of the radiological effects, the discounted damage is much lower and dominated by the non-radiological impacts due to emissions of non-radioactive pollutants from the life cycle. Based on the expected value of risk, the damage from beyond design accidents are small compared to the external costs from the whole fuel cycle. If electricity for upstream processes would be taken from nuclear power plants, the non-radiological impacts from these processes would decrease.

Table 4.10 Damages of the nuclear fuel cycle

	mECU/kWh		σ_g
	0%	**3%**	
POWER GENERATION			
normal operation			
Public health			
fatal cancer[1] - YOLL *(VSL)*	0.059 *(0.099)*	0.00017 *(0.00034)*	B
non-fatal cancer	0.034	0.00010	B
hereditary effects	0.020	0.000060	B
Accidents	ng		
Occupational health - YOLL *(VSL)*	0.063 *(0.084)*	0.056 *(0.071)*	A
Beyond design accidents	0.0034 *(0.0046)*	0.00050 *(0.00076)*	B
OTHER FUEL CYCLE STAGES			
Public health			
radiological impacts YOLL *(VSL)*	3.5 *(4.7)*	0.010 *(0.015)*	B
non-radiological impacts[2] YOLL *(VSL)*	0.56 *(2.7)*	0.43 *(2.1)*	B
Occupational health	0.060		A
Crops	0.00016		B
Ecosystems	iq		
Materials	0.0077		B
Noise	ng		
Visual impacts	ng		
Global warming			C
low	0.075		
mid 3 %	0.35		
mid 1 %	0.91		
high	2.7		

[1] Yoll= mortality impacts based on 'years of life lost' approach, VSL= 'value of statistical life' approach.

[2] Including power generation stage

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

Table 4.11 Sub-total damages of the nuclear fuel cycle

		mECU/kWh	
Discount rate for health effect valuation:		**0%**	**3%**
YOLL *(VSL)*	low	4.4 *(7.8)*	0.60 *(2.3)*
	mid 3 %	4.7 *(8.1)*	0.90 *(2.6)*
	mid 1 %	5.2 *(8.6)*	1.5 *(3.2)*
	upper	7.0 *(10.4)*	3.3 *(5.0)*

5. THE PHOTOVOLTAIC FUEL CYCLE

The following sections summarise the assessment of external costs from the photovoltaic life cycle reported in (ISET, 1995). Results are updated to take into account new findings concerning exposure-response functions and monetary valuation. A detailed discussion of the approach is given in (ISET, 1995).

5.1 Description of reference technologies, quantification of burdens

5.1.1 PV home application

The selected PV plant is a typical application in the frame of the German 1000 Roofs Programme. The PV generator is constructed on the south-facing roof of a household in the village Emstal-Riede. Additionally, a small sculptures workshop is run during the day. The PV plant was put into operation in November 1991 and corresponds to state of technology in 1990. The photovoltaic energy is used to cover the electrical demand of the house and the PV energy surplus flows into the grid. There are no shadow effects from other buildings etc. throughout the whole year. The social acceptance of the PV plant in the location is very high and no complaints have been made.

The PV generator consists of 96 PV polycrystalline modules from the company DASA/AEG with a total peak power of 4.8 kW_p. The rated power is high in comparison to the mean power peak of the PV plants in the 1000 Roofs Programme (2.5 kW_p). The influence of this is negligible for the calculation of the external costs. Other special features of this reference location (e.g. use of three inverters, special cabling, measurement systems etc.) have not been taken into account in the calculation of material and energy use. An ISET measurement system has been installed for energy and performance analysis. The following energy data was measured in the year 1993:

- PV energy production 3,494 kWh/year;
- Energy supply in the grid 2,148 kWh/year

The expected energy balance in the whole life time of 25 years is as follows:

- PV energy production: 87,375 kWh;
- PV energy supply in the grid : 53,750 kWh

5.1.2 PV facade application

Nowadays, new trends in photovoltaic technology with regard to PV integration in buildings are adding a new dimension to the philosophy of energy supply systems. PV modules can be used as multi-functional construction elements i.e. for weather, noise and solar radiation protection. The energy and material use is significantly reduced and no land is required for PV integration.

Today's facades can be mainly classified according to functional and constructional properties as cold, cold-warm, warm and light transparent facades. Although these PV technologies are still in the initial phase of development, first applications have already been implemented. There is large variety in the different PV facade applications (locations and technology used). The selected PV facade of the company SCHÜCO International is integrated in the central office buildings in Bielefeld, Germany. The PV facade was put into operation in October 1993. The shading effects from other neighbouring buildings are very low. The surrounding area is both industrial and residential. There is a highway about 100 m away. The light reflections are very low (the PV facade is darker than the conventional facades of the building).

The PV generator consists of 200 modules with a total module area of 155 m^2 and a rated power of 13 kW_p. Frameless, polycrystalline modules from the company Deutsche Aerospace (DASA) have been used in the required dimensions for integration into the frames of the facade. The mechanical construction of the PV facade is identical to the standard facades of the company. No technical corrections have been made for the integration of the PV modules. For this reason the mechanical construction of the facade is not taken into account in the calculation of PV material and energy use. The glass in the conventional facade of the building will be subtracted from the amount of glass in the PV modules. The material requirements for the PV plant mainly consists of the PV modules and the electrical installation.

5.1.3 Quantification of environmental burdens

Based on a detailed life cycle analysis, emission of SO_2, NO_x, particles and CO_2 during the production and installation phase of the modules are summarised in Table 5.12. In addition to these emissions, a wide range of substances and materials released into the environment during the production of the PV modules has been quantified in a study by Hagedorn and Hellriegel (1992). As it was not possible to perform a full impact pathway analysis for these substances, the potential impacts of these substances on the environment are described qualitatively.

Table 5.12 Emissions from the PV life cycle

	PV Home Application		PV Facade Application	
	per kW_p	per MWh	per kW_p	per MWh
SO_2	1894.6 g	104.1 g	1793.0 g	113.7 g
NO_x	1801.3 g	99.0 g	1287.7 g	81.7 g
Particles	110.3 g	6.1 g	-	-
CO_2	970.8 kg	53.3 kg	777.2 kg	49.3 kg
CH_4	1602.0 g	88.0 g	1025.3 g	65.0 g
N_2O	3.1 g	0.2 g	2.4 g	0.15 g

5.2 Selection of priority pathways

Taking into account the emissions from the full PV life cycle, the priority impact pathways identified for the fossil fuel cycles are analysed, including effects on public health, crops, materials and global warming. In addition, impacts on occupational health, land use and visual intrusion are assessed.

5.3 Quantification of impacts and damages

5.3.1 Impacts from airborne pollutants

Impacts from airborne pollutants on public health, crops, materials and global warming are quantified following the standard approach established for the assessment of fossil power plants. Reasonable reference sites for the life cycle emission sources were quantified to allow the application of EcoSense.

5.3.2 Occupational health impacts

Occupational health impacts are quantified by using data on the work effort required for production and installation, transport processes and operation of the plant, together with occupational health data from the German Employees' Insurance System.

5.3.3 Land use and visual intrusion

Impacts caused by the use of land are discussed for ground-mounted centralised PV systems for example in (Baumann, Hill, 1993). The low energy density of PV systems leads to large land requirements. Damages to natural ecosystems may result from the use of land. Due to the numerous additional disadvantages this kind of application do not have a promising future. As the reference plants examined in this study do not require areas of natural ground, no external costs resulting from the use of land are connected with this kind of application.

Observers could feel annoyed when ground-mounted PV systems are built in areas of high scenic value. Modules integrated in builings of cultural value could also irritate people. However, laws for the protection of historic buildings and monuments do no allow the construction of solar applications on the roofs of such buildings.

Neither point mentioned above applies to the applications examined here. The modules of the home application can not be seen by local residents because they are hidden from view by other parts of the building. The modules of the facade application are integrated in a way that there are no significant differences in design when compared to the rest of the facade.

As no negative visual effects exist no external costs are related to the appearance of the PV plants.

5.4 Summary and interpretation of results

Atmospheric emissions released during the production phase (SO_2, NO_x, particulates, CO_2, CH_4, N_2O) have been determined and the related external costs have been quantified, including impacts on public health, agriculture, forests, materials and the global climatic system. Concerning other substances which are released into the environment during the production phase a quantification of impacts is not possible at the moment. Occupational health impacts caused by accidents and diseases are assessed using statistical information from the relevant industrial sectors. Net risks have been calculated, that is the difference between the risks of average industrial activities and the specific activities related to the life cycle. In the case of photovoltaics this leads to negative damage costs in some areas.

The external costs shown in Table **5.13** are calculated based on the assumption that in the production phase fossil fuels are used and the required electrical energy is taken from the grid. The emissions therefore represent average values for heat processes and power plants in Germany. The external costs are mainly caused by the present use of fossil plants. External costs are much lower when it is assumed that electrical energy required for the production is not taken from the grid but is produced by the PV technology itself.

Table 5.13 External costs of the PV fuel cycle

		PV Home	**PV Facade**	
		mECU/kWh		σ_g
PV LIFE CYCLE				
Public health				
Mortality*- YOLL *(VSL)*		1.1 *(5.1)*	1.1 *(4.9)*	B
Morbidity		0.14	0.13	
Accidents		ng	ng	A
Occupational health		- 0.28	- 0.81	A
Crops		0.00051	0.00041	B
Ecosystems		iq	iq	B
Materials		0.023	0.023	B
	Monuments	nq	nq	
Noise		ng	ng	
Visual impacts		ng	ng	
Global warming				C
	low	0.2	0.2	
	mid 3 %	1.0	0.9	
	mid 1%	2.5	2.3	
	high	7.7	7.0	

*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 5.14 Sub-total damages of the PV fuel cycle

		PV Home	**PV Facade**
		mECU/kWh	
YOLL *(VSL)*	low	1.1 *(5.2)*	0.6 *(4.4)*
	mid 3 %	1.9 *(5.9)*	1.4 *(5.2)*
	mid 1 %	3.3 *(7.3)*	2.8 *(6.6)*
	high	8.1 *(12.1)*	7.6 *(11.4)*

6. THE WIND FUEL CYCLE

The following sections summarise the assessment of external costs from the wind life cycle reported in (ISET, 1995). Results are updated to take into account new findings concerning exposure-response functions and monetary valuation. A detailed discussion of the approach is given in (ISET, 1995).

6.1 Description of the reference technology

The wind park "Nordfriesland Windpark" is located in the coastal area of Friedrich-Wilhelm-Lübke-Koog in the federal state Schleswig-Holstein. All data given below refers to the 45 WECs monitored in the WMEP (Scientific Measurement and Evaluation Programme of the German Ministry for Research and Technology), which consititute the majority of the WECs in the wind park. The manufacturer of the WECs is the Husumer Schiffswerft company in Husum, Germany. The subsidiary "Nordfriesland Windpark GmbH" is the owner and operator of the wind park. The average distance between WECs is about 170 m. **Table 6.15** shows further details about the location and the characteristics of the wind park. The expected energy output of the "Nordfriesland Windpark" (45 WECs) is 24.3 GWh/year, which is 486 GWh for a total life time of 20 years.

6.2 Quantification of burdens

Atmospheric emissions occur mainly in the production and installation phase. These emissions result from the energy used in the production stages of the materials used for the WECs. The most important emissions are determined using data on material weights in the HSW-250 wind energy converter. Using data on energy use and emissions caused by the production of materials from the GEMIS database, the total atmospheric emissions per WEC are calculated (**Table 6.16**). To standardize the emissions to a unit output of electricity they are related to the expected electricity production during the lifetime of the wind park (10.8 GWh per WEC).

Table 6.15 Characteristics of the 'Nordfriesland Windpark'

Site characteristic	
Location	Friedrich-Wilhelm-Lübke-Koog
Wind data	
1992 (average value at 10 m/ 28 m)	5.87 / 7.29 m/s
1993 (average value at 10 m/ 28 m)	5.57 / 7.30 m/s
WECs	
Type	HSW 250
Total number of WECs	51
Number of WECs measured in WMEP	45
Total rated power of measured WECs	11.25 MW
Concept	parallel operation with the grid

Table 6.16 Atmospheric emissions in the Life Cycle of a HSW-250

	Weight/WEC	Primary Energy/WEC	CO_2	SO_2
Aggregates	20000 kg	220 kWh	44 kg	142 g
Aluminium	230 kg	15940 kWh	3365 kg	10423 g
Cement	10000 kg	12350 kWh	8590 kg	3620 g
Copper	694 kg	6993 kWh	1707 kg	13490 g
GRP	2250 kg	101250 kWh	14821 kg	28438 g
Plastic	692 kg	13140 kWh	947 kg	1846 g
Steel	26130 kg	145440 kWh	39509 kg	103893 g
Transport	(232 kg diesel)	3008 kWh	641 kg	609 g
Total per WEC	59996 kg	298341 kWh	69716 kg	162548 g
Total per MWh	5.56 kg	27.6 kWh	6.46 kg	15 g

	NO_x	Particulates	CH_4	N_2O
Aggregates	174 g	20020 g	88 g	0 g
Aluminium	9412 g	1507 g	4149 g	23 g
Cement	24720 g	10680 g	16530 g	290 g
Copper	14489 g	1019 g	1664 g	21 g
GRP	16081 g	1566 g	21710 g	200 g
Plastic	1725 g	141 g	2083 g	9 g
Steel	140762 g	14528 g	173085 g	183 g
Transport	13920 g	?	?	?
Total per WEC	221283 g	49461 g	219309 g	726 g
Total per MWh	20 g	4.6 g	20 g	0.07 g

6.3 Selection of priority pathways

Taking into account the emissions from the full life cycle, the same priority impact pathways as identified for the fossil fuel cycles are analysed, including effects on public health, crops, materials and global warming. In addition, impacts on occupational health, noise and visual intrusion are assessed.

6.4 Quantification of impacts and damages

6.4.1 Impacts from airborne pollutants

Impacts from airborne pollutants on public health, crops, materials and global warming are quantified follwing the standard approach established for the assessment of fossil power plants. Reasonable reference sites for the life cycle emission sources were quantified to allow the application of EcoSense.

6.4.2 Occupational health impacts

Occupational health impacts are quantified by using data on the work effort required for production and installation, transport processes and operation of the plant, together with occupational health data from the German Employees' Insurance System.

6.4.3 Noise impacts

During the operation phase wind energy converters produce noise which can annoy neighbouring residents. The total noise is the sum of aerodynamic and mechanical noise. Aerodynamic noise is caused by the interaction of the rotating blades with the air and mechanical noise is caused by the moving parts in the nacelle.

The residents registration office gives the following figures about inhabitants of the "Friedrich-Wilhelm-Lübke-Koog" for 1994: There are 70 households with 219 inhabitants, composed in the following way: 48 farms, 21 residential buildings and one restaurant. The average number of persons per household is therefore 3.13.

All the farms are built in the same way: the residential part being protected from the wind by large agricultural building e.g. stables. A reduction in noise level is expected due to these buildings. Furthermore, all farms are fenced in by trees or bushes. The background noise level will therefore be even greater than noise from the windpark. For these reasons the values calculated here are probably an overestimation of the real damages. The operation of the windpark leads to a constant increases in sound level as follows:

57	households are affected by an increase between 0.5 and 1.5 dB
6	households are affected by an increase between 1.5 and 2.5 dB
7	households are affected by an increase between 2.5 and 3.5 dB

A willingness to pay (WTP) of 1.97 DM (= 1.02 Ecu) per month for a noise reduction of one dB(A) L_{eq} is given by Rennings (1995) for disbenefits caused by traffic noise. This corresponds to a change in property values of around 1 % per dB(A). Lower noise levels should be calculated with a change in property values of 0.45 % per unit increase in dB(A). According to Rennings this represents an upper limit of disbenefits. Expressed as WTP, this is about 0.89 DM (=0.46 Ecu) per dB(A) per month and person, resulting in a damage costs of 0.064 mEcu per kWh.

6.4.4 Visual intrusion

Along with noise impacts visual intrusion is considered to be the most important environmental effect in the wind energy life cycle. Many factors influence the visual effects caused by a wind park. The most important are the design of the WECs and the wind park as a whole, the characteristics of the surrounding landscape, weather conditions, the distance from the observer and other subjective factors. The area in which the "Nordfriesland-Windpark" is built is not part of a nature reserve area, a national park or a vacation area and there are no spas nearby. This area is apparently not considered to be of high scenic or recreational value by the general public. Impacts on tourists will therefore be neglegted here.

An average willingness to pay (WTP) for visiting intact landscapes of 2.89 DM (= 1.49 Ecu) per person per day is given by Rennings (1995) for Germany. This value is true for one-day-visits but can not be projected to a whole year. A mean WTP on vacation is 145 DM (= 74.88 Ecu) for the whole holiday. It can be assumed that people are willing to spend this amount in one year for intact landscapes. No value is available for residents. The figures given by Eyre (1994) for the UK are almost the same for residents and tourists. Therefore, the same value is used for the WTP of residents.

The energy production per year is about 27.54 GWh (51 WECs and 0.54 GWh per WEC). This leads to costs of 0.6 mEcu per kWh for intact landscapes. This value has to be considered as an upper limit. Costs are in the range from 0 to 0.6 mEcu and the best estimate is considered to be 0.06 mEcu.

6.4.5 Other impacts

Impacts on Animals

The environment in which wind parks are placed is a habitat for quite a number of animals. Therefore it has to be considered to what extent these animals are affected. In most cases WECs and wind parks are built in areas which are intensively used for agriculture. This is also the case for the Nordfriesland-Windpark. In (NNA, 1990) an extremly low number of different vegetation species has been counted for this area. From a botanical point of view it can not be said that valuable area has been destroyed by the construction of the wind park. Extensivation of agriculture was demanded as a compensation for the construction of the wind park. Therefore costs are already internalized and a change for the worse can not be seen. Impairment of birds seems to be more important. Some examinations have been carried out about this question in Germany (NNA, 1990), Denmark (Bleijenberg, 1988) and the Netherlands (Winkelman, 1988). In WEC locations which have been in operation for several years no serious change in the number of species or quantities of hatching birds could be registered. Neither for the construction nor the operation of the wind park "Krummshörn" could a loss of species be noticed, even for protected or sensitive species. Hatching birds approach WECs or wind parks without visible uneasiness. They fly under or above the rotating blades or through the wind park. No change in behaviour could be recognized for very different species concerning their rests or search for food. Birds of passage showed obvious reactions: birds flying towards a WEC or a wind park either rose before it and descended afterwards or flew round it by changing direction. The distance from the WECs was significant being between 50 m and 100 m. For these reasons there is no high risk of flying birds colliding with rotating blades. A statistic for 7 locations with 69 WECs in all came to the result that 32 birds could have been killed by collisions in an observation period of one year (1989/90). This examination and examinations from the neighbouring foreign countries show that nether solitary WECs nor wind parks in Lower Saxony and Schleswig-Holstein represent a serious risk for birds. This is especially true when the risk is compared to other risks e.g. traffic, pylons or transmitter masts.

Epileptic fits

It is expected that epileptic fits can be triggered by frequencies between 2.5 Hz and 3 Hz in susceptible people (Clarke, 1988). As long as the rotation speed is below 50 r.p.m for three-blade rotors no problems are expected. For this reason the rotation speed is usually limited to 45 r.p.m. The highest rotation speed of the HSW-250 is 39.3 r.p.m. and therefore no external effects exist.

Electromagnetic Interference

Rotating blades can produce electromagnetic interference and many communication frequencies might be affected. This problem is discussed by Eyre (1994). It is most important for metallic blade materials because they are strongly reflective. Glass reinforced plastic is partially transparent to electromagnetic waves, therefore the effect is not so much noticable. Eyre comes to the conclusion that problems with domestic television reception cannot always be avoided but can be remedied cheaply by the developer and is therefore no externality. For the case of the "Nordfriesland Windpark" no difficulties are known.

6.5 Summary and interpretation of results

The "Nordfriesland Windpark" is located in the coastal area of Friedrich-Wilhelm-Lübke-Koog in the federal state Schleswig-Holstein. The park includes 51 wind energy converters of the type HSW-250. The rated power of one WEC is about 250 kW. They represent the state of technology in 1990. The wind park is operating parallel to the grid.

The following impacts have been examined in detail:

- Quantities of atmospheric emissions released in the production phase (SO_2, NO_x, particulates, CO_2, CH_4, N_2O) have been calculated. the related external costs have been quantified, including impacts on public health, agriculture, forests, materials and the global climatic system.

- Noise propagation has been calculated according to the VDI-guideline 2714. The increase in sound at the point of the observer has been calculated considering the background noise level. 70 households are affected, most of them by an increase of around 1 dB. Willingness to pay figures for noise reduction have been used to valuate these increases. A value of 0.064 mEcu per kWh has been calculated for noise impacts. This value is highly site specific.
- Wind parks are mainly built in open countryside and are therefore visible from long distances. The quantification of these amenity impacts is very difficult because no valuation studies exist which directly refer to typical wind park sites. Willingness to pay for intact countryside during holidays has been used to valuate the impacts. A zone of 2 km has been considered as mainly affected. Costs are estimated to be in the range from 0 to 0.6 mEcu per kWh and the best estimate is considered to be 0.06 mEcu per kWh.
- Occupational health impacts caused by accidents and diseases are assessed using statistical information from the relevant industrial sectors. Construction, transport, operation and dismantling of the WEC have been considered.
- Impacts on animals and risks of epileptic fits have been discussed but seem to be negligible.

Results are summarised in . The external costs are calculated based on the assumption that in the production phase fossil fuels are used and the required electrical energy is taken from the grid. The emissions therefore represent average values for heat processes and power plants in Germany. The external costs are mainly caused by the present use of fossil plants. External costs are much lower when it is assumed that electrical energy required for the production is not taken from the grid but is produced by the wind technology itself.

Table 6.17 External costs of the wind fuel cycle

		mECU/kWh	σ_g
WIND LIFE CYCLE			
Public health			
Mortality*- YOLL *(VSL)*		0.24 *(1.1)*	B
Morbidity		0.030	
Occupational health		0.044	A
Crops		0.000097	B
Ecosystems		iq	B
Materials		0.0032	B
Noise		0 - 0.062	
Visual impacts		iq	
Global warming			C
	low	0.026	
	mid 3 %	0.12	
	mid 1%	0.3	
	high	1.0	

*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 6.18 Sub-total damages of the wind fuel cycle

		mECU/kWh
YOLL *(VSL)*	low	0.37 *(1.2)*
	mid 3 %	0.47 *(1.3)*
	mid 1 %	0.67 *(1.5)*
	high	1.3 *(2.2)*

7. BIOMASS FUEL CYCLE

7.1 Introduction

Biomass as solid or liquid fuel is discussed more and more in Germany. Two aspects are usually stressed. Firstly, biomass combustion is seen as a CO_2 free technology and therefore considered for mitigation measures. Secondly, as more and more agricultural areas are set aside it is seen as a new market for agriculture and forestry. There are many species that can be cultivated as energy plant, like wood, miscanthus, or cereals. All these options are discussed and analysed in Germany at the moment. For the German National Implementation Study on Biomass it was decided to use residual wood as in Germany CHP plants using industrial residual wood are already operated (e.g. by sawmills). Furthermore, among the different options the use of residual wood from forests is economically the most feasible in the short term as the residual wood is already available and there are no alternative uses for it (Kaltschmitt, Reinhardt, 1997).

In Germany with few exceptions ‘natural’ forests, i.e. completely unmanaged forests, do not exist. More or less all the forests are managed for the production of timber for industrial utilisation. Residual wood arises due to management measures during the growth cycle and at timber harvest. The residual wood volume corresponds to the existing and managed forest areas. Forest areas vary widely in Germany, with a large forest area in the south and a smaller forest area in the north and east of Germany. The potential of residual wood that can be utilised energetically is about 142 PJ per year in the whole of Germany, with about 17 PJ in Baden-Württemberg and about 32 PJ in Bavaria (Kaltschmitt, 1994).

7.2 Definition of the Fuel Cycle, Technologies and Sites 000000

7.2.1 The Reference Combined Heat and Power Plant

Biomass combustion in combined heating and power (CHP) plants is for larger units (20-30 MW_{th}) a sensible economic option. Such facilities are especially suited to supply industrial and/or communal consumers that have a more or less constant heating demand (e.g. hospitals). The CHP plants are usually heat-driven; surplus electricity is supplied to the public electricity supply system.

The already operated CHP plants firing industrial residual wood apply grate combustion. Instead, for the reference plant to be analysed a combined heating and power (CHP) plant with a circulating atmospheric fluidised bed combustion (AFBC) is assumed. The operation costs of this technology are higher than for grate combustion but the emissions and thus the environmental impacts are lower. In circulating AFBC the particles of the bed are held in a fluidised state by an upward flow of air blown into the bottom of the furnace partly as primary air (ca. 60 %) through the fluidisation nozzles and partly as secondary air (ca. 40 %) some meters above. The velocity of the gas is such that it carries the bed solids along with it, thereby filling the entire combustion chamber. The hot combustion gases carry the particles to the top of the combustor and into a heavy duty cyclone where they are separated and recirculated back into the bottom of the main combustion chamber. The circulating bed systems increase the potential reaction time and level of gas mixing, and therefore generally lead to a more efficient combustion and complete adsorption of sulfur (ERM, European Commission, 1995), (Gernhardt *et al.*, 1994). The wood content of the bed is about 2 to 5 %; the purpose of the other bed materials is the reduction of the wood to small pieces and heat storage. The plant is equipped with a multicyclone and fibrous filter for dedusting.

FBC tolerate comparatively high water contents of the wood (up to 50 %) (Bauer, 1994). The CHP plant can be fired by chop wood (< 30 mm) and cereals. Thus, bigger-sized chop wood has to be hacked before combustion. For optimal feeding the wood should not contain more than 0.2 % foreign substances (Bauer, 1994), (Nussbaumer, 1994).

At the CHP plant the supplied chop wood is moved by wheel loader to a ground-level shelter or stored up in silos. Because of the high volume of the needed wood, the on-site storage capacity holds for only one week.

The reference CHP plant has a generator capacity of 20 MW and is operated 3000 h per year. Its total net efficiency is 85 %. Further technical data are summarised in Table 7.1. It is assumed that the CHP plant is located in Tübingen and supplies the hospitals there. Tübingen was chosen as firstly the hospitals there are consumers with an approximately constant heating demand and secondly as around Tübingen there are enough forests to supply the residual wood needed.

7.2.2 Upstream Processes

The use of residual forest wood is analysed for Norway spruce. In comparison to normal tree stands no additional cultivation measures are necessary. There is no alternative usage for the residual wood and no market price exists for it. The residual wood would remain otherwise in the forest. The loss of nutrients for the forest is negligible because most of the needles, bark, etc., which contain most of the nutrients, is not removed. Thus, the process step cultivation is not taken into account in this analysis.

The upstream process steps of the biomass fuel cycle are shown in Figure 7.1. As only residual wood is used no additional areas have to be cultivated and thus the process step cultivation does not have to be taken into account.

The maximum distance from the CHP plant, for which it is economically sensible to supply the plant with residual wood, is 50 km. Therefore, it is assumed that the tree stands from which the residual wood is taken are in that area. For the analysis of the upstream process steps it does not make sense to specify one specific site of the tree stands to calculate energy

Table 7.1 Technical data of the reference CHP plant

Plant type	circulating atmospheric fluidised bed combustion (AFBC) with multicyclone and fibrous filter
Generator capacity	20 MW
Heat produced	12.8 MJ/s
Electricity sent out	3.6 MW
Net efficiency	18%
Total efficiency	85%
Full load hours per year	3000 h
Projected lifetime	30 a
Data relevant for atmospheric transport modelling	
Stack height	40 m
Stack diameter	4 m
Flue gas volume stream (full load)	23 730 Nm^3/h
Flue gas temperature	100°C
Fuel specification	
Calorific value H_u	18.6 MJ/kg dry mass
Sulfur content	0.01 %
Emissions relative to calorific value	
SO_2	3.6 mg/MJ
NO_x	97.2 mg/MJ
Particulates	2.9 mg/MJ
CO_2	105.9 mg/MJ
CH_4	0.6 mg/MJ
N_2O	5.7 mg/MJ
Bulk materials and wastes	
Cyclone ash	35 t/year
Filter ask	3 t/year

demand and transport distances of the upstream processes. Instead an average of all German sites is assumed.

The harvest takes place in spring by water contents of about 50 %. The residual wood is transported first to the next forest road and then on to the edge of the forest. The wood is intermediately stored at the edge of the forest. In the summer months about 10 % of the water content of the wood is lost during storage. If necessary, the timber is chopped with mobile hackers, then it is transferred to containers and transported to the CHP plant.

7.2.3 Waste Disposal

The ashes from the CHP plant consist above all of basic compounds like calcium, potassium, magnesium, etc. The cyclone ash is distributed on agricultural area. Because of the high content of heavy metal this is not possible for filter ash. Instead it is transported to a disposal site (see Figure 7.1).

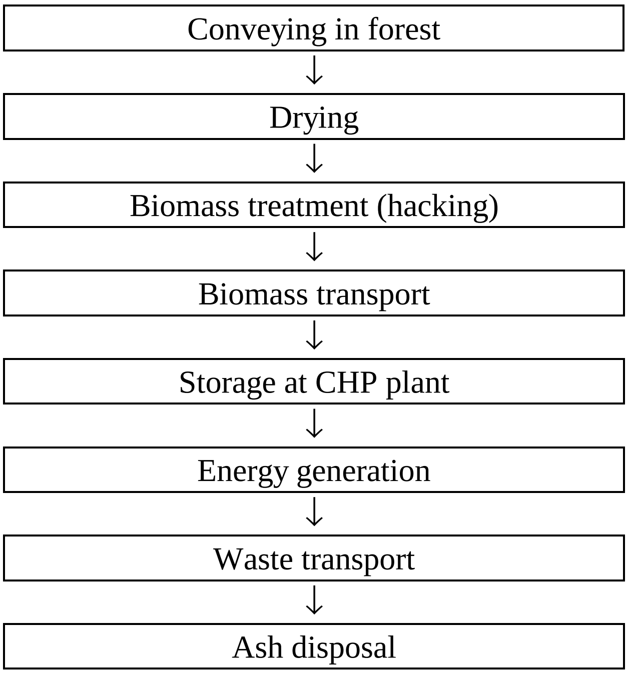


Figure 7.1 Process step of the biomass fuel cycle under analysis

7.3 Air-Borne Emissions Associated With The Biomass Fuel Cycle

Data on emissions from wood combustion in FBC can only be sporadically found in the literature. Accordingly estimates are necessary for these. Emission standards can serve as guidelines but often they are well above the actual flue gas concentrations. The emissions into air of the different upstream process steps of the German biomass fuel cycle have been analysed in detail (Kaltschmitt, Reinhardt, 1997). The analysis of the upstream processes is based on the fuel use and emission factors of trucks and other machinery. For the specific fuel use, different load factors for the trucks and machinery have been taken into account, including (for the forest machinery) different load factors during set-up time and other loss times. Table 7.2 shows the annual emissions per process step and in total. Further details can be found in Appendix VIII.

The process step ‘combustion’ contributes above all to the total air-borne emissions - with the exception of CO_2, diesel particulates, NH_3, non-methane hydrocarbons (NMHC) and benzo(*a*)pyrene. CO_2 is a special case. The most common position concerning CO_2 produced by biomass combustion is that there is no net atmospheric CO_2 build-up from using biomass *grown sustainably* because CO_2 released in combustion is compensated for by that withdrawn from the atmosphere during growth (IPCC, 1996). Without the CO_2 emissions from the combustion, the overall CO_2 emissions of the biomass fuel cycle are very low.

Table 7.2 Annual air-borne emissions of the different process steps of the biomass fuel cycle

Process step	Tractor	Hacker	Truck transport	Storage at CHP plant	Combustion	Ash transport	Total
SO_2 [kg/year]	16.7	63.4	10.1	1.2	784.6	0.0	876.1
NO_x [kg/year]	552.1	2210.2	405.9	40.5	21010.3	1.0	24220.1
Particulates [kg/year]	0.0	0.0	0.0	0.0	618.0	0.0	618.0
Diesel part. [kg/year]	49.2	143.4	22.3	3.6	0.0	0.1	218.6
CO_2 [t/year]	53.2	201.2	32.2	3.9	22874.4[3]/0	0.1	23164.9/290.5
CO [kg/year]	193.2	355.0	101.5	14.2	12005.9	0.3	12670.0
CH_4 [kg/year]	2.1	5.6	1.2	0.2	120.1	0.0	129.1
NMHC[1] [kg/year]	85.7	226.0	49.5	6.3	360.2	0.1	727.9
Benzene [kg/year]	1.7	4.4	1.0	0.1	40.3	0.0	47.5
Benzo(a)pyrene [mg/year]	102.2	500.2	78.3	7.5	1081.5	0.2	1769.8
N_2O [kg/year]	2.4	9.1	1.5	0.2	1235.5	0.0	1248.6
NH_3 [kg/year]	1.9	7.4	1.2	0.1	0.0	0.0	10.6
HCl [kg/year]	0.3	1.2	0.2	0.0	706.1	0.0	707.8
Formaldehyde [kg/year]	7.1	18.8	4.1	0.5	0.0	0.0	30.5
TE[2] [µg/year]	1.0	3.8	0.6	0.1	1544.9	0.0	1550.4

[1] including benzene and benzo(a)pyrene

[2] TCDD-Equivalent calculated from toxic equivalence quotients of dioxins and dibenzofurans after (NATO/CCMS, 1988)

[3] These CO2 emissions do not have to be considered in the assessment of global warming impacts (see text).

Source: Kaltschmitt, Reinhardt (1997)

7.4 Selection of Priority Impact Pathways

In the Portuguese and Greek reports on the externalities of biomass fuel cycles (Ribeiro da Silva et al., 1995), (Koukios et al., 1995) a list of priority impact pathways had been identified. Not all of these impacts are relevant in Germany (e.g. forest fires) or for the biomass fuel cycle under analysis (e.g. cultivation effects). For some impacts it is questionable whether it is a *priority* impact pathway, i.e. a pathway that contributes in a significant way to the total costs. Traffic noise was e.g. suggested as priority impact pathway but the transport volume is not so significant that major effects are expected.

The impacts of cultivation do not have to be taken into account for the biomass fuel cycle under analysis. So far (and in the near future) no market (and thus no market price) exists for residual wood. Neither there is an alternative usage of the residual wood. While the residual wood has to be removed from the felling site anyway, without the energetic use it would remain at some place in the forest. Therefore, cultivation effects can be attributed to the main object of the harvest, timber production. Another aspect is the potential nutrient loss for the forest due to the removal of the residual wood. However, needles, bark, etc. containing most of the nutrients remain in the forest (Frühwald *et al.*, 1993). So, the actual nutrient loss is minor and does not contribute to a significant effect.

For cultivation the following priority impact pathways would be relevant:
- effects of fertiliser runoff on water treatment,
- effects of soil erosion,
- occupational health effects, and
- effects of atmospheric pollution on human health, terrestrial ecosystems, buildings.

Soil erosion is of no importance as long as ‘gute fachliche Praxis’ (good professional practice) is kept, a condition true in most cases in forestry in Germany. Furthermore, in German forestry, fertilisers are not applied at all. Thus, fertiliser runoff is out of the question here. In the last years nitrogen is accumulated more and more in the forests, but this is caused by the present high atmospheric nitrogen input. The additional air-borne emissions from the tree felling would not significantly increase the total emission balance of the fuel cycle (see section 7.3) and therefore cause no additional significant effects. In summary, besides the occupational health effects, the process step cultivation would not contribute significantly to the external costs of this fuel cycle if it would be completely attributed to the residual wood instead of to the timber production. For the occupational health effects, it cannot be avoided that the tree felling is included in the quantified occupational risk as it cannot be separated from other forest activities.

The human health effects of ash distributed on agricultural area is another impact often discussed. The problem is the potential high heavy metal content of the ash. However, this is only true for the filter ash not for the ash from the cyclone. As long as only the cyclone ash is distributed on agricultural area while the filter ash is disposed at an appropriate site, as it is assumed for the biomass fuel cycle under analysis, no human health effects are expected (Obernberger, 1994).

The following priority impact pathways can be identified for the biomass fuel cycle under analysis:

- direct and indirect effects (acidification, eutrophication) of atmospheric pollution (SO_2, NO_x, particulates, acid deposition, ozone, etc.) due to air-borne emissions of the biomass fuel cycle on
  - human health,
  - crops,
  - forests,
  - unmanaged ecosystems, and
  - buildings and constructions;
- occupational health impacts; and
- impacts of global warming due to greenhouse gas emissions (CO_2, CH_4, N_2O).

For some of the impacts lack of knowledge or data prevent a complete or any assessment of the impacts. This is especially true for forest damages and eutrophication effects on unmanaged ecosystems as well as the analysis of ozone effects. Due to the low CO_2 emissions of the biomass fuel cycle the inclusion of global warming in this list could be argued. However, a discussion was started on the CO_2 balance of biomass (Schlamadinger, Marland, 1994), which stresses the importance of the analysis of the greenhouse gas effects.

7.5 Quantification of Impacts and Damages

The impacts and damages of the biomass fuel cycle under analysis were quantified following the ExternE methodology established by now. Appendix I to VII summarise the approaches, exposure-response functions and monetary values used and describe the software tool Eco-Sense employed for the assessment. For diesel particulates emitted by the upstream processes the health functions for fine particles (PM2.5), i.e. particles of less than 2.5 µm, have been applied instead of the functions for PM10 (see Appendix II).

The PCDD/F risk factors used in the Waste Incineration Project (European Commission, 1997) as well as the risk factors for cancer effects of diesel particulates and benzo(*a*)pyrene proposed in Appendix II have been applied. Cancer effects from these substances were not identified as priority impact pathways but as the analysis is comparatively fast to carry out, the impacts were assessed. In that way, annual damages due to the PCDD/F emissions of the CHP plant of about 0.1 ECU were quantified, the annual damages due to the diesel particulates and benzo(*a*)pyrene emissions are even 3–4 order of magnitudes lower than that. The results confirmed the judgement that these effects do not contribute in a significant way to the external costs

Table 7.3 summarises the quantified damages for the fuel cycle. Annual damages are given as well as the damages per electricity and heat produced as allocated by their exergy content (Krewitt *et al.*, 1996). Further details of the results can be found in Appendix VIII.

Employing the YOLL approach for mortality effects annual damages without global warming of 490400 ECU/year were quantified, employing the VSL approach the annual damages increase to 1648860 ECU/year. Increased mortality, mostly due to the NO_x emissions of the generation stage, contribute the most to the total quantified damage costs. NO_x emissions of the CHP plant are high if compared to the fossil power plants because emission standards for plants of this size are not as stringent as for power plants of more than 50 MW.

Applying the ExternE results for CO_2 the global warming damages of 12200–31300 ECU/year are quantified (illustrative restricted range). These damages are small compared to the damages quantified for the other effects.

Table 7.4 summarises the totals of the quantified damages, depending on choice of YOLL/VSL for mortality effects and on the global warming damage costs per tonne CO_2. Allocated to electricity, the total damages are about 27 to 32 mECU/kWh for the YOLL approach and about 90 to 94 mECU/kWh for the VSL approach. The damages allocated to the produced heat are 1450 to 1700 mECU/MJ and 4800 to 5080 mECU/MJ, respectively.

7.6 Conclusions

For the German implementation of the biomass fuel cycle the combustion of residual wood (Norway spruce) in a CHP plant in Tübingen has been chosen as reference technology as this is already in the short-term an economically sensible option in Germany. For the reference plant a circulating atmospheric fluidised bed combustion is assumed. The emissions of this technology are comparatively low - especially for sulphur and nitrogen.

The fuel cycle consists of the following major process steps: conveying in forest, storage and drying, hacking, transport, generation, and waste disposal. In comparison to normal tree stands no additional cultivation measures are necessary. There is no alternative usage for the residual wood and no market price exists for it. The residual wood would remain otherwise in the forest. Thus the process step cultivation does not have to be taken into account in this analysis.

The emissions into air of the different process steps of the fuel cycle have been analysed in detail for the following pollutants: SO_2, NO_x, particulates, diesel particulates, CO_2, CO, CH_4, NMHC, benzene, benzo(*a*)pyrene, N_2O, NH_3, HCl, formaldehyde and PCDD/F. Thereby, the combustion of the residual wood contributes above all to the total air-borne emissions - with the exception of CO_2, diesel particulates, NH_3 and NMHC.

The effects of the air-borne emissions on human health, terrestrial ecosystems and buildings, occupational health effects and global warming were identified as priority impact pathways for the fuel cycle under analysis. Other impacts like ash disposal effects or fertiliser runoff effects were discussed but they either do not apply to the fuel cycle under analyse or do not cause significant effects.

Without global warming annual damage costs of 490400 ECU/year have been quantified assuming that life years lost instead of lives lost are the appropriate end-point to value for the mortality effects. Including the global warming damage costs based on the new EXTERNE results for damage costs per tonne CO_2 the total annual damage costs of the biomass fuel cycle are 502600 to 521700 ECU (illustrative restricted range). Allocated based on exergy between the products electricity and heat of the CHP plant these annual costs are equivalent to 27.6–28.6 mECU/kWh electricity produced and to 1480–1540 mECU/MJ heat produced.

Table 7.3 Damages of the biomass fuel cycle (negative numbers constitute benefits)

	Damage Costs [ECU/year]	Damage Costs [mECU/kWh] allocated to electricity production (59.2%)[1]	Damage Costs [ECU/TJ] allocated to heat production (40.8%)[1]	σ_g
POWER GENERATION				
Public health				
Mortality – YOLL[2] *(VSL)*	336000 *(1241700)*	18.4 *(68.0)*	991 *(3670)*	B
of which TSP	12040 *(26050)*	0.7 *(1.4)*	36 *(77)*	
SO_2	9140 *(41680)*	0.5 *(2.3)*	27 *(123)*	
NO_x	314400 *(1155700)*	17.2 *(63.4)*	928 *(3411)*	
Morbidity	50860	2.8	150	A
Accidents	ng	ng	ng	A
Occupational health	-300	-0.02	-1	A
Ozone impacts (human health & crops) – YOLL[2] *(VSL)*	31700 *(240600)*	1.7 *(13.2)*	94 *(710)*	
Crops	-42	-0.002	-0.1	B
Ecosystems	iq	iq	iq	B
Materials	3710	0.20	11	B
Monuments	nq	nq	nq	
Noise	ng	ng	ng	
Visual impacts	ng	ng	ng	
Global warming				C
low	1465	0.08	4	
mid 3%	6940	0.4	21	
mid 1%	17734	1.0	52	
high	53588	2.9	158	
OTHER FUEL CYCLE STAGES				
Public health – YOLL[2] *(VSL)*	62700 *(71900)*	3.4 *(11.5)*	168 *(620)*	
Outside EU	0	0	0	
Inside EU	62700 *(71900)*	3.4 *(11.5)*	168 *(620)*	
Occupational health	3310	0.2	10	
Outside EU	0	0	0	
Inside EU	3310	0.2	10	
Ozone impacts (human health & crops) – YOLL[2] *(VSL)*	5100 *(39800)*	0.3 *(2.2)*	15 *(117)*	

	Damage Costs [ECU/year]	Damage Costs [mECU/kWh] allocated to electricity production (59.2%)[1]	Damage Costs [ECU/TJ] allocated to heat production (40.8%)[1]	σ_g
Crops	-1	-0.0001	-0.004	B
Ecological effects	ng			B
Materials	555	0.03	2	B
Road damages	ng			A
Global warming				C
low	1120	0.06	3	
mid 3%	5306	0.3	16	
mid 1%	13559	0.7	40	
high	40970	2.2	121	

[1] based on exergy (flow temperature of 110 °C, out-going temperature 60 °C, ambient temperature of 15 °C)

[2] Yoll= mortality impacts based on 'years of life lost' approach; here results are calculated assuming a discount rate of 3 %, VSL= impacts evaluated based on 'value of statistical life' approach.

[3] CO_2 equivalent emissions are calculated from the CH_4 and N_2O emissions employing the Global Warming Potentials of IPCC (1996a) for the time horizon of 100 years.

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

Table 7.4 Sub-total damages of the German biomass fuel cycle

	Damage Costs [ECU/year]	Damage Costs [mECU/kWh] allocated to electricity production (59.2%)[1]	Damage Costs [ECU/TJ] allocated to heat production (40.8%)[1]
YOLL ***(VSL)***			
low	492900	27.0	1454
	(1628700)	*(89.3)*	*(4806)*
mid 3%	502600	27.6	1483
	(1638400)	*(89.8)*	*(4835)*
mid 1%	521700	28.6	1539
	(1657500)	*(90.9)*	*(4891)*
high	584900	32.1	1726
	(1720700)	*(94.3)*	*(5078)*

[1] based on exergy (flow temperature of 110 °C, out-going temperature 60 °C, ambient temperature of 15 °C)

Table 7.5 Damages by pollutant

	ECU / t of pollutant
SO_2 *- YOLL *(VSL)*	11700 *(54200)*
NO_x *- YOLL *(VSL)*	15100 *(57100)*
PM_{10} *- YOLL *(VSL)*	19500 *(9321)*
NO_x (via ozone)	1500
CO_2	
low	3.8
mid 3%	18
mid 1%	46
high	139

* Yoll= mortality impacts based on ‘years of life lost’ approach; here results are calculated assuming a discount rate of 3 %, VSL= impacts evaluated based on ‘value of statistical life’ approach.

8. AGGREGATION

8.1 Introduction

The current results of the ExternE project provide estimates of marginal external costs of electricity generation from a wide range of specific technologies at various locations in Europe. The detailed ‘bottom-up’ approach that has been followed allows the calculation of site specific and technology specific damage costs for new increments of power generation. However, although the ‘impact pathway approach’ developed in ExternE is widely recognised as currently the scientifically most elaborated methodology for calculating external costs, the approach has been criticised for being too complex and thus being of limited use only for energy policy analysis. While marginal costs per kWh derived for a large number of technologies and sites are important for environmental regulation, there is in fact a clear need for aggregated information to be used at national or European level policy analysis. Past experience showed that the (mis)use of ‘point’-values derived for a specific plant at a specific site might be misleading in a more general context (e. g. if the external cost from the ‘Lauffen’ power station are considered as representative of the German electricity generation from fossil fuels), as they do not take into account plant characteristics as well as the spatial distribution of receptors and other emission sources. In order to maintain the advantages and benefits from a detailed bottom-up modelling within an operational aggregation task, the EcoSense model that has been used as a standard tool for analysing external costs from single point sources is currently extended towards a so called *multi-source* version. This new multi-source version supports the assessment of environmental impacts and resulting damage costs from a whole industry sector (e. g. power sector) within a specific region, but still follows the traditional detailed impact pathway approach, taking into account site specific conditions and possible non-linearities in chemical conversion of airborne pollutants and impact mechanisms. The present section describes the application of a preliminary version of the new multi-source EcoSense to calculate external costs from fossil electricity generation in Germany.

8.2 The German electricity sector

As a basis for further analysis, this section gives an outline of the structure of the German power sector. Because of modelling reasons (see section 3) we have used CORINAIR emission data from 1990, so that 1990 is considered as base-year for analysis. In order to reflect the drastical changes in the German power sector after the re-unification, data from subsequent years are reported in this section for information. Because of the different structure of the power sector in the 'former Federal Territory' and the 'neue Länder' (former GDR), the reporting of average data for the whole of Germany might be misleading, so that data for the former Federal Territory and the 'neue Länder' are presented separately.

Table 8.6 shows the gross domestic product, primary energy use and the net electricity consumption in Germany over the last ten years. In the late '80s, due to the improvement of energy efficiency and the policy of promoting energy conservation, the overall rise in net electricity consumption was lower than the increase of the gross domestic product in the former Federal Territory. This trend was disturbed due to the restructuring of the industry in the 'neue Länder' after the re-unification, leading to significant implications also on the former Federal Territory's economy. However, data from the most recent years indicate that electricity demand is growing again, with growth rates below the increase of the gross domestic product.

Table 8.6 Gross domestic product, primary energy use and electricity consumption in Germany

Year	Gross domestic product		Primary energy use		Net electricity use	
	10^9 DM	% change to previous year	PJ	% change to previous year	TWh	% change to previous year
1985	2149.8	+ 1.9	11284	+ 2.4	367.6	+ 2.7
1986	2198.6	+ 2.3	11339	+ 0.5	371.8	+ 1.2
1987	2232.6	+ 1.5	11372	+ 0.3	380.5	+ 2.3
1988	2314.3	+ 3.7	11424	+ 0.5	386.3	+ 1.5
1989	2410.9	+ 4.2	11219	- 1.8	391.8	+ 1.4
1990	2543.9	+ 5.5	11495	+ 1.6	398.2	+ 1.6
1991$^{1)}$	2668.0	+ 4.3	11990	+ 4.3	409.7	+ 2.9
1991$^{2)}$	214.0	-	2471	-	63.1	-
1992$^{1)}$	2701.0	+ 1.2	11958	- 0.3	408.5	- 0.3
1992$^{2)}$	232.2	+ 8.5	2216	- 10.3	58.7	- 7.0
1993$^{1)}$	2639.0	- 2.3	11999	+ 0.3	403.8	- 1.2
1993$^{2)}$	243.5	+ 4.9	2139	- 3.4	58.3	- 0.8
1994$^{1)}$	2680.3	+ 1.6	11914	- 0.5	408.4	+ 1.1
1994$^{2)}$	264.0	+ 8.4	2093	- 2.2	56.7	- 3.0
1995$^{1)}$			12043	+ 1.1		
1995$^{2)}$			2122	+ 1.4		

$^{1)}$ former Federal Territory; $^{2)}$ 'neue Länder'

Table 8.7 Net electricity consumption in Germany in TWh (BMWI, 1996), (Schiffer, 1991)

	1989 1)	 2)	1990 1)	 2)	1991	1992	1993	1994	1995
Industry	199.4	57.5	203.1	45.3	232.1	228.7	218.3	222.9	229.0
Private households	97.7	17.6	98.5	17.5	122.2	122.8	126.1	124.5	124.7
other small consumers	85.4	20.0	87.6	18.7	103.3	100.8	102.7	102.3	101.4
Transport	11.1	2.9	11.0	2.5	15.3	14.9	15.0	15.4	15.5
total net electricity consumption	393.6	98.1	400.2	84.0	472.9	467.2	462.1	465.1	470.6

1) former Federal Territory; 2) 'neue Länder'

In 1990, the net electricity consumption totalled 484,2 TWh with 400,2 TWh in the former Federal Territory and 84,0 TWh in the 'neue Länder' (Table 8.7). Net electricity consumption by consumer groups reveals a similar structure in the former Federal Territory and the 'neue Länder'. The same applies to the electricity consumption figures in the individual branches of industry. In 1990, industry consumed about half of the electric power both in the former Federal Territory and the 'neue Länder'.

Gross electricity production in 1990 totalled 550 TWh (Table 8.8). Public utilities accounted for 85 % of gross electricity production, industry for 14.2 %, and the Deutsche Bahn AG (German railways stock corporation) for 1.1 %. The structure of the electricity generation sector in the former Federal Territory and the 'neue Länder' differs significantly with regard to the fuel used. In 1990, nuclear energy with a contribution of 33 % was the major source for electricity generation in the former Federal Territory. In the 'neue Länder', nuclear contributed to 5 % of electricity generation in 1990, but after shut-down of the Greifswald nuclear power plant in December 1990 there is no nuclear plant in operation any more. In the 'neue Länder', lignite is the dominant fuel contributing to 86 % of electricity generation. In the former Federal Territory, hard coal contributed to 31 %, natural gas to 8 %, hydro to 4 %, oil to 2 % and other sources to 3 % of electricity generation, while these sources contributed to less than 10 % of electricity generation in the 'neue Länder' (Table 8.9).

Table 8.8 Gross electricity generation in Germany by power plant operator (in TWh) (BMWI, 1996), (Schiffer, 1991)

	1989 1)	 2)	1990 1)	 2)	1991	1992	1993	1994	1995
Public utilities	378.2	97.8	385.1	80.9	459.1	460.9	452.7	455.5	460.5
Industry	57.2	21.0	58.7	19.3	74.2	70.0	66.7	65.1	63.2
German Railways corp.	5.4	0.1	5.7	0.2	6.1	6.2	6.3	6.2	6.2
Total	440.9	119.0	449.5	100.4	539.4	537.1	525.7	526.8	529.9

1) former Federal Territory; 2) 'neue Länder'

Table 8.9 Gross electricity generation in Germany by fuel source (in TWh) (BMWI, 1996), (Schiffer, 1991)

	1989		1990		1991		1992		1993		1994		1995	
	TWh	%	TWh	%	TWh	%	TWh	%	TWh	%	TWh	%	TWh	%
Hard coal	130.3[1] 0.3[2]	29.6[1] 0.3[2]	141.5[1] 0.9[2]	31.6[1] 0.9[2]	149.8	27.8	141.9	26.4	146.2	27.8	144.6	27.4	145.1	27.4
Lignite	82.6[1] 97.5	18.8[1] 81.9[2]	82.5[1] 86.0[2]	18.4[1] 85.7[2]	158.4	29.4	154.5	28.8	147.5	28.1	146.1	27.7	146.3	27.6
Fuel oil	9.9[1] 1.1	2.3[1] 0.9[2]	10.1[1] 2.9[2]	2.2[1] 2.9[2]	13.6	2.5	12.0	2.2	8.9	1.7	8.8	1.7	7.4	1.4
Natural gas	34.7[1] 6.2	7.9[1] 5.3[2]	35.7[1] 3.9[2]	7.9[1] 3.9[2]	36.3	6.7	33.0	6.1	32.8	6.2	36.1	6.9	37.3	7.0
Nuclear	149.4[1] 12.3	33.9[1] 10.3[2]	147.2[1] 5.3[2]	32.7[1] 5.3[2]	147.4	27.3	158.8	29.5	153.5	29.2	151.2	28.7	154.1	29.1
Hydro	19.1[1] 1.6	4.3[1] 1.3[2]	18.4[1] 1.3[2]	4.1[1] 1.3[2]	18.5	3.4	21.1	3.9	21.5	4.1	22.5	4.3	24.5	4.6
Others	14.0[1] -	3.2[1] -	14.1[1] -	3.1[1]	15.4	2.9	15.8	2.9	15.3	2.9	17.5	3.3	15.2	2.9
Total	440.0[1] 119.0		449.5[1] 100.4[2]		539.4		537.1		525.7		526.8		529.9	

[1] former Federal Territory; [2] 'neue Länder';

SO_2, NO_x, particle and CO_2 emissions from power and cogeneration plants as reported by (BMWI, 1996) are presented in Table 8.10. Although in 1990 electricity generation in the 'neue Länder' was much lower than in the former Federal Territory, emissions from the power sector partly were much higher than in the former Federal Territory. As shown below, this spatial distribution of major emission sources has a major impact on the results. Due to restructuring of the power sector in the 'neue Länder' a significant decrease of emissions can be observed, so that results from the present study using 1990 data cannot necessarily be transferred to current conditions.

Table 8.10 Emissions from power and cogeneration plants (BMWI, 1996)

	1989	1990	1991	1992	1993	1994
SO_2 (in kt)						
former Federal Territory	334	295	316	313	312	323
'neue Länder'	4115	2514	2159	1877	1655	1553
total	4449	2809	2475	2190	1967	1876
NO_x (in kt)						
former Federal Territory	484	335	352	316	315	326
' neue Länder'	299	252	216	196	173	162
total	783	587	568	512	488	488
Particles (in kt)						
former Federal Territory	23	23	24	24	24	25
' neue Länder'	1138	454	293	179	158	148
total	1161	477	317	203	182	173
CO_2 (in Mt)						
former Federal Territory	247	255	267	259	256	259
'neue Länder'	156	143	122	110	99	93
total	403	398	389	369	355	352

8.3 The modelling approach for fossil electricity generation

While the current ExternE approach is focused on the detailed bottom-up analysis of a single power station at a specific site, this procedure is not appropriate to derive results on a more aggregated level, e. g. to calculate externalities from a country's power sector. The detailed analysis of each individual emission source within the power sector is prohibitive time consuming, and in addition this approach does not take into account potential non-linearities in chemical conversion processes in the atmosphere as well as in impact mechanisms which might be of importance as soon as significant changes in emission levels are analysed. In order to maintain the advantages and benefits from a detailed bottom-up modelling within an operational aggregation procedure, the EcoSense model that has been used as the standard tool for analysing external costs from single point sources is currently extended towards a so called multi-source version.

As a first step prior to air quality modelling and impact assessment, the multi-source version of EcoSense supports the definition of any European wide emission scenario by using a link to the CORINAIR database. In a subsequent analysis, differences in concentration levels and environmental impacts between different scenarios can be evaluated within the system.

The CORINAIR database provides emission data for a wide range of pollutants according to both a sectoral (SNAP categories; SNAP: 'Selected Nomenclature for Air Pollution') and geographic (NUTS categories; NUTS: Nomenclature of Territorial Units for Statistics') dissaggregation scheme (Table 8.11). A transformation module implemented in EcoSense supports the transformation of emission data between the NUTS administrative units (country, state, municipality) and the grid system required for air quality modelling (EUROGRID or EMEP), see Figure 8.2.

Based on this functionality, a user can change emissions from a selected industry sector within a specific administrative unit, create a new gridded European-wide emission scenario taking into account the previously specified modifications, and compare environmental impacts and resulting external costs between different scenarios. Following this approach, we have used the CORINAIR 1990 emission data as reference scenario, and created an additional scenario by setting emissions from the German 'public power and cogeneration plants' (SNAP category 0101) to zero.

The implementation of the approach described depends on the availability of CORINAIR emission data, which is currently available for 1990 (data for 1994 are expected to be published at the end of this year). Due to the major changes in the electricity industry in particular in the German 'neue Länder' within the last years, results derived from 1990 data do not very well reflect current conditions. Expected changes in the results due to the use of more up to date data are discussed in a qualitative way in the following sections.

CORINAIR 1990 does not provide data on particulate emissions. For the present analysis, particulate emissions from the power sector were taken from other sources (see below). As particulates are considered as non-reactive pollutants, there are no problems arising from this procedure.

Table 8.11 CORINAIR sectoral and geographical dissaggregation scheme (examples)

SNAP Categories		NUTS Categories	
01	**Public power, cogeneration**	**R**	**EUR 15**
01 01 01	Combustion plants >= 300 MW	**R1**	**Germany**
01 01 04	Gas turbines	R18	Baden-Württemberg
03	**Industrial combustions**	R181	Stuttgart
04	**Production processes**	**R2**	**France**
04 01 01	Petroleum products processing	R21	Ile de France
04 03 01	Aluminium production	**R5**	**Belgium**
05	**Extraction/Distribution of fossil fuels**	R5300	Brussels
07	**Road transport**		
11	**Nature**		
11 08	Volcanoes		

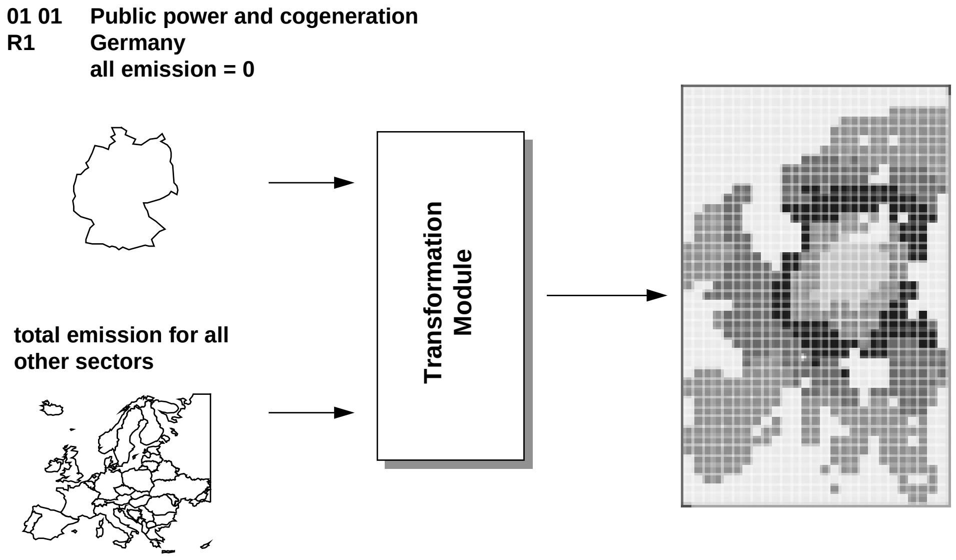


Figure 8.2 Generation of emission scenarios

8.4 Electricity generation from fossil fuels

8.4.1 Impacts from SO_2, NO_x and PM_{10} on health, crops and materials

Emissions from SO_2, NO_x, and particulates from the German 'public power and cogeneration' sector (SNAP 01 01) as reported in CORINAIR 1990 are presented in Table 8.12. The spatial distribution of emissions is shown in Figure 8.3. Emissions in the 'neue Länder' are very high compared to the emissions in the western part of Germany. As discussed below, this specific pattern of emission sources has an important impact on the resulting external costs.

Although the CORINAIR emissions data do not correspond exactly to data reported by national statistics (see Table 8.10), they are in a similar order of magnitude. As damage costs are calculated as costs per tonne of pollutant emitted, these differences between data sources do not effect the results.

Table 8.12 Emissions from the German public power and cogeneration plants (in kt)

	SO_2 $^{1)}$	NO_x $^{1)}$	Particles $^{2)}$
Germany	2232	411	477

$^{1)}$ (EMEP/CORINAIR, 1996); $^{2)}$ (BMWI, 1996);

To estimate the external costs caused by the German power sector, we have used the CORINAIR 1990 emission inventory as the reference baseline scenario. Following the procedure described in section 8.3, we have generated two additional scenarios by substracting the emissions from the German power sector from the baseline emission scenario, so that results should be interpreted as avoided damage costs due to emission reduction. Figure 8.4 show examples of the change in concentration levels and the spatial distribution of impacts. Damage costs resulting from the operation of fossil fired public power and cogeneration plants in Germany in 1990 are presented in Table 8.13, while Table 8.14 shows aggregated damage costs per tonne of pollutant emitted.

For the purpose of comparison, Table 8.14 includes results that have been calculated before for the Lauffen coal fired power station. While the damage costs per tonne of PM_{10} are similar, the damage costs per tonne of SO_2, and in particular per tonne of NO_x differ considerably. As discussed below, theses differences are explained by the spatial variations in SO_2, NO_x and NH_3 emissions, which strongly influence the formation of sulfate and nitrate aerosols.

The drastical reduction of emissions in the 'neue Länder' that we have observed since 1990 at the same time leads to a decrease of the annual environmental damage costs. However, emission reduction in the power sector leads to a decrease also of the SO_2 to NH_3 and NO_x to NH_3 ratios, which are expected to result in an increase of specific damage costs per tonne of pollutant emitted

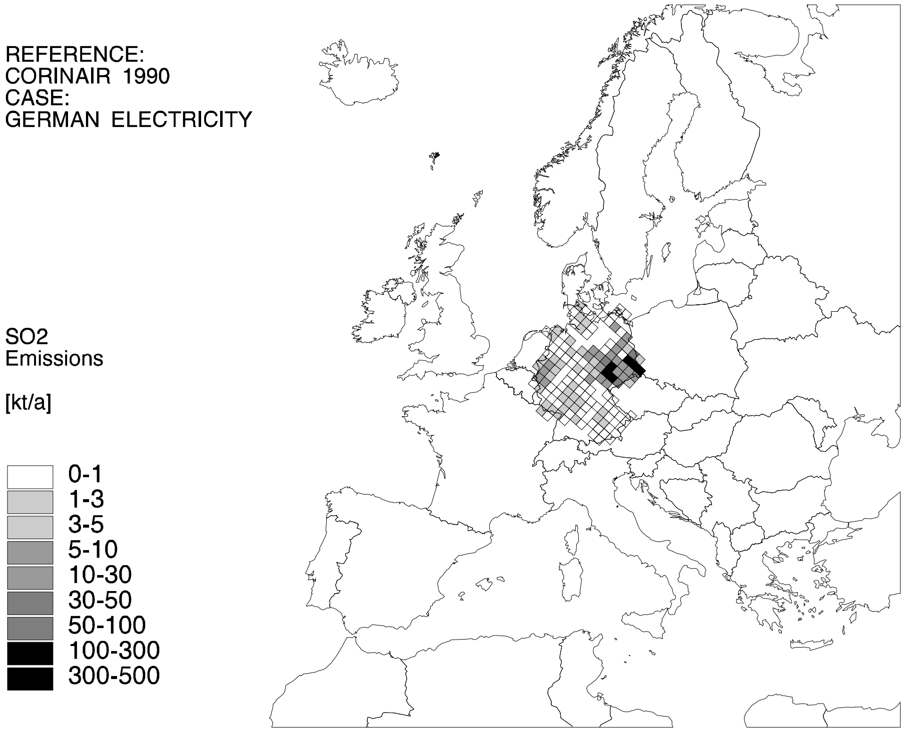


Figure 8.3 SO$_2$ emissions from the German public power sector

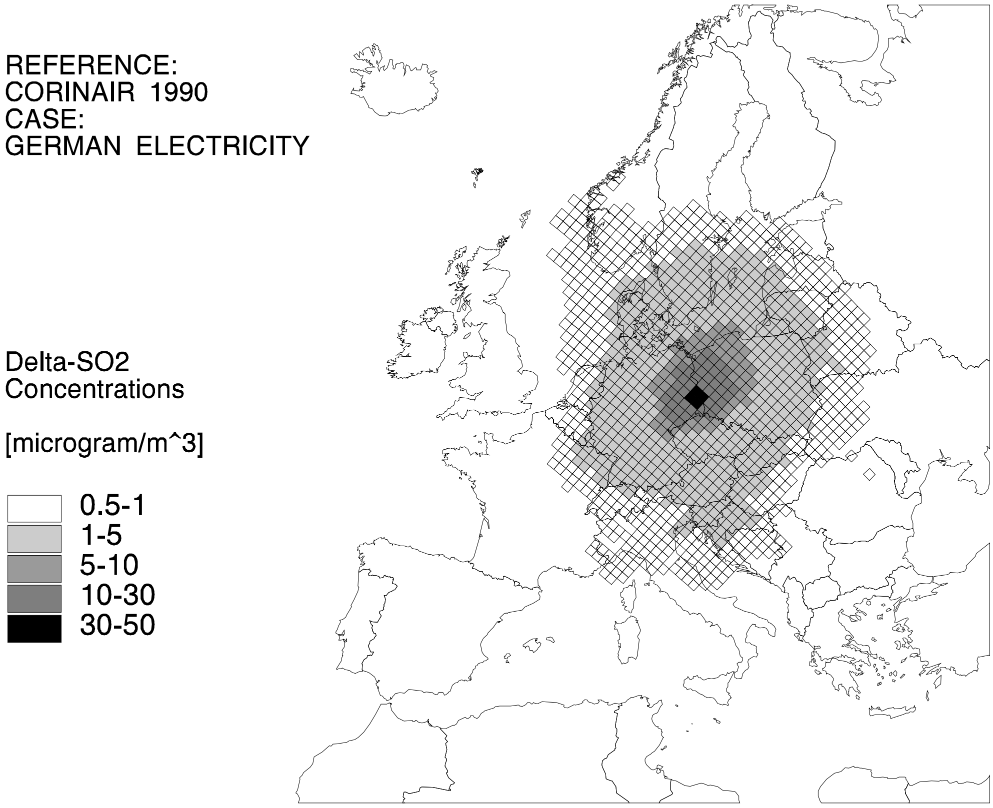


Figure 8.4 Increment on SO$_2$ concentration due to German public power sector

Table 8.13 Damage costs in Mill. ECU from fossil fired public power and cogeneration plants in Germany in 1990 (Emission data from CORINAIR 1990)

	Mill. ECU/a
SO_2, NO_x , PM_{10}	
Health effects	
mortality [1)]	28027
morbidity	2987
Crops	247
Materials	509
Ozone impacts (aggregated)	617
Global warming	
low	1512
mid 3 %	7164
mid 1 %	18308
high	55322

[1)] Valuation of mortality is based on the YOLL-approach, 0% discounting.

.Table 8.14 **Damage costs per tonne of pollutant emitted (excluding ozone damage)**

	SO_2		NO_x		PM_{10}	
	Change in annual emissions (in kt)	Damage costs per tonne SO_2 (ECU/t)	Change in annual emissions (in kt)	Damage costs per tonne NO_x (ECU/t)	Change in annual emissions (in kt)	Damage costs per tonne PM_{10} (ECU/t)
Germany	- 2232	9732	- 411	4214	- 477	18655
Lauffen plant	+ 2.2	13676	+ 2.2	15684	0.55	23857

Discussion of results

For the present analysis we have estimated environmental damage costs resulting from *non-marginal* changes in emission levels. One of the issues of concern when using results derived in this study within a different context is the potential non-linearity within impact pathways. As most of the exposure-response functions are assumed to be linear, the most sensitive and potentially non-linear mechanism is the formation of sulfate and nitrate aerosols, which dominate external costs from fossil fuels due to impacts on human health.

In the chemical model (as for example described in (Sandnes, 1993)) one assumes that SO_2 reacts quickly and irreversibly with NH_3 to form ammonium sulphate which is a mixture of $(NH_4)_2SO_4$ and NH_4HSO_4. Thus ammonia is eliminated in regions with high SO_2 background emissions. The remaining NH_3 concentration has influence on the formation of ammonium nitrate. To illustrate the geographical variation in SO_2 and NH_3 emissions in Germany, Figure 8.5 shows emissions in the EUROGRID gridcells covering Germany ordered by descending SO_2 background emissions. The 'SO_2 background' summarises the SO_2 emissions from all sources except power and cogeneration plants. SO_2 emissions show a strong spatial variation over two orders of magnitudes, whereas the NH_3 emissions show much smaller variations. The dotted line indicates the maximal amount of SO_2 in the grid cell that can react with NH_3 to form ammonium sulphate ignoring the influence of the neighbour cells.

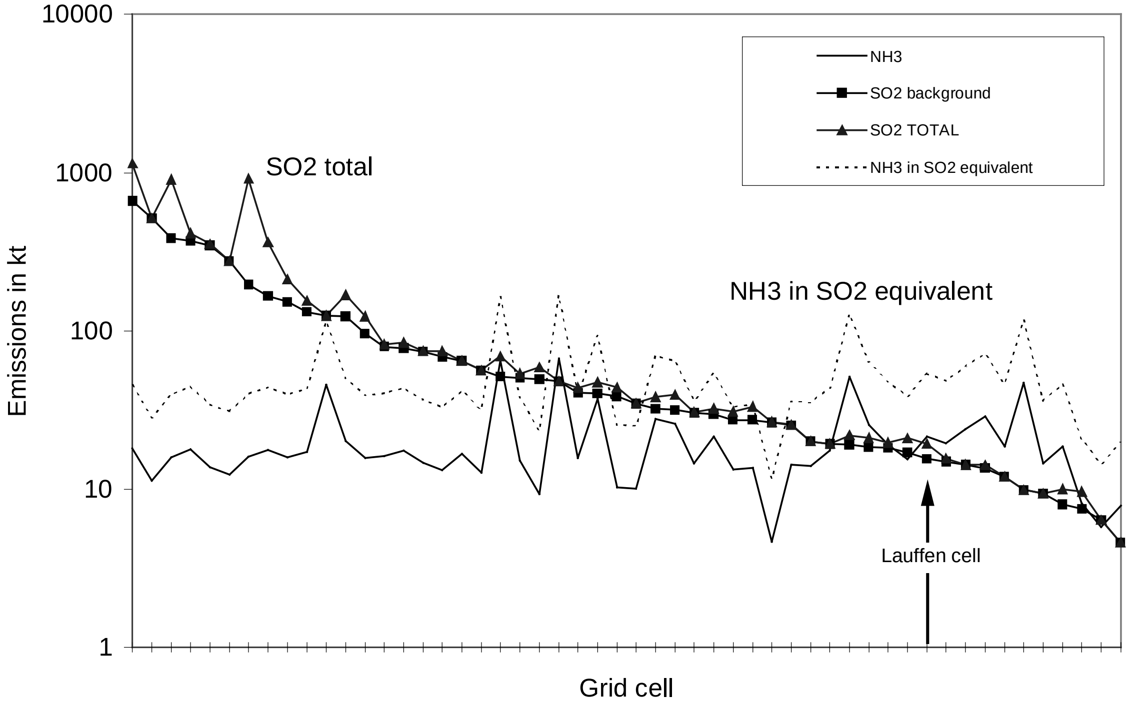


Figure 8.5 Geographical variation in SO_2 and NH_3 emissions in Germany

Neglecting pollutant transport across gridcell borders, additional ammonium sulphate formation can occur in those cells in which the SO_2 emissions stay below this limit (right side in Figure 8.5). In cells with SO_2 emissions significantly exceeding the dotted line (left side in Figure 8.5) only very limited ammonium formation is expected as the local NH_3 is already consumed. The site of the Lauffen reference plant is located in a gridcell with relatively low SO_2 background emissions and enough NH_3 available for additional ammonium sulphate reactions leading to damage costs per tonne of SO_2 emitted above the average.

Because of the exchange of pollutants between gridcells the reality is obviously much more complex. Nebertheless, the simplified explanation given here qualitatively described the mechanism of action, and thus helps to understand the results derived from the model application.

8.4.2 Impacts from ozone

In the abscence of detailed own ozone modelling, we use the damage costs per ton of precursor for average emissions in Europe (1500 ECU/t NO_2) estimated by (Rabl and Eyre, 1997) to give a first estimate of ozone impacts on human health and crops due to increased level of NO_x emissions. Resulting damage costs from the German electricity sector in 1990 are presented in Table 8.13.

8.4.3 Global warming

Global warming damage costs are estimated by using marginal damage values of 3.8, 18, 46 and 139 ECU(1995)/t CO_2 as recommended by the ExternE Task Group on Global Warming. The resulting damage costs for the German electricity sector in 1990 are presented in Table 8.13.

8.4.4 Occupational health impacts

The assessment of damage costs resulting from occupational health impacts is based on results derived from detailed calculation for specific reference plants for each fuel type (see (CEC, 1995c), (CEC, 1995d), (Krewitt et al., 1995)). As fuel extraction and fuel transport is the main source of occuptional health impacts for the fossil fuel cycles, impacts do strongly depend on the fuel requirement, and thus on the thermal efficiency of the power station. As the reference power stations analysed in the fuel cycle studies mentioned above do not necessarily represent average technologies of the national power sector, results are adjusted by taking into account the national average thermal efficiency of electricity generation for each fuel type (Table 8.15).

Table 8.15 Damage costs from occupational health effects due to electricity generation in Germany

		Reference plant	$\frac{\eta_{ref.plant}}{\eta_{average}}$	Power sector	
		mECU/kWh		mECU/kWh	Mill. ECU/year
Coal	mortality	0.68	43.0/40.3	0.73	104.0
	morbidity	0.61		0.65	92.6
Lignite	mortality	0.062	36.2/33.8	0.066	11.1
	morbidity	0.066		0.07	11.8
Oil	mortality	0.37	31.1/44.6	0.26	3.4
	morbidity	0.13		0.09	1.2
Natural Gas	mortality	0.068	33.2/30.9	0.073	2.9
	morbidity	0.062		0.066	2.6
Total	mortality				121.4
	morbidity				108.2

8.4.5 External costs per unit electricity

Although our interest was focused on the calculation of aggregated damage costs per unit pollutant emitted to be used in various types of energy and environmental policy analysis, we can also convert our results into costs per unit electricity generation. Unfortunately, the CORINAIR SNAP 01 01 category includes cogeneration plants, so that damage costs have to be allocated to either heat or electricity production. In 1990, the elctricity generation from fossil fuels was 363.5 TWh ($1.3 \cdot 10^{18}$ J), while heat production amounted to $1.9 \cdot 10^{17}$ J. Following the ExternE approach of allocating environemntal damage between heat and electricity according to the exergy content of the products (Krewitt et al., 1996), and assuming an exergy to enthalpie ratio of 0.174 for the heat output as calculated for a German reference CHP plant, 97.5 % of the total damage costs should be allocated to electricity generation.

Taking into account the overall uncertainties of the impact assessment procedure, for simplicity reasons we allocate the full damage costs to electricity generation only. The resulting external costs in terms of mECU/kWh are presented in Table 8.16.

Table 8.16 Damage costs in mECU/kWh from fossil fired public power and cogeneration plants in Germany in 1990

	Germany	
	former Federal Territory	'neue Länder'
SO_2, NO_x , PM_{10}		
Health effects		
mortality	15.5	320.2
morbidity	1.6	33.5
Crops	0.12	3.0
Materials	0.25	6.1
Ozone impacts (aggregated)	1.9	4.0
Global warming	3.6 - 131	5.8 - 212
Occupational health effects	0.6	0.6
Sub-Total	23.6 - 151	373 - 579

8.5 Electricity generation from nuclear energy

It has been shown in various ExternE case studies that the external costs resulting from the nuclear fuel cycle are dominated by the process steps uranium mining and milling, power plant generation and reprocessing. Assuming an 'open' fuel cycle (conditioning and storage of waste without reprocessing) we don't have to consider emissions from the reprocessing plant. The recycling of uranium and plutonium would of course increase emissions from reprocessing, but at the same time reduce the demand of uranium ore and thus emissions from mining and milling. A comparison of effects from mining and milling and reprocessing has shown that the increase in emissions from reprocessing is comparable to the decrease of emissions from mining and milling, so that our working assumption of an open fuel cycle with a given fuel demand expressed as equivalent of natural uranium is reasonable. Following this approach, the present analysis is focused only on the mining and milling and power generation stages of the fuel cycle.

Uranium mining and milling

For Germany, the fuel requirement expressed as equivalent of natural uranium was 3333 t in 1990 (Michaelis and Salander, 1995). We assume an 'open' fuel cycle, i. e. no recycling of uranium and plutonium, leading to a U_3O_8 requirement of 3933 tonnes. Taking into account the electricity generation from German nuclear power plants in 1990 (see **Table 8.9**), the specific demand of uraniumoxide results in 25.8 t U_3O_8/TWh.

Like in the ExternE German Implementation Study, we use Rabbit Lake in Canada as a reference mine, assuming that all uranium required is produced from this specific mine. The relevant emission data taken from UNSCEAR are shown in Table 8.17. Using the conversion factor of 0,015 manSv per TBq release of Radon-222 as reported by UNSCEAR, the collective dose resulting from uranium mining and milling is 16.5 manSv/TWh, which is mainly caused by the release of Radon from abandoned tailing piles assumed to continue over 10 000 years. Physical impacts are quantified using the risk factors from ICRP 60 (ICRP, 1991). Because of the time horizon considered, the discounted present value of the damage is rather small, while the undiscounted damage from the uranium mining and milling stage dominates the total external costs of the fuel cycle.

Table 8.17 Radon-222 emissions from the uranium reference mine (UNSCEAR, 1993)

Mine	
Annual production of U_3O_8	2011 t
Annual emissions of Rn-222	1600 TBq
Mill	
Annual production of U_3O_8	1900 t
Annual emissions of Rn-222	9200 GBq
Uranium mill tailings	
Tailings generation	1 ha/GWa
Operation	
Emission rate	3.7 Bq/m^2/s
Release duration	5 a
Abandoned mill tailings	
Emission rate	3 Bq/m^2/s
Release duration	10 000 a

Power generation - routine operation

The release of radioactive nuclides from German nuclear power plants in 1990 is shown in Table 8.18 (BMU, 1992). The resulting collective dose is estimated by using a set of ‘collective dose per unit release’ conversion factors reported by UNSCEAR. The physical impacts are quantified using the ICRP 60 risk factors. The main fraction of damage results from a global and long-term (10 000 years) exposure to Tritium and Carbon-14, i. e. from the cumulated exposure of a large population to a very small dose.

Table 8.18 Radioactive release in TBq from German nuclear power plants in 1990

Noble gases	Tritium	Carbon-14	Iodines	Aerosols
433.5	10.2	3.2	0.0054	0.00089

Power generation - major accidents

Data on accidental release rates and related frequency of occurrence is not available for the various reactor types operated in Germany. To give a first indication of aggregated external costs from major nuclear power plant accidents, we use results from a detailed accident consequence assessment for the Biblis B power plant, which is the only German nuclear power plant for which release terms for different accident scenarios were quantified. Accident consequences were calculated using the COSYMA programme (Krewitt, 1996). As the expected value of damage from major accidents is small compared to external costs from routine operation, the use of the Biblis B results as an 'average' is not expected to distort the overall results, although we recognise that the consequences from reactor accidents might differ significantly between reactor types.

Impacts from 'classical' pollutants

Although the emissions of 'classical' pollutants (SO_2, No_x, PM, CO_2) so far have not been considered as a priority burden of the nuclear fuel cycle within ExternE, impacts from these pollutants do outweigh the effects from radioactive emissions if a positive discount rate is applied, so that they should not be neglected. Generic emission factors derived from a full Life Cycle Analysis of a German nuclear power plant are shown in Table 8.19. Resulting damage costs are estimated by multiplying these emission factors with the damage costs per tonne of pollutant calculated for fossil fuels.

Table 8.19 Emission of 'classical' pollutants from the nuclear life cycle in g/MWh (Wiese et al., 1995)

SO_2	NO_x	Particles	CO_2
32	70	7	19 700

Occupational health effects

For occupational health effects, we use the damage costs of 0.046 mECU/kWh calculated in the German National Implementation case study.

External costs per unit electricity

The 'average' external costs from nuclear electricity generation in Germany in the year 1990 are summarised in Table 8.20 by impact category and fuel cycle stage. Taking into account the electricity production from nuclear fuels of 152.5 TWh, the total damage costs amount to 716.8 Mill. ECU in the case of 0 % discounting, and 125.1 Mill. ECU for 3 % discounting in the year 1990.

For all the effects caused by an increased level of exposure to radiation, the main fraction of damage results from a global and long-term (10 000 years) exposure to extremely long-living nuclides, i. e. from the cumulated exposure of a large population to a very small dose. Problems arising from the application of the ICRP risk factors which have been established for the field of radiation protection within this context have been discussed several times elsewhere within ExternE.

Table 8.20 External costs from nuclear electricity generation in Germany in mECU/kWh

	Discountrate = 0 %	Discountrate = 3 %
Uranium mining and milling	2.9	0.0086
Power generation		
routine operation	0.32	0.00094
major accidents	0.012	0.0018
Effects from ‘classical’ pollutants		
SO_2	0.31	0.27
NO_x	0.29	0.26
Particles	0.13	0.11
CO_2	0.73	0.12
Occupational health effects	0.046	0.046
Sub-total	4.7	0.82

8.6 Electricity generation from renewable energy sources

The main source of electricity from renewable energy in Germany are small scale run-of-river plants, which in 1990 have produced 19.7 TWh or 3.6 % of the total electricity. In the ExternE National Implementation Project we have not analysed the hydro fuel cycle, but results from other countries suggest that externalities are close to zero. External costs from the wind and PV fuel cycles in Germany were estimated by (Raptis et al., 1995), resulting in costs of < 0.56 mECU/kWh for wind and < 5.3 mECU/kWh for photovoltaic. Taking into account the current low contribution of renewable energy sources to the total electricity generation in Germany, and the relatively low external costs per kWh, we neglect external costs from renewable energy sources without distorting the overall results derived for the German electricity sector.

8.7 Sensitivity analysis on mortality valuation

Results reported in the above sections are calculated using the *Value of Life Year Lost* approach, and a 0 % discount rate. While the approach of putting a value on a life year lost seems to be theoretically the most consistent way for mortality valuation, in particular as it better takes into account the specific context of premature death than the VSL based valuation, to date there is only limited empirical evidence supporting this approach. Thus in Table 8.21 mortality damage costs from the German power sector are presented both for the *Value of Life Year Lost- (VLYL)* and the *Value of Statistical Life- (VSL)* valuation approach, taking into account different discount rates. As the VSL approach puts the full Value of Statistical Life to any ‘additional’ premature death regardless of the loss of life expectancy, damage from the ‘classical’ pollutants derived with the VSL approach are about a factor of 3 higher than those calculated by using the VLYL approach. As discussed above, long term effects from radiation become negligible in the case of positive discounting, so that the discounted damage costs from the nuclear fuel cycle are dominated by effects from the 'classical' pollutants emitted from the fuel cycle.

Table 8.21 Mortality damage costs in Mill. ECU from the German power sector in 1990, taking into account different valuation schemes

	Value of Life Year Lost (VLYL)		Value of Statistical Life (VSL)	
Discount rate	0 %	3 %	0 %	3 %
Germany				
Fossil fuels	28027	24118	92489	79588
Nuclear	590	86	998	281
others	n. q.	n. q.	n. q.	n. q.

8.8 Summary and Conclusions

Within the Aggregation Task of the current ExternE Project we have successfully demonstrated the applicability of the detailed bottom-up impact pathway approach to the whole electricity sector in Germany by using an extended *multi-source* version of the EcoSense software. One of the main findings concerning the aggregation methodology is that damage costs per tonne of pollutant emitted might differ significantly even within a country. The main reason for such differences is the spatial variation in SO_2, NO_x, and NH_3 emissions. The availability of free ammonia contributing to the formation of ammonium sulfate and ammonium nitrate, which in turn as secondary particles have a significant impact on human health, is an important parameter determining the damage costs resulting from power plant emissions. As ammonia is mainly emitted from agricultural activities, and the availability of free ammonia in the atmosphere also depends on the level of SO_2 and NO_x emissions from other sources, the damage costs we refer to as 'energy' externalities in fact strongly depend on emissions from various industrial activities.

In the absence of more up-to-date data, we have used the CORINAIR 1990 emission inventory for Europe as a starting point for air quality modelling. The main results from the detailed impact pathway analysis are average damage costs per tonne of pollutant for the German power sector. In contrast to the mECU/kWh figures reported so far in ExternE, the damage costs per tonne of pollutant do not depend on the fuel and thus are much more appropriate to address a wide range of energy policy issues.

In Germany, we have to take into account the specific situation in the former GDR ('neue Länder') with very high emissions from the power sector, leading to external costs which were much higher than the private costs of electricity generation in 1990. The damage costs from electricity generation in Germany excluding global warming are estimated to result in about $30 \cdot 10^9$ ECU, which is more than 1 % of the 1990 GDP. Estimates of global warming damage costs are very uncertain, they are estimated to be within a range of 1.5 to 55 billion ECU/a. While emissions from the power sector in the Former Federal Territory have been constant or slightly increasing over the last years, there was a drastical reduction of emissions in the 'neue Länder', leading to a reduction of the overall damage costs of about 25 % since 1990. As soon as data from CORINAIR 1990 are available, the results will be updated to reflect these changes. The quantified damage costs from nuclear power generation are relatively low compared to the fossil fuels. Although nuclear energy contributes to nearly 30 % of power production in 1990, the share of damage costs from nuclear electricity is only about 1.5 %.

9. POLICY CASE STUDIES

IER has applied the ExternE methodology together with ETSU in two policy oriented case studies on the assessment of benefits of an acidification strategy for the European Union, and on the costs and benefits of pollution abatement options for large combustion plants. The following sections summarise results from these case studies.

9.1 Benefits of an acidification strategy for the European Union

This case study applies the ExternE methodology to quantify the benefits of reducing emissions of SO_2, NO_x and NH_3 in line with a proposed acidification strategy for the European Union. Benefits are assessed in terms of reduced damage to human health, building materials and crops. This work complements a study being conducted at IIASA (Amann *et al*, 1996), which has assessed the costs of various scenarios designed to meet policy related goals for protection of ecosystems against air pollution effects.

9.1.1 Scope of the analysis

The starting point for the assessment is a study for DGXI by Amann *et al* (1996), the purpose of which is to investigate cost effective control of acidification and ground level ozone in Europe. Scenarios of emissions reduction for SO_2, NO_x and NH_3, meeting different levels of policy objective with respect to critical loads attainment have been developed and costed in this work. The study has investigated 9 scenarios covering emissions of SO_2, NO_x and NH_3 in the year 2010, of which the following 5 are of most interest:

Reference - emission levels permitted under current legislation and under agreed commission proposals, such as Auto-Oil. Emissions everywhere apart from Moldova and sea areas fall, compared to 1990 emissions.

45%, 50%, 55% GAP - emission levels successively reduced to close the ‘gap’ between 1990 critical loads exceedance and full protection. These scenarios are based on a least cost solution assuming that only EU Member States take action. The only exception is for 55% gap closure where emissions are also reduced in the Baltic Sea - otherwise 55% is unattainable. With the partial exception of this scenario it is assumed that all non-EU countries keep their emissions at the level of the reference scenario.

Maximum feasible reduction, realistic (MFR-real) - assumes full application of feasible technical abatement measures, and the extension of such application to all European countries.

Benefits due to avoided impacts on human health, crops and materials resulting from the implementation of these emission reduction strategies are quantified following the standard ExternE methodology. A preliminary version of the ‘multi-source’ EcoSense model was used to quantify impacts from complex European-wide emission scenarios following a detailed bottom-up approach.

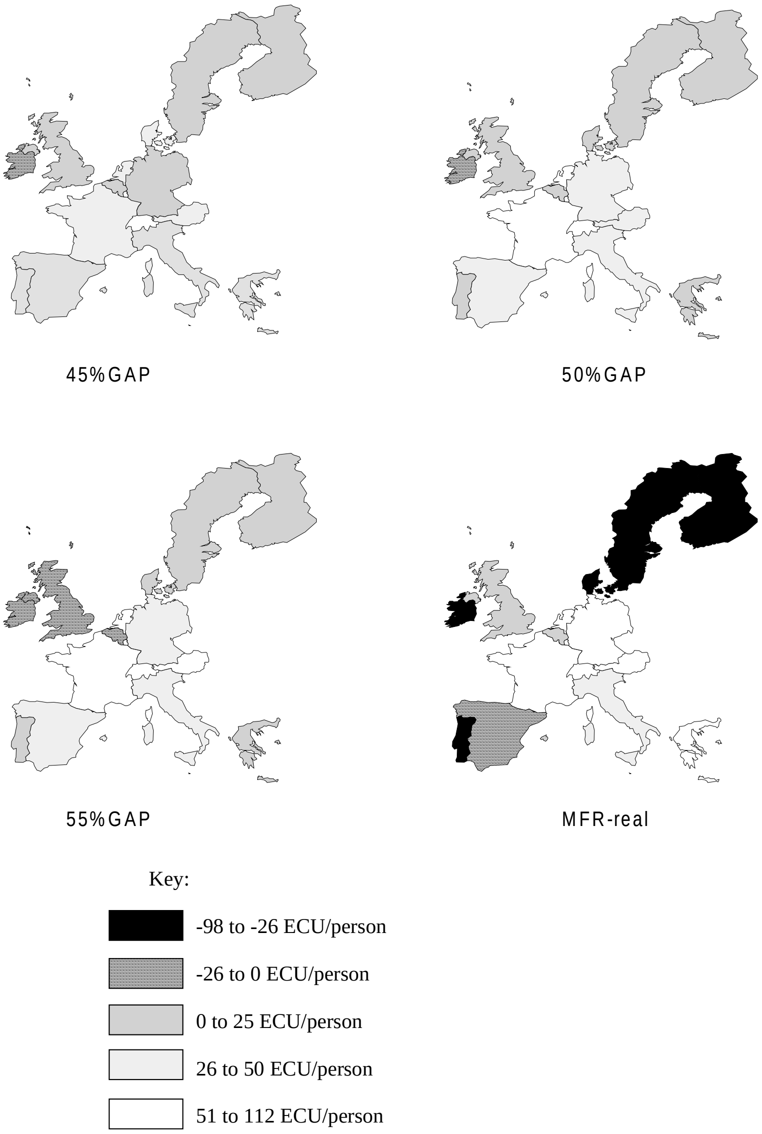
9.1.2 Results

Estimates of the annual total avoided damage costs (avoided in comparison to the reference scenario) are 16 000 Mill. ECU for the 45% gap-closure scenario, 24 000 Mill. ECU for the 50% gap-closure scenario, 31 000 Mill. ECU for the 55% gap-closure scenario, and 89 000 Mill. ECU for the maximum feasible reduction scenario. *(These results are based on the ‘old’ approach of valuing each ‘additional’ death with the full Value of Statistical Life, but only acute mortality was taken into account. Valuation of chronic mortality following the Value of Life Years Lost approach leads to very similar results).* The largest reductions in damages are found, not surprisingly, in the countries with the largest populations, France, Germany, Italy, Spain and the UK. Avoided damages also tend to be larger in central states because of the reduction in emissions in neighbouring areas. In contrast, for some countries on the fringes of the EU, most notably Finland, Greece, Ireland, and Portugal benefits are modest, reflecting less significant emission reductions in several of these countries, the distance of these countries from emission reductions made elsewhere, and, in the case of Ireland and Portugal their position in Europe with respect to the prevailing wind direction. Finland and Greece benefit particularly from the reduction in emissions under the Maximum Feasible Reduction scenario because of emission reductions in countries outside the EU. In both countries estimated benefits increase by a factor in excess of 10 between the 55%GAP and MFR-real scenarios.

9.1.3 Comparison of costs and quantified benefits

An overall comparison of costs and benefits indicates that estimated benefits of moving from the REFERENCE scenario to scenarios implementing more stringent abatement measures, substantially exceed costs at the European level. However, there appears to be no additional net benefit of moving from the 55%GAP scenario to MFR-real. Our assessment predicts net benefits of 18 ECU billion for both. However, the level of ecosystem protection increases from 55%GAP to MFR-real, leading to greater, but unmonetised, ecosystem benefits. In addition, extension of emissions reduction to eastern European countries will lead to a disproportionate increase in benefits outside of the assessment area, particularly in view of the predominant south-westerly winds in Europe.

Figure 9.6 shows that under some scenarios some countries are predicted to experience a net cost (negative net per capita benefit). Only for Ireland is this predicted under all scenarios. Countries identified as showing a net loss tend to be on the fringes of Europe.


45%GAP

50%GAP

55%GAP

MFR-real

Figure 9.6 Net per-capita benefits in each EU Member State for each scenario

9.1.4 Conclusions

This case study demonstrates that the ExternE methodology and the multi-source EcoSense model can be applied to provide sophisticated and detailed analysis of pan-European emission scenarios, in addition to assessment of individual plant, upon which previous work in the ExternE Project has concentrated. Effects of primary and secondary pollutants arising from emissions of SO_2, NO_x and NH_3 have been quantified for health, materials and crops. A major advantage of this approach is that it is able to take account of geographical variation in damages with respect to the source of emissions and the location of damage receptors.

9.2 Cost-Benefit Analysis of Pollution Abatement Options for Large Combustion Plants

9.2.1 Scope of the analysis

This case study applies ExternE Project results for pollution damage assessment using impact pathway analysis to consider the costs and benefits of measures to reduce the emission of air pollutants from large combustion plant. The starting point for the cost assessment is the report by ERM (1996), produced for DGXI of the European Commission. This provides a cost analysis of various measures for SO_2, NO_x and particle reduction, and recommends a number of options as Best Available Technology.

Damage costs per tonne of pollutant emitted are calculated for a German and UK reference site (Lauffen and West Burton) following the standard ExternE approach by using the EcoSense model. Estimates of external costs include impacts on human health, crops, and materials.

9.2.2 Cost-benefit analysis

The analysis is concerned with the control of emissions of SO_2, NO_x and primary TSP. Costs and benefits can be grouped as 5 types;

1. Private costs for construction, operation and maintenance of emissions abatement plant.
2. External benefits arising from a reduction in emissions of air pollution.
3. External costs arising from transfer of pollutants from flue gas to land and water.
4. External costs from construction, maintenance and operation of emissions abatement plant, and from the supply of operational materials (e.g. limestone, ammonia, bag filters).
5. External costs associated with reduced efficiency of a facility, due to energy demand of emissions abatement technologies.

In order for an abatement technology to be considered worthwhile it is necessary for benefits to exceed costs. Comparison of the private costs with the estimated damage costs per tonne of pollutant emitted suggests that the abatement measures reviewed by ERM (1996) are justified for both UK and German plant. However, the externality estimates are subject to significant uncertainty. To take into account these uncertainties, we rank the results for each impact of the three pollutants in terms of the confidence attached to each (see e.g. Figure 9.7). For the German plant, current best available emissions control techniques as defined in ERM (1996) is justified without reference to mortality effects. In fact for SO_2 it is only effects on materials and crops that need to be included before the lower end of the range of private costs is passed. For the UK plant, where overall damages are lower because of the location of the power plant site close to the North Sea, the combined effect of damage to materials and crops (where appropriate) and acute morbidity are sufficient to take results for all three pollutants past the lower end of the range for the private costs of abatement, and also past the upper end of the range for particulates.

9.2.3 Conclusions

The conclusion of this case study is that current best available emission control techniques for SO_2, NO_x and particulates from Large Combustion Plant are justified. In many cases this can be justified without consideration of mortality effects. No assessment has been possible on the exact level of abatement that can be justified on the basis of our analysis. Costs inevitably rise as any technology is pushed to a higher level of abatement. The source of data used for private costs of emissions abatement (ERM, 1996) provides no insight on this issue.

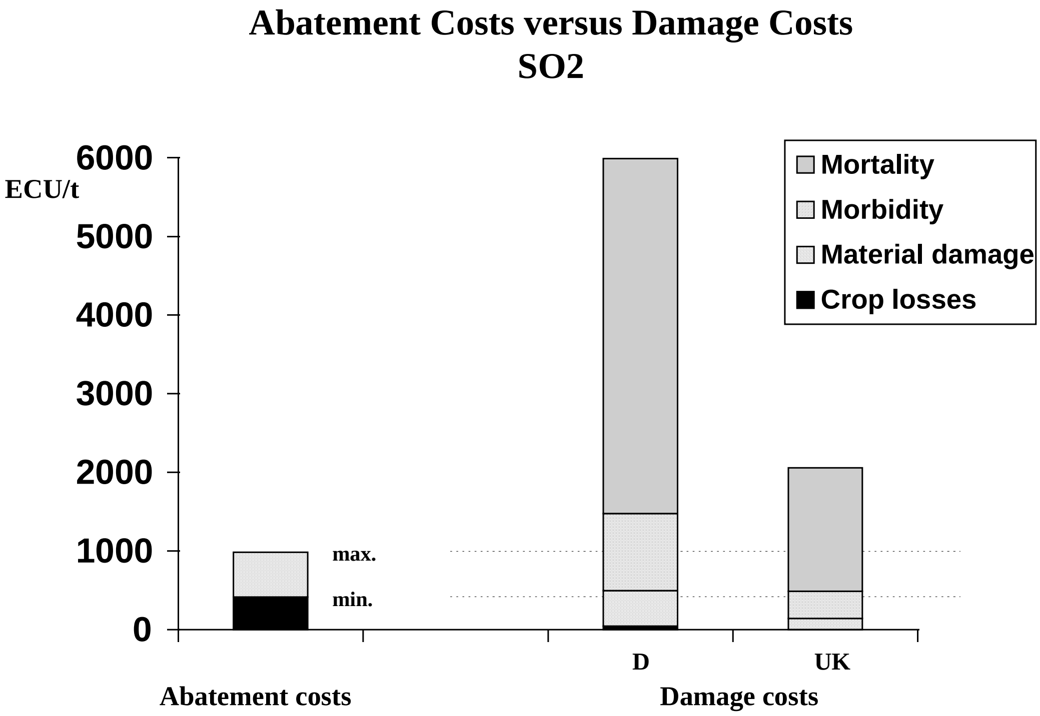


Figure 9.7 Comparison of abatement costs and damage costs per tonne of SO_2 emitted from a coal fired power plant in Germany and the UK

10. CONCLUSIONS

Germany has been among those countries that started their National Implementation Project within the second phase of ExternE already, and continued work in ExternE phase 3, so that the German team had the opportunity to follow methodological discussions and developments and the process of standardisation over a long time. During the first phase of the German Implementation project, activities were focused on the detailed analysis of reference fuel cycles, including coal, lignite, oil, natural gas, nuclear, wind and photovoltaic, and on the identification of specific issues related to the evaluation of externalities in a German contexts.

While results from this phase of the project were presented in a detailed report, the present report summarises again the approach and provides an update of results. The major methodological developments since ExternE phase 2 are related to the quantification and valuation of mortality. As there is a growing evidence of 'chronic' mortality impacts from long term exposure to fine particles, this endpoint is included now in our estimates. However, we have learned that the effect of concern is the reduction of life expectancy rather than 'additional' deaths which we tried to measure before. To take into account this better understanding of the actual impact, for monetary valuation we now apply the concept of *Value of Life Years Lost* (instead of the *Value of Statistical Life*) that was developed within the ExternE-Core group. By incidence, the valuation of years of life lost leads to results that are very similar to the 'old' approach of valuing cases of acute mortality only with the Value of Statistical Life.

In the second Phase of the German Implementation study, the list of fuel cycles covered was completed by estimating external costs from combined heat and power production from biomass. These results, together with the updated results of the other fuel cycles, provide a comprehensive set of external cost data for a wide range of technologies operated in Germany. External cost estimates are calculated following a standardised methodology that is widely accepted now on the international level, and similar data sets are produced in all member states of the European Union. Although there are significant remaining uncertainties in some areas, our results indicate that external costs of some fuel cycles are high enough to affect energy policy decisions.

Besides of analysing external costs from the biomass fuel cycle, the work in the second phase of the German Implementation project was focused on the development of the EcoSense software, and on the application of the ExternE methodology in a more policy oriented context.

EcoSense Version 2.0 was successfully used by teams in all EU countries. The use of a common database and a set of standardised air quality and impact assessment models has very much simplified the assessment of external costs resulting from airborne pollutants and supported the generation of comparable external cost data in all EU countries.

Although the detailed bottom-up impact pathway analysis which attempts to calculate external costs from a single power plant with a specific technology at a specific sites corresponds to the requirements of economic theory, we have learned that decision makers often need information on a more aggregated level to be used in a more general type of policy analysis. To address these needs, we have used a preliminary ‘multi-source’ version of the EcoSense model to calculate aggregated damage costs from the German power sector, and to estimate environmental benefits resulting from the implementation of European emission reduction strategies. The possibility of carrying out a type of cost-benefit analysis for environmental policy measures is certainly a promising field of application for the ExternE methodology, and first results created an increasing interest of policy makers.

Although further research is required to reduce the existing uncertainties, this report provides a comprehensive analysis of environmental impacts and resulting external costs from electricity generation in Germany, and we believe that results give helpful support to the integration of environmental aspects into energy policy.

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APPENDICES

8 DEFINITION OF THE COAL FUEL CYCLE, DATA AND RESULTS

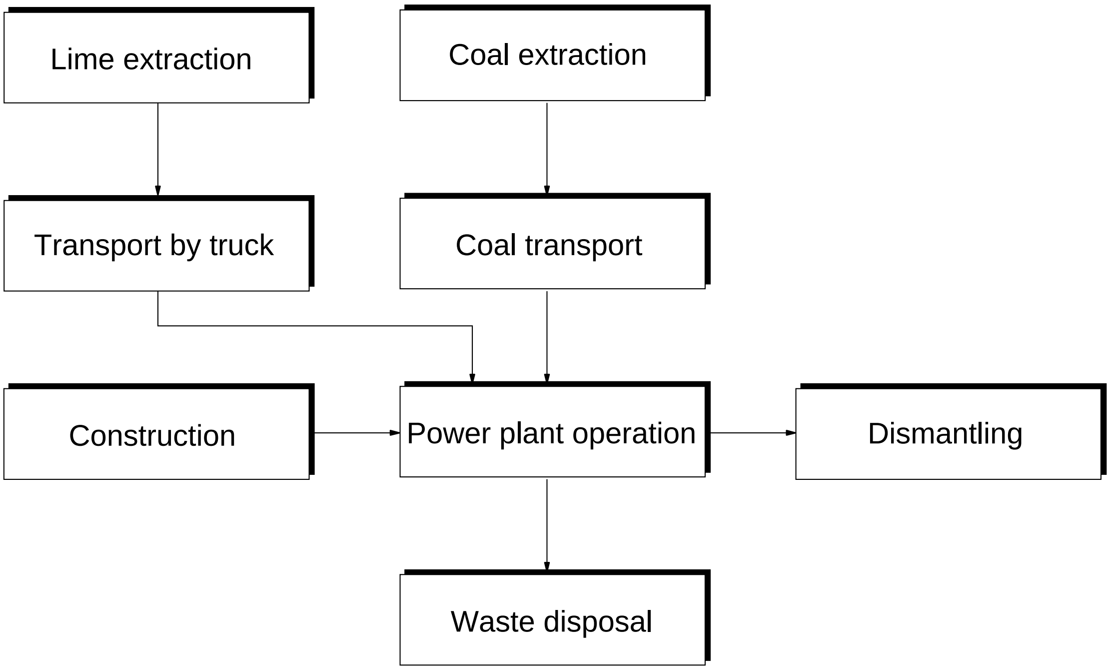

Figure 8.1 Process steps of the German coal fuel cycle

Table 8.1 Definition of the coal fuel cycle

Stage	Parameter	Value	Source
1. Coal mining			
	Location	Ruhrgebiet & Saarland, Germany	European Commission (1995)
	Type of mine	Underground	
	Calorific value of coal	29.2 MJ/kg	Wehovsky *et al.* (1994)
	Mine air quality control	not specified	
	Control of mine methane emissions	not specified	
	Mine waste disposal site	not specified	
	Composition of coal		
	Water	not specified	
	Ashes	7.0%	Wehovsky *et al.* (1994)
	Carbon	74.3%	Wehovsky *et al.* (1994)
	Oxygen	3–9%	European Commission (1995)
	Sulphur	0.9%	Wehovsky *et al.* (1994)
	Hydrogen	4.5–5.6%	European Commission (1995)
	Chlorine	0.05–0.3%	European Commission (1995)
	Nitrogen	0.8–2.0%	European Commission (1995)
2. Coal transport			
	Distance to power station	300 km	FDE (1996)
	Mode of transport	33% railway, 66% barge	European Commission (1995)
	Number of trainloads	not specified	
3. Coal cleaning		not specified	
4. Limestone extraction		not specified	
5. Limestone transport			
	Distance to power station	200 km (return voyage)	European Commission (1995)
	Mode of transport	Road	European Commission (1995)

Stage	Parameter	Value	Source
6. Power generation			
	Fuel	Coal	
	Type of plant	Pulverised coal	
	Location	Lauffen, Germany	
	Installed power	652.2 MW	Wehovsky *et al.* (1994)
	Efficiency	43.0 %	Wehovsky *et al.* (1994)
	Full load hours	6500	
	Lifetime	35 years	Wehovsky *et al.* (1994)
	Pollution control		Wehovsky *et al.* (1994)
	ESP	not specified	
	DENOX	not specified	
	FGD	not specified	
	recirculation of cooling water	nq	
	Stack parameters		
	height	240 m	
	diameter	10 m	
	flue gas volume	*1720738* Nm^3/h	Wehovsky *et al.* (1994)
	flue gas temperature	403 K	
	Material demands		
	coal	*1.1 Mt per year*	Wehovsky *et al.* (1994)
	limestone	77 t per year	
	cooling water	*7520 t per day*	Wehovsky *et al.* (1994)
	boiler feed water	*280 t per day*	Wehovsky *et al.* (1994)
	FGD water	*565 t per day*	Wehovsky *et al.* (1994)
7. Transmission			
	Length of new lines	0 km	
8. Transport of waste			
	Site	not specified	
	Distance to power station	200 km (return voyage)	European Commission (1995)
	Mode of transport	Road	European Commission (1995)
	Number of loads	not specified	
9. Waste disposal			
	Type of facility	Landfill	European Commission (1995)
10. Construction of power plant			

Stage	Parameter		Value	Source
	Material demands			Wehovsky *et al.* (1994)
		concrete, etc.	168 000 t	
		metals	48 000 t	

Table 8.2 Burdens of the coal fuel cycle

Stage	Burden	Quantity	Source of data	Impact assessed?
1. Coal mining	Occupational health			
	accidents - fatal	0.55 /Mt		✓
	accidents - major injury	27.5 /Mt		✓
	accidents - minor injury	211 /Mt		✓
	noise levels	nq		x - no data
	exposure to physical stress	nq		x - no data
	radon levels in mines	1.2 mSv/a		✓
	other mine air pollutants	dust: 4 mg/m^3		✓
	Air emissions			
	CO_2	31.1 kg/MWh	FDE (1996)	✓
	SO_2	35.1 g/MWh	FDE (1996)	✓
	NO_x	20.6 g/MWh	FDE (1996)	✓
	PM_{10}	2.9 g/MWh	FDE (1996)	✓
	CH_4	3268 g/MWh	DGMK (1992)	✓
	Other burdens			
	mine drainage	nq		x - negligible
	solid wastes- gypsum	nq		x - negligible
	subsidence	nq		x - negligible
	noise	nq		x - negligible
2. Coal transport	Occupational health			
	accidents - fatal	0.081 /Mt		✓
	accidents - major injury	0.50 /Mt		✓
	accidents - minor injury	16.3 /Mt		✓
	Public health			
	accidents - fatal	nq		✓
	accidents - injury	nq		✓
	Air emissions			
	CO_2	2.9 kg/MWh	FDE (1996)	✓
	SO_2	3.0 g/MWh	FDE (1996)	✓
	NO_x	23.8 g/MWh	FDE (1996)	✓
	PM_{10} - combustion	0.6 g/MWh	FDE (1996)	✓
	PM_{10} - fugitive dust	115 g/MWh	UBA (1989)	x - negligible
	Other burdens			
	noise	nq		x - negligible
	burden on infrastructure	nq		x - negligible
3. Coal cleaning	burdens included in other stages			
4. Limestone extraction	Occupational health			
	accidents - fatal	0.010 /Mt		✓
	accidents - major injury	0.21 /Mt		✓
	accidents - minor injury	5.6 /Mt		✓
	noise levels	nq		x - negligible
	exposure to physical stress	nq		x - negligible
	Air emissions			
	CO_2	nq		x - negligible
	SO_2	nq		x - negligible

Stage	Burden	Quantity	Source of data	Impact assessed?
	NO_x	nq		x - negligible
	PM_{10} - combustion	nq		x - negligible
	PM_{10} - fugitive dust	nq		x - negligible
	Emissions to water			
	suspended solids	nq		x - negligible
	Other burdens			
	noise	nq		x - negligible
5. Limestone transport	Occupational health			
	accidents - fatal	0.0049 /Mt		✓
	accidents - major injury	0.061 /Mt		✓
	accidents - minor injury	1.9 /Mt		✓
	Public health			
	accidents - fatal	nq		✓
	accidents - injury	nq		✓
	Air emissions	included in other stages		
	Noise	nq		x - negligible
	Burden on infrastructure	nq		x - negligible
6. Power generation	Occupational health			
	accidents - fatal	0.00073 /TWh		✓
	accidents - major injury	0.016 /TWh		✓
	accidents - minor injury	0.76 /TWh		✓
	noise levels	nq		x - negligible
	exposure to physical stress	nq		x - negligible
	Air emissions			
	CO_2	*781 kg/MWh*	Wehovsky *et al.* (1994)	✓
	SO_2	*288 g/MWh*	Wehovsky *et al.* (1994)	✓
	NO_x	*516 g/MWh*	Wehovsky *et al.* (1994)	✓
	PM_{10}	*57 g/MWh*	Wehovsky *et al.* (1994)	✓
	trace elements	nq		x - negligible
	evaporated water from cooling system	nq		x - negligible
	Noise emissions	nq		x - negligible
	Solid waste production			
	ashes	150 t/yr	Wehovsky *et al.* (1994)	x - negligible
	gypsum	nq		x - negligible
	Water abstraction			
	Emissions to water from.			
	cooling system	nq		x - negligible
	temperature of cooling water on return	nq		x - negligible
	chloride	nq		x - negligible
	FGD plant	nq		x - negligible

Stage	Burden	Quantity	Source of data	Impact assessed?
7. Transmission	No additional burdens			
8. Transport of waste	Occupational health			
	accidents - fatal	0.0056 /TWh		✓
	accidents - major injury	0.071 /TWh		✓
	accidents - minor injury	2.2 /TWh		✓
	Public health			
	accidents - fatal	nq		✓
	accidents - injury	nq		✓
	Air emissions	included in other stages		
	Noise	nq		x - negligible
	Burden on infrastructure	nq		x - negligible
10. Construction	Occupational health			
	accidents - fatal	0.0036 /TWh		✓
	accidents - major injury	0.11 /TWh		✓
	accidents - minor injury	4.2 /TWh		✓
	Air emissions from materials transport			
	CO2	nq		x - negligible
	SO2	nq		x - negligible
	NOx	nq		x - negligible
	PM_{10} - combustion	nq		x - negligible
	Noise	nq		
	Road use	nq		
11. Demolition	Occupational health			
	accidents - fatal	0.00017 /TWh		✓
	accidents - major injury	0.0041 /TWh		✓
	accidents - minor injury	0.15 /TWh		✓
	Noise	nq		x - negligible
	Road use	nq		x - negligible

Table 8.3 Impacts and damages of the coal fuel cycle

			Impacts		Damages		
Receptor	**ReceptorSubGroup**	**Impact**	**per TWh**	**Units**	**mECU/kWh**	**ECU/tpoll**	**s_g**
1. Coal mining							
Occupational accidents							
human	workers	occupational accidents	0.15	deaths		na	A
human	workers	occupational accidents	7.9	major injuries		na	A
human	workers	occupational accidents	60.6	minor injuries		na	A
Air Pollution Effects							
Impacts and damages assessed together with other upstream processes							
Global warming x CO_2, CH_4 and N_2O							
Damages assessed together with all other process steps							
2. Coal transport							
Occupational accidents							
human	workers	occupational accidents	0.023	deaths		na	A
human	workers	occupational accidents	0.14	major injuries		na	A
human	workers	occupational accidents	4.7	minor injuries		na	A
Public accidents							
human	total	public accidents	nq	deaths	nq	na	A
human	total	public accidents	nq	major injuries	nq	na	A
human	total	public accidents	nq	minor injuries	nq	na	A
Air Pollution Effects							
Impacts and damages assessed together with other upstream processes							
Global warming x CO_2, CH_4 and N_2O							
Damages assessed together with all other process steps							
4. Limestone extraction							
Occupational accidents							
human	workers	occupational accidents	0.0030	deaths		na	A
human	workers	occupational accidents	0.062	major injuries		na	A
human	workers	occupational accidents	1.6	minor injuries		na	A
5. Limestone transport							
Road accidents							
human	total	road accidents	0.0014	deaths		na	A
human	total	road accidents	0.018	major injuries		na	A
human	total	road accidents	0.55	minor injuries		na	A
Air Pollution Effects							
Impacts and damages assessed together with other upstream processes							
Global warming x CO_2, CH_4 and N_2O							
Damages assessed together with all other process steps							
6. Power generation							
Air pollution x crops							
Acidity							
crops	total	add. lime needed in kg	1.6E+05	[kg] per TWh	0.003		A
crops	total	add. fertil. needed [kg]	-2.6E+04	[kg] per TWh	-0.01		A
SO_2							
crops	barley	yield loss [dt]	-40	[dt] per TWh	-0.0002		A
crops	potato	yield loss [dt]	-258	[dt] per TWh	-0.002		A
crops	wheat	yield loss [dt]	908	[dt] per TWh	0.01		A
crops	sugar beet	yield loss [dt]	-129	[dt] per TWh	-0.0007		A
crops	oats	yield loss [dt]	17	[dt] per TWh	0.0001		A
crops	rye	yield loss [dt]	-42	[dt] per TWh	-0.0007		A
Ozone							
crops	total	yield loss [dt]			0.01	490	B
Air pollution x ecosystems							
ecosystems	alk. unimpr. grass	Relative exceedance weighted N deposition exceedance area	0.5	[km2] per TWh	na		B
ecosystems	alpine meadows		1.9	[km2] per TWh	na		B
ecosystems	beech, various oaks		3.4	[km2] per TWh	na		B
ecosystems	birch, pine, ... mix		18.6	[km2] per TWh	na		B
ecosystems	mediterranean scrub		0.02	[km2] per TWh	na		B

			Impacts		Damages		
Receptor	**ReceptorSubGroup**	**Impact**	**per TWh**	**Units**	**mECU/kWh**	**ECU/tpoll**	s_g
ecosystems	non-alk.unimpr.grass		1.1	[km2] per TWh	na		B
ecosystems	peat bog		0.7	[km2] per TWh	na		B
ecosystems	swamp marsh		0.04	[km2] per TWh	na		B
ecosystems	tundra/rock/ice		0.4	[km2] per TWh	na		B
ecosystems	total	Relative exceedance weighted NOx exceedance area	0	[km2] per TWh	na		B
ecosystems	total	Relative exceedance weighted SO2 exceedance area	7.6	[km2] per TWh	na		B
Air pollution x human health							
NOx-all from nitrate aerosol							
Acute effects							
human	above_65_yrs	congestive heart failure	0.45	[case] per TWh	0.0034		B
human	adults	Restr. activity days	2659	[days] per TWh	0.19		B
human	asthma_adults	Bronchodilator usage	608	[case] per TWh	0.022		B
human	asthma_adults	cough	625	[day] per TWh	0.0042		A
human	asthma_adults	Lower resp. symptoms	226	[days] per TWh	0.0016		A
human	asthma_children	Bronchodilator usage	122	[case] per TWh	0.0043		B
human	asthma_children	cough	210	[day] per TWh	0.0014		A
human	asthma_children	Lower resp. symptoms	162	[days] per TWh	0.0012		A
human	total	resp. hosp. admission	0.39	[case] per TWh	0.0029		A
human	total	cerebrovascular hosp. adm	0.94	[case] per TWh	0.0071		B
Chronic effects							
human	adults	’chronic’ mortality	7.7	[deaths] per TWh			B
human	adults	’chronic’ YOLL	77	[years] per TWh	6.2		B
human	adults	chronic bronchitis	5.2	[cases] per TWh	0.52		A
human	children	chronic cough	93	[episode] per TWh	0.020		B
human	children	case of chr. bronchitis	72	[case] per TWh	0.016		B
NOx-via ozone							
Acute effects							
human	total	mortality			7.01E-01	4.12E+02	B
human	total	morbidity			1.25E+00	7.32E+02	B
SO2-all from sulphate, unless marked $_{SO2}$							
Acute effects							
human	total	acute’ mortality $_{SO2}$		[deaths] per TWh			B
human	total	acute’ YOLL $_{SO2}$	0.85	[years] per TWh	0.13		B
human	total	resp. hosp. Admission	0.17	[case] per TWh	0.0013		A
human	above_65_yrs	congestive heart failure	0.20	[case] per TWh	0.0015		B
human	adults	Restr. activity days	1182	[days] per TWh	0.085		B
human	asthma_adults	Bronchodilator usage	270	[case] per TWh	0.0096		B
human	asthma_adults	cough	278	[day] per TWh	0.0019		A
human	asthma_adults	Lower resp. Symptoms	101	[days] per TWh	0.0007		A
human	asthma_children	Bronchodilator usage	54	[case] per TWh	0.0019		B
human	asthma_children	cough	93	[day] per TWh	0.00060		A
human	asthma_children	Lower resp. Symptoms	72	[days] per TWh	0.00050		A
human	total	cerebrovascular hosp. adm	0.42	[case] per TWh	0.0032		B
Chronic effects							
human	adults	’chronic’ mortality	3.4	[deaths] per TWh			B
human	adults	’chronic’ YOLL	34	[years] per TWh	2.8		B
human	adults	chronic bronchitis	2.2	[cases] per TWh	0.22		A
human	children	chronic cough	41	[episode] per TWh	0.0089		B
human	children	case of chr. bronchitis	32	[case] per TWh	0.0069		B
Primary $_{PM10}$							
Acute effects							
human	above_65_yrs	congestive heart failure	0.076	[case] per TWh	0.00060		B
human	adults	Restr. activity days	448	[days] per TWh	0.032		B
human	asthma_adults	Bronchodilator usage	102	[case] per TWh	0.0036		B
human	asthma_adults	cough	105	[day] per TWh	0.0007		A
human	asthma_adults	Lower resp. symptoms	38	[days] per TWh	0.0003		A

			Impacts		**Damages**		
Receptor	**ReceptorSubGroup**	**Impact**	**per TWh**	**Units**	**mECU/kWh**	**ECU/tpoll**	**s_g**
human	asthma_children	Bronchodilator usage	20	[case] per TWh	0.0007		B
human	asthma_children	cough	35	[day] per TWh	0.0002		A
human	asthma_children	Lower resp. symptoms	27	[days] per TWh	0.0002		A
human	total	cerebrovascular hosp. adm	0.16	[case] per TWh	0.0012		A
human	total	resp. hosp. Admission	0.065	[case] per TWh	0.0005		B
Chronic effects							
human	adults	’chronic’ mortality	1.3	[deaths] per TWh			B
human	adults	’chronic’ YOLL	13	[years] per TWh	1.0		B
human	adults	chronic bronchitis	0.88	[cases] per TWh	0.088		A
human	children	chronic cough	16	[episode] per TWh	0.0034		B
human	children	case of chr. bronchitis	12	[case] per TWh	0.0026		B
Air pollution x materials							
SO$_2$ and acid deposition							
material	galvanised st.	maintenance surface (m2)	546	[m2] per TWh	0.02		B
material	limestone	maintenance surface (m2)	1.4	[m2] per TWh	0.0004		B
material	mortar	maintenance surface (m2)	5.4	[m2] per TWh	0.0002		B
material	natural stone	maintenance surface (m2)	1.4	[m2] per TWh	0.0004		B
material	paint	maintenance surface (m2)	9483	[m2] per TWh	0.1		B
material	rendering	maintenance surface (m2)	173.3	[m2] per TWh	0.005		B
material	sandstone	maintenance surface (m2)	2.0	[m2] per TWh	0.0006		B
material	zinc	maintenance surface (m2)	64	[m2] per TWh	0.002		B
Occupational accidents							
human	workers	occupational accidents	0.00073	deaths		na	A
human	workers	occupational accidents	0.016	major injuries		na	A
human	workers	occupational accidents	0.76	minor injuries		na	A
Global warming x CO$_2$, CH$_4$ and N$_2$O							
Damages assessed together with all other process steps							
8. Waste transport							
Road accidents							
human	total	road accidents	nq	deaths	nq	na	A
human	total	road accidents	nq	major injuries	nq	na	A
human	total	road accidents	nq	minor injuries	nq	na	A
Air Pollution Effects							
Impacts and damages assessed together with other upstream processes							
Global warming x CO$_2$, CH$_4$ and N$_2$O							
Damages assessed together with all other process steps							
1.+2.+5.+8. Upstream processes together							
Air pollution x crops							
Acidity							
crops	total	add. lime needed in kg	0.2E+05	[kg] per TWh	0.0003		A
crops	total	add. fertil. needed [kg]	-0.2E+04	[kg] per TWh	-0.001		A
SO$_2$							
crops	barley	yield loss [dt]	-6	[dt] per TWh	-0.00001		A
crops	potato	yield loss [dt]	-34	[dt] per TWh	-0.0003		A
crops	wheat	yield loss [dt]	908	[dt] per TWh	0.01		A
crops	sugar beet	yield loss [dt]	-15	[dt] per TWh	-0.00008		A
crops	oats	yield loss [dt]	2	[dt] per TWh	0.00001		A
crops	rye	yield loss [dt]	-6	[dt] per TWh	-0.00001		A
Ozone							
crops	total	yield loss [dt]			0.0006	490	B
Air pollution x human health							
NOx-all from nitrate aerosol							
Acute effects							
human	above_65_yrs	congestive heart failure	0.037	[case] per TWh	2.8e-4		B
human	adults	Restr. activity days	220	[days] per TWh	1.6e-2		B
human	asthma_adults	Bronchodilator usage	50	[case] per TWh	1.8e-3		B
human	asthma_adults	cough	52	[day] per TWh	3.5e-4		A
human	asthma_adults	Lower resp. symptoms	19	[days] per TWh	1.3e-4		A
human	asthma_children	Bronchodilator usage	10	[case] per TWh	3.6e-4		B

			Impacts		**Damages**		
Receptor	**ReceptorSubGroup**	**Impact**	**per TWh**	**Units**	**mECU/kWh**	**ECU/tpoll**	s_g
human	asthma_children	cough	17	[day] per TWh	1.2e-4		A
human	asthma_children	Lower resp. symptoms	13	[days] per TWh	9.6e-5		A
human	total	resp. hosp. admission	0.032	[case] per TWh	2.4e-4		A
human	total	cerebrovascular hosp. adm	0.078	[case] per TWh	5.9e-4		B
Chronic effects							
human	adults	’chronic’ mortality	0.6	[deaths] per TWh			B
human	adults	’chronic’ YOLL	6.3	[years] per TWh	5.1e-1		B
human	adults	chronic bronchitis	0.43	[cases] per TWh	4.4e-2		A
human	children	chronic cough	7.7	[episode] per TWh	1.6e-3		B
human	children	case of chr. bronchitis	6.0	[case] per TWh	1.3e-3		B
NOx-via ozone							
Acute effects							
human	total	mortality			7.01E-01	4.12E+02	B
human	total	morbidity			1.25E+00	7.32E+02	B
SO2-all from sulphate, unless marked SO_2							
Acute effects							
human	total	acute’ mortality SO_2		[deaths] per TWh			B
human	total	acute’ YOLL SO_2	0.12	[years] per TWh	1.7e-2		B
human	total	resp. hosp. admission	0.024	[case] per TWh	1.8e-4		A
human	above_65_yrs	congestive heart failure	0.028	[case] per TWh	2.1e-4		B
human	adults	Restr. activity days	167	[days] per TWh	1.2e-2		B
human	asthma_adults	Bronchodilator usage	38	[case] per TWh	1.4e-3		B
human	asthma_adults	cough	39	[day] per TWh	2.6e-4		A
human	asthma_adults	Lower resp. symptoms	14	[days] per TWh	1.0e-4		A
human	asthma_children	Bronchodilator usage	7.6	[case] per TWh	2.7e-4		B
human	asthma_children	cough	13	[day] per TWh	8.8e-5		A
human	asthma_children	Lower resp. symptoms	10	[days] per TWh	7.3e-5		A
human	total	cerebrovascular hosp. adm	0.006	[case] per TWh	4.5e-4		B
Chronic effects							
human	adults	’chronic’ mortality	0.48	[deaths] per TWh			B
human	adults	’chronic’ YOLL	4.8	[years] per TWh	3.9e-1		B
human	adults	chronic bronchitis	0.31	[cases] per TWh	3.1e-2		A
human	children	chronic cough	5.8	[episode] per TWh	1.3e-3		B
human	children	case of chr. bronchitis	4.5	[case] per TWh	9.8e-4		B
Primary PM_{10}							
Acute effects							
human	above_65_yrs	congestive heart failure	0.013	[case] per TWh	9.6e-5		B
human	adults	Restr. activity days	75	[days] per TWh	5.4e-3		B
human	asthma_adults	Bronchodilator usage	17	[case] per TWh	6.1e-4		B
human	asthma_adults	cough	18	[day] per TWh	1.2e-4		A
human	asthma_adults	Lower resp. symptoms	6.4	[days] per TWh	4.6e-5		A
human	asthma_children	Bronchodilator usage	3.5	[case] per TWh	1.2e-4		B
human	asthma_children	cough	5.9	[day] per TWh	4.0e-5		A
human	asthma_children	Lower resp. symptoms	4.6	[days] per TWh	3.3e-5		A
human	total	resp. hosp. admission	0.011	[case] per TWh	8.2e-5		A
human	total	cerebrovascular hosp. adm	0.027	[case] per TWh	2.0e-4		B
Chronic effects							
human	adults	’chronic’ mortality	0.22	[deaths] per TWh			B
human	adults	’chronic’ YOLL	2.2	[years] per TWh	1.8e-1		B
human	adults	chronic bronchitis	0.15	[cases] per TWh	1.5e-2		A
human	children	chronic cough	2.6	[episode] per TWh	5.7e-4		B
human	children	case of chr. bronchitis	2.1	[case] per TWh	4.4e-4		B
Air pollution x materials							
SO_2 and acid deposition							
material	galvanised st.	maintenance surface (m2)	65	[m2] per TWh	0.002		B
material	limestone	maintenance surface (m2)	0.2	[m2] per TWh	0.00006		B
material	mortar	maintenance surface (m2)	0.7	[m2] per TWh	0.00002		B
material	natural stone	maintenance surface (m2)	0.2	[m2] per TWh	0.00005		B
material	paint	maintenance surface (m2)	1067	[m2] per TWh	0.02		B
material	rendering	maintenance surface (m2)	21	[m2] per TWh	0.0007		B

			Impacts		Damages		
Receptor	**ReceptorSubGroup**	**Impact**	**per TWh**	**Units**	**mECU/kWh**	**ECU/tpoll**	**s_g**
material	sandstone	maintenance surface (m2)	0.3	[m2] per TWh	0.00007		B
material	zinc	maintenance surface (m2)	7	[m2] per TWh	0.0002		B
1.+2.+5.+6.+8. All processes together							
Global warming x CO_2, CH_4 and N_2O		mECU/kWh					
	low	3.4					
	mid 3%	16.2					
	mid 1%	41.3					
	high	128.8					

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9 DEFINITION OF THE LIGNITE FUEL CYCLE, DATA AND RESULTS

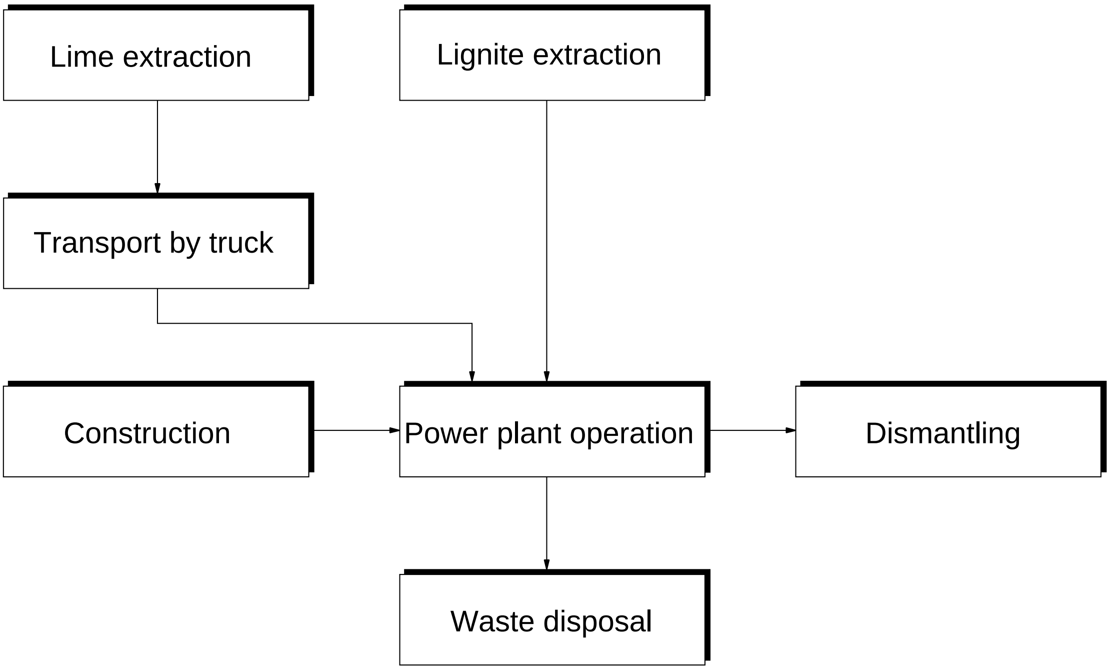

Figure 9.2 Process steps of the German lignite fuel cycle

Table 9.4 Detailed definition of the specimen example of the lignite fuel cycle analysed in this study. Data in normal type are taken from sources that are directly applicable to the case considered. Data in italics have been extrapolated from other sources with possible limited applicability to the case considered.

Stage	**Parameter**	**Quantity**	**Source of data, comments**
1. Lignite mining	Location(s)	Garzweiler, Rhenish lignite mining district, Germany	
	Type of mine	Opencast-mine	
	Calorific value of lignite	8.5 MJ/kg	Rheinbraun AG
	Mine waste disposal site	In cleared opencast-mines	Rheinbraun AG
	Composition of lignite		
	water	56%	Rheinbraun AG
	ash	5.4%	Rheinbraun AG
	carbon	na	
	oxygen	na	
	hydrogen	na	
	sulphur	0.3%	Rheinbraun AG
	nitrogen	na	
	chlorine	na	
	trace elements	na	
2. Lignite transport	Distance to power station	*20 km*	
	Mode of transport	Conveyor belts - 100%	Rheinbraun AG
3. Lignite conditioning	Processes adopted	iron separated magnetically during transport by conveyor belts	Rheinbraun AG
	Advanced treatments	not used	
	Waste streams		
	overburden	transported by conveyor belts to cleared part of the mine	Rheinbraun AG
4. Limestone extraction			
	Location	Wülfrath, Germany	
	Annual production	9 Mill. t	Anonymous (1991)
5. Limestone transport			
	Distance to power station	*40 km*	
	Mode of transport	Truck - 100%	
6. Power generation			
	Fuel	lignite	
	Type of plant	pulverised fuel, flue gas desulphurisation	
	Location	Grevenbroich, Germany	

Stage	Parameter	Quantity	Source of data, comments
	Power generation		
	gross	887.9 MW	Wehovsky *et al.* (1994) Wehovsky *et al.* (1994)
	sent out	800 MW	
	Efficiency	40.1% (HHV basis)	Wehovsky *et al.* (1994)
	Load factor	*74%*	
	Lifetime	35 years	
	Pollution control		
	ESPs	not specified	
	FGD	90% effective	Wehovsky *et al.* (1994)
	recirculation of cooling water	not specified	
	waste water precipitators	not specified	
	Stack parameters		
	height	*200 m*	
	diameter	*10 m*	
	flue gas volume	*3286113* Nm^3	Brandt (1981)
	flue gas temperature	*403.15 K*	
	Material demands		
	lignite	5.5 Mill. t/yr	Wehovsky etal (1994)
	limestone	*380 600 t/yr*	
	cooling water	not specified	
	boiler feed water	not specified	
	domestic water	not specified	
7. Transmission			
	Length of new lines	0 km	
8. Transport of waste			
	Site	Garzweiler, Germany	
	Distance to power station	*20 km*	
	Mode of transport	Truck - 100%	
9. Waste disposal			
	Type of facility	Landfill (opencast-mine)	
10. Construction of power plant			
	Construction materials	negligible	
	surfacing material		
	cement		
	sand		
	coarse aggregates		
	PFA		
	steel		

Table 9.5 Burdens of the lignite fuel cycle

Stage	Burden	Quantity	Source of data	Impact assessed?
1. Lignite mining in EU	Occupational health			
	accidents - fatal	0.0065/Mt		✓
	accidents - major injury	0.21/Mt		✓
	accidents - minor injury	3.5/Mt		✓
	noise levels	not quantified	-	x - no data
	exposure to physical stress	not quantified	-	x - no data
	Air emissions			
	CO_2	30.4 kg/MWh	FDE (1996)	✓
	CH_4	11.8 g/MWh	DGMK (1992)	✓
	SO_2	12.3 g/MWh	FDE (1996)	✓
	NO_x	22.1 g/MWh	FDE (1996)	✓
	PM_{10} - combustion	2.5 g/MWh	FDE (1996)	✓
	PM_{10} - fugitive dust	nq		x - no data
	Other burdens			
	lowering of ground water level	max. 200 m below surface	Rheinbraun AG	partially internalised
	mine drainage	not quantified		0 - internalised
	solid wastes	not quantified		x - no data
	noise	not quantified		x - negligible
	resettlement	not quantified		0 - internalised
2. Lignite transport	Occupational health			
	accidents - fatal			incl. in mining
	accidents - major injury			incl. in mining
	accidents - minor injury			incl. in mining
	Air emissions			
	CO_2	2.9 kg/MWh	FDE (1996)	✓
	SO_2	1.5 g/MWh	FDE (1996)	✓
	NO_x	28.5 g/MWh	FDE (1996)	✓
	PM_{10} - combustion	0.6 g/MWh	FDE (1996)	✓
	PM_{10} - fugitive dust	425 g/MWh	UBA (1989)	x - negligible
3. Lignite conditioning	burdens included in other stages			
4. Extraction, production of pollution abatement materials				
4a. Limestone	Occupational health			
	accidents - fatal	0.0024/Mt		
	accidents - major injury	0.050/Mt		
	accidents - minor injury	1.3/Mt		
	noise levels			
	exposure to physical stress	not quantified		
	Air emissions			
	CO_2	nq		x - negligible
	SO_2	nq		x - negligible
	NO_x	nq		x - negligible
	PM_{10} - combustion	nq		x - negligible
	PM_{10} - fugitive dust	nq		x - negligible
	Emissions to water			
	suspended solids	nq		x - negligible

Stage	Burden	Quantity	Source of data	Impact assessed?
	Other burdens			
	noise	nq		x - negligible
5. Transport of pollution abatement materials				
	burdens included in other stages			
6. Power generation	Occupational health			
	accidents - fatal	0.00073/TWh		
	accidents - major injury	0.016/TWh		
	accidents - minor injury	0.76/TWh		
	noise levels	nq		x - negligible
	exposure to physical stress	nq		x - negligible
	Air emissions			
	CO_2	1015 kg/MWh	Wehovsky *et al.*, (1994)	✓
	N_2O	45 g/MWh	CORINAIR (1992)	✓
	CH_4	42 g/MWh	Wehovsky *et al.* (1994)	✓
	SO_2	*411 g/MWh*	Wehovsky *et al.* (1994)	✓
	NO_x	*739 g/MWh*	Wehovsky *et al.* (1994)	✓
	PM_{10}	*82 g/MWh*	Wehovsky *et al.* (1994)	✓
	NMHC	nq		x - negligible
	trace elements	nq		x - negligible
	evaporated water from cooling system	nq		x - negligible
	Noise emissions	nq		x - negligible
	Solid waste production			
	Ash	53.5 g/MWh		x - negligible
	gypsum	134.0 g/MWh		x - negligible
	FGD sludge	nq		x - negligible
	silt from cooling towers	nq		x - negligible
	Water abstraction	805 g/MWh	Wehovsky *et al.* (1994)	x - negligible
	Emissions to water from.			
	cooling system			x - no data
	temperature of cooling water on return			x - no data
	chloride			x - no data
	FGD plant			x - no data
7. Transmission	No additional burdens			
8. Transport of waste	burdens included in other stages			
9. Waste disposal	Occupational health			
	accidents - fatal	0.0023/TWh		

Stage	Burden	Quantity	Source of data	Impact assessed?
	accidents - major injury	0.029/TWh		
	accidents - minor injury	0.96/TWh		
	Air emissions			x - negligible
	Leachate			x - no data
	Quantity of waste			x - no data
	Noise			x - negligible
	Road use	km/yr		x - negligible
10. Construction	Occupational health			x - negligible
	accidents - fatal	0.0047/TWh		
	accidents - major injury	0.14/TWh		
	accidents - minor injury	5.5/TWh		
	Air emissions from materials production	nq		x - negligible
	Air emissions from materials transport	nq		x - negligible
	Air emissions from activities on site	nq		x - negligible
	Noise	nq		x - negligible
	Road use	nq		x - negligible
11. Demolition	Occupational health			
	accidents - fatal	0.00022/TWh		
	accidents - major injury	0.0054/TWh		
	accidents - minor injury	0.20/TWh		
	Air emissions from materials production	nq		x - negligible
	Noise	nq		x - negligible
	Road use	nq		x - negligible

Table 9.6 Impacts and damages of the lignite fuel cycle

			Impacts		Damages		
Receptor	**ReceptorSubGroup**	**Impact**	**per TWh**	**Units**	**mECU/kWh**	**ECU/tpoll**	**s_g**
1. Lignite mining							
Occupational accidents							
human	workers	occupational accidents	0.0069	deaths		na	A
human	workers	occupational accidents	0.22	major injuries		na	A
human	workers	occupational accidents	3.7	minor injuries		na	A
Air Pollution Effects							
Impacts and damages assessed together with other upstream processes							
Global warming x CO_2, CH_4 and N_2O							
Damages assessed together with all other process steps							
2. Lignite transport							
Occupational accidents							
human	workers	occupational accidents	na	deaths		na	A
human	workers	occupational accidents	na	major injuries		na	A
human	workers	occupational accidents	na	minor injuries		na	A
Public accidents							
human	total	public accidents	na	deaths		na	A
human	total	public accidents	na	major injuries		na	A
human	total	public accidents	na	minor injuries		na	A
Air Pollution Effects							
Impacts and damages assessed together with other upstream processes							
Global warming x CO_2, CH_4 and N_2O							
Damages assessed together with all other process steps							
4. Limestone extraction							
Occupational accidents							
human	workers	occupational accidents	0.0026	deaths		na	A
human	workers	occupational accidents	0.053	major injuries		na	A
human	workers	occupational accidents	1.4	minor injuries		na	A
5. Limestone transport							
Road accidents							
human	total	road accidents	0.00091	deaths		na	A
human	total	road accidents	0.011	major injuries		na	A
human	total	road accidents	0.35	minor injuries		na	A
Air Pollution Effects							
Impacts and damages assessed together with other upstream processes							
Global warming x CO_2, CH_4 and N_2O							
Damages assessed together with all other process steps							
6. Power generation							
Air pollution x crops							
Acidity							
crops	total	add. lime needed in kg	2.2E+05	[kg] per TWh	0.004		A
crops	total	add. fertil. needed [kg]	-3.4E+04	[kg] per TWh	-0.02		A
SO_2							
crops	barley	yield loss [dt]	-9	[dt] per TWh	-0.00005		A
crops	potato	yield loss [dt]	-586	[dt] per TWh	-0.005		A
crops	wheat	yield loss [dt]	13	[dt] per TWh	0.0001		A
crops	sugar beet	yield loss [dt]	-46	[dt] per TWh	-0.0002		A
crops	oats	yield loss [dt]	4	[dt] per TWh	0.00002		A
crops	rye	yield loss [dt]	-32	[dt] per TWh	-0.0005		A
Ozone							
crops	total	yield loss [dt]			0.01	490	B
Air pollution x ecosystems							
ecosystems	alk. unimpr. grass	Relative exceedance	0.3	[km2] per TWh	na		B
ecosystems	alpine meadows	weighted N deposition	1.4	[km2] per TWh	na		B
ecosystems	beech, various oaks	exceedance area	4.4	[km2] per TWh	na		B
ecosystems	birch, pine, ... mix		14.6	[km2] per TWh	na		B
ecosystems	mediterranean scrub		0.01	[km2] per TWh	na		B

			Impacts		Damages		
Receptor	**ReceptorSubGroup**	**Impact**	**per TWh**	**Units**	**mECU/kWh**	**ECU/tpoll**	s_g
ecosystems	non-alk.unimpr.grass		0.9	[km2] per TWh	na		B
ecosystems	peat bog		2.6	[km2] per TWh	na		B
ecosystems	swamp marsh		0.02	[km2] per TWh	na		B
ecosystems	tundra/rock/ice		0.6	[km2] per TWh	na		B
ecosystems	total	Relative exceedance weighted NOx exceedance area	0	[km2] per TWh	na		B
ecosystems	total	Relative exceedance weighted SO2 exceedance area	27.2	[km2] per TWh	na		B
Air pollution x human health							
NOx-all from nitrate aerosol							
Acute effects							
human	above_65_yrs	congestive heart failure	0.51	[case] per TWh	0.0038		B
human	adults	Restr. activity days	3019	[days] per TWh	0.22		B
human	asthma_adults	Bronchodilator usage	690	[case] per TWh	0.024		B
human	asthma_adults	cough	710	[day] per TWh	0.0048		A
human	asthma_adults	Lower resp. symptoms	257	[days] per TWh	0.0018		A
human	asthma_children	Bronchodilator usage	138	[case] per TWh	0.0049		B
human	asthma_children	cough	238	[day] per TWh	0.0016		A
human	asthma_children	Lower resp. symptoms	184	[days] per TWh	0.0013		A
human	total	resp. hosp. admission	0.44	[case] per TWh	0.0033		A
human	total	cerebrovascular hosp. adm	1.1	[case] per TWh	0.0081		B
Chronic effects							
human	adults	’chronic’ mortality	8.7	[deaths] per TWh			B
human	adults	’chronic’ YOLL	87	[years] per TWh	7.0		B
human	adults	chronic bronchitis	5.9	[cases] per TWh	0.60		A
human	children	chronic cough	106	[episode] per TWh	0.023		B
human	children	case of chr. bronchitis	82	[case] per TWh	0.018		B
NOx-via ozone							
Acute effects							
human	total	mortality			7.01E-01	4.12E+02	B
human	total	morbidity			1.25E+00	7.32E+02	B
SO2-all from sulphate, unless marked SO_2							
Acute effects							
human	total	acute’ mortality SO_2		[deaths] per TWh			B
human	total	acute’ YOLL SO_2	1.6	[years] per TWh	0.24		B
human	total	resp. hosp. admission	0.25	[case] per TWh	0.0019		A
human	above_65_yrs	congestive heart failure	0.29	[case] per TWh	0.0022		B
human	adults	Restr. activity days	1690	[days] per TWh	0.12		B
human	asthma_adults	Bronchodilator usage	387	[case] per TWh	0.014		B
human	asthma_adults	cough	398	[day] per TWh	0.0027		A
human	asthma_adults	Lower resp. symptoms	144	[days] per TWh	0.0010		A
human	asthma_children	Bronchodilator usage	77	[case] per TWh	0.0027		B
human	asthma_children	cough	133	[day] per TWh	0.00089		A
human	asthma_children	Lower resp. symptoms	103	[days] per TWh	0.00074		A
human	total	cerebrovascular hosp. adm	0.60	[case] per TWh	0.0045		B
Chronic effects							
human	adults	’chronic’ mortality	4.9	[deaths] per TWh			B
human	adults	’chronic’ YOLL	49	[years] per TWh	3.9		B
human	adults	chronic bronchitis	3.2	[cases] per TWh	0.32		A
human	children	chronic cough	59	[episode] per TWh	0.013		B
human	children	case of chr. bronchitis	46	[case] per TWh	0.0099		B
Primary PM_{10}							
Acute effects							
human	above_65_yrs	congestive heart failure	0.12	[case] per TWh	0.00093		B
human	adults	Restr. activity days	735	[days] per TWh	0.053		B
human	asthma_adults	Bronchodilator usage	168	[case] per TWh	0.0059		B
human	asthma_adults	cough	173	[day] per TWh	0.0012		A
human	asthma_adults	Lower resp. symptoms	62	[days] per TWh	0.00045		A

			Impacts		Damages		
Receptor	**ReceptorSubGroup**	**Impact**	**per TWh**	**Units**	**mECU/kWh**	**ECU/tpoll**	**s_g**
human	asthma_children	Bronchodilator usage	34	[case] per TWh	0.0012		B
human	asthma_children	cough	58	[day] per TWh	0.00039		A
human	asthma_children	Lower resp. symptoms	45	[days] per TWh	0.00032		A
human	total	resp. hosp. admission	0.11	[case] per TWh	0.00080		A
human	total	cerebrovascular hosp. adm	0.26	[case] per TWh	0.0020		B
Chronic effects							
human	adults	’chronic’ mortality	2.1	[deaths] per TWh			B
human	adults	’chronic’ YOLL	21	[years] per TWh	1.7		B
human	adults	chronic bronchitis	1.4	[cases] per TWh	0.14		A
human	children	chronic cough	26	[episode] per TWh	0.0055		B
human	children	case of chr. bronchitis	20	[case] per TWh	0.0043		B
Air pollution x materials							
SO_2 and acid deposition							
material	galvanised st.	maintenance surface (m2)	818	[m2] per TWh	0.03		B
material	limestone	maintenance surface (m2)	2.9	[m2] per TWh	0.0008		B
material	mortar	maintenance surface (m2)	15.2	[m2] per TWh	0.0005		B
material	natural stone	maintenance surface (m2)	2.8	[m2] per TWh	0.0008		B
material	paint	maintenance surface (m2)	12230	[m2] per TWh	0.4		B
material	rendering	maintenance surface (m2)	292	[m2] per TWh	0.009		B
material	sandstone	maintenance surface (m2)	4.0	[m2] per TWh	0.001		B
material	zinc	maintenance surface (m2)	68	[m2] per TWh	0.002		B
Occupational accidents							
human	workers	occupational accidents	0.00073	deaths		na	A
human	workers	occupational accidents	0.016	major injuries		na	A
human	workers	occupational accidents	0.76	minor injuries		na	A
Global warming x CO_2, CH_4 and N_2O							
		Damages assessed together with all other process steps					
8. Waste transport							
Road accidents							
human	total	road accidents	0.0027	deaths		na	A
human	total	road accidents	0.034	major injuries		na	A
human	total	road accidents	1.1	minor injuries		na	A
Air Pollution Effects							
		Impacts and damages assessed together with other upstream processes					
Global warming x CO_2, CH_4 and N_2O							
		Damages assessed together with all other process steps					
1.+2.+5.+8. Upstream processes together							
Air pollution x crops							
Acidity							
crops	total	add. lime needed in kg	0.1E+05	[kg] per TWh	0.0003		A
crops	total	add. fertil. needed [kg]	-0.3E+04	[kg] per TWh	-0.002		A
SO_2							
crops	barley	yield loss [dt]	-0.3	[dt] per TWh	-0.000002		A
crops	potato	yield loss [dt]	-20	[dt] per TWh	-0.0002		A
crops	wheat	yield loss [dt]	0.4	[dt] per TWh	0.00004		A
crops	sugar beet	yield loss [dt]	-2	[dt] per TWh	-0.00001		A
crops	oats	yield loss [dt]	0.1	[dt] per TWh	0.0000008		A
crops	rye	yield loss [dt]	-0.5	[dt] per TWh	-0.00001		A
Ozone							
crops	total	yield loss [dt]			0.001	490	B
Air pollution x human health							
NOx-all from nitrate aerosol							
Acute effects							
human	above_65_yrs	congestive heart failure	0.036	[case] per TWh	2.7e-4		B
human	adults	Restr. activity days	213	[days] per TWh	1.5e-2		B
human	asthma_adults	Bronchodilator usage	49	[case] per TWh	1.7e-3		B
human	asthma_adults	cough	50	[day] per TWh	3.3e-4		A
human	asthma_adults	Lower resp. symptoms	18	[days] per TWh	1.3e-4		A
human	asthma_children	Bronchodilator usage	9.7	[case] per TWh	3.4e-4		B

			Impacts		Damages		
Receptor	**ReceptorSubGroup**	**Impact**	**per TWh**	**Units**	**mECU/kWh**	**ECU/tpoll**	**s_g**
human	asthma_children	cough	17	[day] per TWh	1.1e-4		A
human	asthma_children	Lower resp. symptoms	13	[days] per TWh	9.2e-5		A
human	total	resp. hosp. admission	0.031	[case] per TWh	2.3e-4		A
human	total	cerebrovascular hosp. adm	0.075	[case] per TWh	5.7e-4		B
Chronic effects							
human	adults	’chronic’ mortality	0.61	[deaths] per TWh			B
human	adults	’chronic’ YOLL	6.1	[years] per TWh	5.0e-1		B
human	adults	chronic bronchitis	0.42	[cases] per TWh	4.2e-2		A
human	children	chronic cough	7.4	[episode] per TWh	1.6e-3		B
human	children	case of chr. bronchitis	5.8	[case] per TWh	1.2e-3		B
NOx-via ozone							
Acute effects							
human	total	mortality			7.01E-01	4.12E+02	B
human	total	morbidity			1.25E+00	7.32E+02	B
SO2-all from sulphate, unless marked SO_2							
Acute effects							
human	total	acute’ mortality SO_2		[deaths] per TWh			B
human	total	acute’ YOLL SO_2	0.15	[years] per TWh	2.3e-2		B
human	total	resp. hosp. admission	0.0079	[case] per TWh	5.9e-5		A
human	above_65_yrs	congestive heart failure	0.0091	[case] per TWh	6.9e-5		B
human	adults	Restr. activity days	54	[days] per TWh	3.9e-3		B
human	asthma_adults	Bronchodilator usage	12.3	[case] per TWh	4.4e-4		B
human	asthma_adults	cough	13	[day] per TWh	8 .5e-5		A
human	asthma_adults	Lower resp. symptoms	4.6	[days] per TWh	3.3e-5		A
human	asthma_children	Bronchodilator usage	2.5	[case] per TWh	8.7e-5		B
human	asthma_children	cough	4.3	[day] per TWh	2.8e-5		A
human	asthma_children	Lower resp. symptoms	3.3	[days] per TWh	2.4e-5		A
human	total	cerebrovascular hosp. adm	0.019	[case] per TWh	1.4e-4		B
Chronic effects							
human	adults	’chronic’ mortality	0.16	[deaths] per TWh			B
human	adults	’chronic’ YOLL	1.6	[years] per TWh	1.3e-1		B
human	adults	chronic bronchitis	0.10	[cases] per TWh	1.0e-2		A
human	children	chronic cough	1.9	[episode] per TWh	4.1e-4		B
human	children	case of chr. bronchitis	1.5	[case] per TWh	3.1e-4		B
Primary PM_{10}							
Acute effects							
human	above_65_yrs	congestive heart failure	0.0043	[case] per TWh	3.2e-5		B
human	adults	Restr. activity days	26	[days] per TWh	1.8e-3		B
human	asthma_adults	Bronchodilator usage	5.8	[case] per TWh	2.1e-4		B
human	asthma_adults	cough	6.0	[day] per TWh	4.0e-5		A
human	asthma_adults	Lower resp. symptoms	2.2	[days] per TWh	1.6e-5		A
human	asthma_children	Bronchodilator usage	1.2	[case] per TWh	4.1e-5		B
human	asthma_children	cough	2.0	[day] per TWh	1.3e-5		A
human	asthma_children	Lower resp. symptoms	1.6	[days] per TWh	1.1e-5		A
human	total	resp. hosp. admission	0.0037	[case] per TWh	2.8e-5		A
human	total	cerebrovascular hosp. adm	0.0091	[case] per TWh	6.8e-5		B
Chronic effects							
human	adults	’chronic’ mortality	0.073	[deaths] per TWh			B
human	adults	’chronic’ YOLL	0.73	[years] per TWh	5.9e-2		B
human	adults	chronic bronchitis	0.050	[cases] per TWh	5.0e-3		A
human	children	chronic cough	0.89	[episode] per TWh	1.9e-4		B
human	children	case of chr. bronchitis	0.69	[case] per TWh	1.5e-4		B
Air pollution x materials							
SO_2 and acid deposition							
material	galvanised st.	maintenance surface (m2)	45	[m2] per TWh	0.001		B
material	limestone	maintenance surface (m2)	0.1	[m2] per TWh	0.00005		B
material	mortar	maintenance surface (m2)	0.6	[m2] per TWh	0.00002		B
material	natural stone	maintenance surface (m2)	0.2	[m2] per TWh	0.00005		B
material	paint	maintenance surface (m2)	780	[m2] per TWh	0.003		B
material	rendering	maintenance surface (m2)	18	[m2] per TWh	0.0006		B

			Impacts		Damages		
Receptor	**ReceptorSubGroup**	**Impact**	**per TWh**	**Units**	**mECU/kWh**	**ECU/tpoll**	**s_g**
material	sandstone	maintenance surface (m2)	0.2	[m2] per TWh	0.00007		B
material	zinc	maintenance surface (m2)	5	[m2] per TWh	0.0001		B
1.+2.+5.+6.+8. All processes together							
Global warming x CO_2, CH_4 and N_2O		mECU/kWh					
	low	4.0					
	mid 3%	19.6					
	mid 1%	48.8					
	high	148.6					

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10 DEFINITION OF THE OIL FUEL CYCLE, DATA AND RESULTS

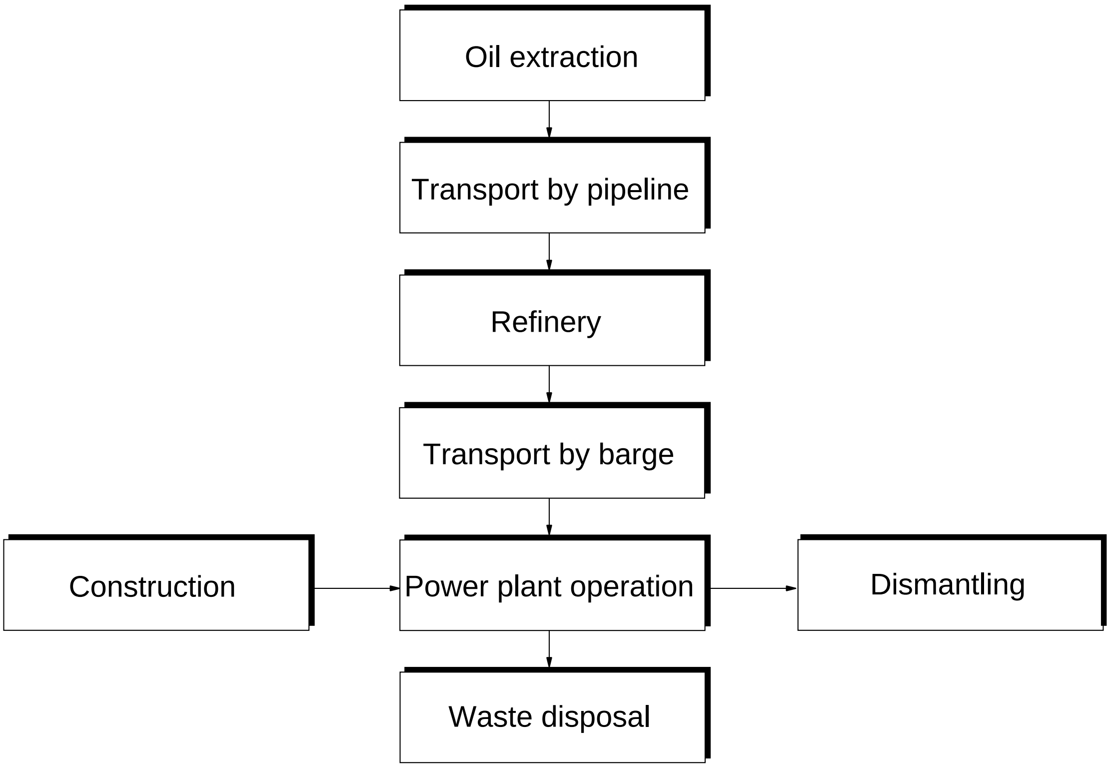

Figure 10.3 Process steps of the German oil fuel cycle

Table 10.7 Definition of the oil fuel cycle

Stage	Parameter	Value	Source
Fuel properties			
	Calorific value		
	MJ/kg	42.7	Wehovsky *et al.* (1994)
	Composition		
	S	0.2%	Wehovsky *et al.* (1994)
1. Oil extraction			
	Location	2% Germany, 42% OPEC, 34% North Sea, 22% GUS	FDE (1996)
	Oil field production	not specified	
	Composition of oil	not specified	
	Heating value	not specified	
2. Oil transport			
	Mode of transport	Pipeline / oil tanker	FDE (1996)
	Tanker transport lenght		FDE (1996)
	GUS	2000 km	
	OPEC-Netherlands	8800 km	
	OPEC-Italy	3000 km	
	OPEC-France	3000 km	
	Pipeline length		
	Germany	300 km	FDE (1996)
	France	800 km	VIA (1990)
	Italy	500 km	VIA (1990)
	Netherlands	300 km	VIA (1990)
	North Sea	500 km	FDE (1996)
	GUS	2500 km	FDE (1996)
	Pipeline diameter	not specified	
	Oil volume transported	not specified	
	Number of compressor stations	not specified	
	Compression station	not specified	
	Air emissions		FDE (1996)
	NO_x	*7282 kg/yr*	
	CH_4	*1020 kg/yr*	
	CO_2	*873 t/yr*	
	Labour	128 person-years/TWh	
2a. Construction of pipeline		not specified	
3. Power generation			
	Fuel	Oil	
	Technology	Gas turbine	
	Location	Lauffen, Germany	
	Installed power	157.2 MW	Wehovsky *et al.* (1994)
	Efficiency	31.1%	Wehovsky *et al.* (1994)
	Gas consumption	*3.7 kg/s*	Wehovsky *et al.*

Stage	**Parameter**	**Value**	**Source**
			(1994)
	Full load hours	675 h/yr	Wehovsky *et al.* (1994)
	Lifetime	35 years	
	Pollution control	none	Wehovsky *et al.* (1994)
	Size of the plant		
	land area required	0.65 ha	Wehovsky *et al.* (1994)
	cooling system	/	Wehovsky *et al.* (1994)
	reservoir volume	not relevant	
	stack height	170 m	
	stack diameter	6 m	
	Labour	47 person-years/TWh	
	Air emissions		
	flue gas volume	*1425185 Nm^3/h*	Wehovsky *et al.* (1994)
	flue gas temperature	433 K	
	CO_2	858 g/kWh	Wehovsky *et al.* (1994)
	TSP	*2 mg/Nm^3*	Wehovsky *et al.* (1994)
	SO_2	*132 mg/Nm^3*	Wehovsky *et al.* (1994)
	NO_x	*89 mg/Nm^3*	Wehovsky *et al.* (1994)
	Waste products	*2841 kg/yr*	Wehovsky *et al.* (1994)
3a. Construction of power plant			
	Material demands		Wehovsky *et al.* (1994)
	concrete, etc.	2400 t	
	metals	1600 t	
	Labour	160 person-years/TWh	
	Construction period	not specified	

Table 10.8 Burdens of the oil fuel cycle

Stage	Burden	Quantity	Source of data	Impact assessed?
1. Oil extraction	Occupational health			
	accidents - fatal	0.022 /Mt		✓
	accidents - major injury	0.39 /Mt		✓
	accidents - minor injury	3.6 /Mt		✓
	noise levels	nq		x - no data
	exposure to physical stress	nq		x - no data
	Air emissions			
	CO_2	30.3 kg/MWh	FDE (1996)	✓
	SO_2	224.0 g/MWh	FDE (1996)	✓
	NO_x	74.6 g/MWh	FDE (1996)	✓
	PM_{10}	13.5 g/MWh	FDE (1996)	✓
	CH_4	90.9 g/MWh	FDE (1996), Frischknecht *et al.* (1996)	✓
	Other burdens			
	noise	nq		x - negligible
2. Oil transport	Occupational health			
	accidents - fatal	0.29 /Mt		✓
	accidents - major injury	1.6 /Mt		✓
	accidents - minor injury	28.5 /Mt		✓
	Public health			
	accidents - fatal	nq		✓
	accidents - injury	nq		✓
	Air emissions			
	CO_2	8.3 kg/MWh	FDE (1996)	✓
	SO_2	88.4 g/MWh	FDE (1996)	✓
	NO_x	69.2 g/MWh	FDE (1996)	✓
	PM_{10} - combustion	34.0 g/MWh	FDE (1996)	✓
	CH_4	9.7 g/MWh	FDE (1996)	✓
	Other burdens			
	noise	nq		x - negligible
	burden on infrastructure	nq		x - negligible
3. Power generation	Occupational health			
	accidents - fatal	0.0011 /TWh		✓
	accidents - major injury	0.025 /TWh		✓
	accidents - minor injury	1.2 /TWh		✓
	noise levels	nq		x - negligible
	exposure to physical stress	nq		x - negligible
	Air emissions			
	CO_2	*858 kg/MWh*	Wehovsky *et al.* (1994)	✓
	SO_2	*1207 g/MWh*	Wehovsky *et al.* (1994)	✓
	NO_x	*814 g/MWh*	Wehovsky *et al.* (1994)	✓

Stage	**Burden**	**Quantity**	**Source of data**	**Impact assessed?**
	PM_{10}	*18 g/MWh*	Wehovsky *et al.* (1994)	✓
	trace elements	nq		x - negligible
	evaporated water from cooling system	nq		x - negligible
	Noise emissions	nq		x - negligible
	Solid waste production			
	ashes	2.8 kg/MWh	Wehovsky *et al.* (1994)	x - negligible
	gypsum	nq		x - negligible
	Water abstraction			
	Emissions to water from.			
	cooling system	nq		x - negligible
	temperature of cooling water on return	nq		x - negligible
	chloride	nq		x - negligible
	FGD plant	nq		x - negligible
4. Transmission	No additional burdens			
5. Construction	Occupational health			
	accidents - fatal	0.010 /TWh		✓
	accidents - major injury	0.29 /TWh		✓
	accidents - minor injury	11.6 /TWh		✓
	Air emissions from materials transport			
	CO_2	nq		x - negligible
	SO_2	nq		x - negligible
	NO_x	nq		x - negligible
	PM_{10} - combustion	nq		x - negligible
	Noise	nq		
	Road use	nq		
6. Demolition	Occupational health			
	accidents - fatal	0.00047 /TWh		✓
	accidents - major injury	0.011 /TWh		✓
	accidents - minor injury	0.43 /TWh		✓
	Noise	nq		x - negligible
	Road use	nq		x - negligible

Table 10.9 Impacts and damages of the oil fuel cycle

			Impacts		**Damages**		
Receptor	**ReceptorSubGroup**	**Impact**	**per TWh**	**Units**	**mECU/kWh**	**ECU/tpoll**	s_g
1. Oil extraction							
Occupational accidents							
human	workers	occupational accidents	0.0063	deaths		na	A
human	workers	occupational accidents	0.11	major injuries		na	A
human	workers	occupational accidents	1.0	minor injuries		na	A
Air Pollution Effects							
Impacts and damages assessed together with other upstream processes							
Global warming x CO_2, CH_4 and N_2O							
Damages assessed together with all other process steps							
2. Oil transport							
Occupational accidents							
human	workers	occupational accidents	0.081	deaths		na	A
human	workers	occupational accidents	0.45	major injuries		na	A
human	workers	occupational accidents	7.9	minor injuries		na	A
Public accidents							
human	total	public accidents	nq	deaths		na	A
human	total	public accidents	nq	major injuries		na	A
human	total	public accidents	nq	minor injuries		na	A
Oil spills							
		oil tanker accident			0.18		
Air Pollution Effects							
Impacts and damages assessed together with other upstream processes							
Global warming x CO_2, CH_4 and N_2O							
Damages assessed together with all other process steps							
3. Power generation							
Air pollution x crops							
Acidity							
crops	total	add. lime needed in kg	4.2E+05	[kg] per TWh	0.007		A
crops	total	add. fertil. needed [kg]	-4.2E+04	[kg] per TWh	-0.02		A
SO_2							
crops	barley	yield loss [dt]	-50	[dt] per TWh	-0.0003		A
crops	potato	yield loss [dt]	-811	[dt] per TWh	-0.007		A
crops	wheat	yield loss [dt]	908	[dt] per TWh	0.01		A
crops	sugar beet	yield loss [dt]	-506	[dt] per TWh	-0.003		A
crops	oats	yield loss [dt]	108	[dt] per TWh	0.0007		A
crops	rye	yield loss [dt]	-173	[dt] per TWh	-0.003		A
Ozone							
crops	total	yield loss [dt]			0.02	490	B
Air pollution x ecosystems							
ecosystems	alk. unimpr. grass	Relative exceedance weighted N deposition exceedance area	0.7	[km2] per TWh	na		B
ecosystems	alpine meadows		3.0	[km2] per TWh	na		B
ecosystems	beech, various oaks		5.0	[km2] per TWh	na		B
ecosystems	birch, pine, ... mix		28.6	[km2] per TWh	na		B
ecosystems	mediterranean scrub		0.04	[km2] per TWh	na		B
ecosystems	non-alk.unimpr.grass		1.7	[km2] per TWh	na		B
ecosystems	peat bog		1.1	[km2] per TWh	na		B
ecosystems	swamp marsh		0.06	[km2] per TWh	na		B
ecosystems	tundra/rock/ice		0.7	[km2] per TWh	na		B
ecosystems	total	Relative exceedance weighted NOx exceedance area	0	[km2] per TWh	na		B
ecosystems	total	Relative exceedance weighted SO2 exceedance area	31.8	[km2] per TWh	na		B
Air pollution x human health							
NOx-all from nitrate aerosol							

			Impacts		Damages		
Receptor	**ReceptorSubGroup**	**Impact**	**per TWh**	**Units**	**mECU/kWh**	**ECU/tpoll**	**s_g**
Acute effects							
human	above_65_yrs	congestive heart failure	0.66	[case] per TWh	0.0050		B
human	adults	Restr. activity days	3924	[days] per TWh	0.28		B
human	asthma_adults	Bronchodilator usage	897	[case] per TWh	0.032		B
human	asthma_adults	cough	923	[day] per TWh	0.0062		A
human	asthma_adults	Lower resp. symptoms	334	[days] per TWh	0.0024		A
human	asthma_children	Bronchodilator usage	180	[case] per TWh	0.0064		B
human	asthma_children	cough	309	[day] per TWh	0.0021		A
human	asthma_children	Lower resp. symptoms	239	[days] per TWh	0.0017		A
human	total	resp. hosp. admission	0.57	[case] per TWh	0.0043		A
human	total	cerebrovascular hosp. adm	1.4	[case] per TWh	0.010		B
Chronic effects							
human	adults	’chronic’ mortality	11.3	[deaths] per TWh			B
human	adults	’chronic’ YOLL	113	[years] per TWh	9.1		B
human	adults	chronic bronchitis	7.7	[cases] per TWh	0.77		A
human	children	chronic cough	137	[episode] per TWh	0.029		B
human	children	case of chr. bronchitis	107	[case] per TWh	0.023		B
NOx-via ozone							
Acute effects							
human	total	mortality			7.01E-01	4.12E+02	B
human	total	morbidity			1.25E+00	7.32E+02	B
SO2-all from sulphate, unless marked SO_2							
Acute effects							
human	total	acute’ mortality SO_2		[deaths] per TWh			B
human	total	acute’ YOLL SO_2	3.8	[years] per TWh	0.56		B
human	total	resp. hosp. admission	0.76	[case] per TWh	0.0058		A
human	above_65_yrs	congestive heart failure	0.89	[case] per TWh	0.0067		B
human	adults	Restr. activity days	5231	[days] per TWh	0.38		B
human	asthma_adults	Bronchodilator usage	1196	[case] per TWh	0.042		B
human	asthma_adults	cough	1231	[day] per TWh	0.0082		A
human	asthma_adults	Lower resp. symptoms	445	[days] per TWh	0.0032		A
human	asthma_children	Bronchodilator usage	240	[case] per TWh	0.0085		B
human	asthma_children	cough	413	[day] per TWh	0.0028		A
human	asthma_children	Lower resp. symptoms	318	[days] per TWh	0.0023		A
human	total	cerebrovascular hosp. adm	1.9	[case] per TWh	0.014		B
Chronic effects							
human	adults	’chronic’ mortality	15.1	[deaths] per TWh			B
human	adults	’chronic’ YOLL	151	[years] per TWh	12.2		B
human	adults	chronic bronchitis	9.8	[cases] per TWh	0.99		A
human	children	chronic cough	183	[episode] per TWh	0.039		B
human	children	case of chr. bronchitis	143	[case] per TWh	0.031		B
Primary PM_{10}							
Acute effects							
human	above_65_yrs	congestive heart failure	0.025	[case] per TWh	0.00019		B
human	adults	Restr. activity days	150	[days] per TWh	0.011		B
human	asthma_adults	Bronchodilator usage	34	[case] per TWh	0.0012		B
human	asthma_adults	cough	35	[day] per TWh	0.00024		A
human	asthma_adults	Lower resp. symptoms	13	[days] per TWh	9.2e-5		A
human	asthma_children	Bronchodilator usage	6.9	[case] per TWh	0.00024		B
human	asthma_children	cough	12	[day] per TWh	7.9e-5		A
human	asthma_children	Lower resp. symptoms	9.1	[days] per TWh	6.5e-5		A
human	total	resp. hosp. admission	0.022	[case] per TWh	0.00016		A
human	total	cerebrovascular hosp. adm	0.053	[case] per TWh	0.00040		B
Chronic effects							
human	adults	’chronic’ mortality	0.43	[deaths] per TWh			B
human	adults	’chronic’ YOLL	4.3	[years] per TWh	0.35		B
human	adults	chronic bronchitis	0.30	[cases] per TWh	0.030		A
human	children	chronic cough	5.2	[episode] per TWh	0.0011		B
human	children	case of chr. bronchitis	4.1	[case] per TWh	0.00088		B
Air pollution x materials							

			Impacts		Damages		
Receptor	**ReceptorSubGroup**	**Impact**	**per TWh**	**Units**	**mECU/kWh**	**ECU/tpoll**	**s_g**
SO_2 and acid deposition							
material	galvanised st.	maintenance surface (m2)	1765	[m2] per TWh	0.05		B
material	limestone	maintenance surface (m2)	4.9	[m2] per TWh	0.001		B
material	mortar	maintenance surface (m2)	17.7	[m2] per TWh	0.0005		B
material	natural stone	maintenance surface (m2)	4.8	[m2] per TWh	0.001		B
material	paint	maintenance surface (m2)	2.6E+04	[m2] per TWh	0.3		B
material	rendering	maintenance surface (m2)	589	[m2] per TWh	0.02		B
material	sandstone	maintenance surface (m2)	6.9	[m2] per TWh	0.002		B
material	zinc	maintenance surface (m2)	202	[m2] per TWh	0.005		B
Occupational accidents							
human	workers	occupational accidents	0.0011	deaths		na	A
human	workers	occupational accidents	0.025	major injuries		na	A
human	workers	occupational accidents	1.2	minor injuries		na	A
Global warming x CO_2, CH_4 and N_2O							
		Damages assessed together with all other process steps					
1.+2. Upstream processes together							
Air pollution x crops							
Acidity							
crops	total	add. lime needed in kg	1.2E+05	[kg] per TWh	0.0002		A
crops	total	add. fertil. needed [kg]	-0.8E+04	[kg] per TWh	-0.005		A
SO_2							
crops	barley	yield loss [dt]	-17	[dt] per TWh	-0.0001		A
crops	potato	yield loss [dt]	-275	[dt] per TWh	-0.003		A
crops	wheat	yield loss [dt]	7	[dt] per TWh	0.00007		A
crops	sugar beet	yield loss [dt]	-170	[dt] per TWh	-0.001		A
crops	oats	yield loss [dt]	36	[dt] per TWh	0.0002		A
crops	rye	yield loss [dt]	-58	[dt] per TWh	-0.001		A
Ozone							
crops	total	yield loss [dt]			0.003	490	B
Air pollution x human health							
NOx-all from nitrate aerosol							
Acute effects							
human	above_65_yrs	congestive heart failure	0.13	[case] per TWh	9.8e-4		B
human	adults	Restr. activity days	771	[days] per TWh	5.5e-2		B
human	asthma_adults	Bronchodilator usage	176	[case] per TWh	6.2e-3		B
human	asthma_adults	cough	181	[day] per TWh	1.2e-3		A
human	asthma_adults	Lower resp. symptoms	66	[days] per TWh	4.7e-4		A
human	asthma_children	Bronchodilator usage	35	[case] per TWh	1.2e-3		B
human	asthma_children	cough	61	[day] per TWh	4.1e-4		A
human	asthma_children	Lower resp. symptoms	47	[days] per TWh	3.4e-4		A
human	total	resp. hosp. admission	0.11	[case] per TWh	8.4e-4		A
human	total	cerebrovascular hosp. adm	0.27	[case] per TWh	2.1e-3		B
Chronic effects							
human	adults	'chronic' mortality	2.2	[deaths] per TWh			B
human	adults	'chronic' YOLL	22	[years] per TWh	1.8		B
human	adults	chronic bronchitis	1.5	[cases] per TWh	1.5e-1		A
human	children	chronic cough	27	[episode] per TWh	5.8e-3		B
human	children	case of chr. bronchitis	21	[case] per TWh	4.5e-3		B
NOx-via ozone							
Acute effects							
human	total	mortality			7.01E-01	4.12E+02	B
human	total	morbidity			1.25E+00	7.32E+02	B
SO2-all from sulphate, unless marked SO_2							
Acute effects							
human	total	acute' mortality SO_2		[deaths] per TWh			B
human	total	acute' YOLL SO_2	1.2	[years] per TWh	1.9e-1		B
human	total	resp. hosp. admission	0.26	[case] per TWh	1.9e-3		A
human	above_65_yrs	congestive heart failure	0.30	[case] per TWh	2.3e-3		B
human	adults	Restr. activity days	1771	[days] per TWh	1.3e-1		B
human	asthma_adults	Bronchodilator usage	405	[case] per TWh	1.4e-2		B

			Impacts		Damages		
Receptor	**ReceptorSubGroup**	**Impact**	**per TWh**	**Units**	**mECU/kWh**	**ECU/tpoll**	**s_g**
human	asthma_adults	cough	416	[day] per TWh	2.8e-3		A
human	asthma_adults	Lower resp. symptoms	151	[days] per TWh	1.1e-3		A
human	asthma_children	Bronchodilator usage	81	[case] per TWh	2.9e-3		B
human	asthma_children	cough	140	[day] per TWh	9.4e-4		A
human	asthma_children	Lower resp. symptoms	108	[days] per TWh	7.7e-4		A
human	total	cerebrovascular hosp. adm	0.63	[case] per TWh	4.7e-3		B
Chronic effects							
human	adults	'chronic' mortality	5.1	[deaths] per TWh			B
human	adults	'chronic' YOLL	51	[years] per TWh	4.1		B
human	adults	chronic bronchitis	3.3	[cases] per TWh	3.3e-1		A
human	children	chronic cough	62	[episode] per TWh	1.3e-2		B
human	children	case of chr. bronchitis	48	[case] per TWh	1.0e-2		B
Primary PM$_{10}$							
Acute effects							
human	above_65_yrs	congestive heart failure	0.068	[case] per TWh	5.1e-4		B
human	adults	Restr. activity days	401	[days] per TWh	2.9e-2		B
human	asthma_adults	Bronchodilator usage	92	[case] per TWh	3.2e-3		B
human	asthma_adults	cough	94	[day] per TWh	6.3e-4		A
human	asthma_adults	Lower resp. symptoms	34	[days] per TWh	2.4e-4		A
human	asthma_children	Bronchodilator usage	18	[case] per TWh	6.5e-4		B
human	asthma_children	cough	32	[day] per TWh	2.1e-4		A
human	asthma_children	Lower resp. symptoms	24	[days] per TWh	1.7e-4		A
human	total	resp. hosp. admission	0.058	[case] per TWh	4.4e-4		A
human	total	cerebrovascular hosp. adm	0.14	[case] per TWh	1.1e-3		B
Chronic effects							
human	adults	'chronic' mortality	1.2	[deaths] per TWh			B
human	adults	'chronic' YOLL	12	[years] per TWh	9.3e-1		B
human	adults	chronic bronchitis	0.79	[cases] per TWh	7.9e-2		A
human	children	chronic cough	14	[episode] per TWh	3.0e-3		B
human	children	case of chr. bronchitis	11	[case] per TWh	2.3e-3		B
Air pollution x materials							
SO$_2$ and acid deposition							
material	galvanised st.	maintenance surface (m2)	552	[m2] per TWh	0.02		B
material	limestone	maintenance surface (m2)	1.6	[m2] per TWh	0.0005		B
material	mortar	maintenance surface (m2)	5.5	[m2] per TWh	0.0002		B
material	natural stone	maintenance surface (m2)	1.5	[m2] per TWh	0.0004		B
material	paint	maintenance surface (m2)	7930	[m2] per TWh	0.1		B
material	rendering	maintenance surface (m2)	189	[m2] per TWh	0.006		B
material	sandstone	maintenance surface (m2)	2.3	[m2] per TWh	0.0006		B
material	zinc	maintenance surface (m2)	63	[m2] per TWh	0.002		B
1.+2.+3. All processes together							
Global warming x CO$_2$, CH$_4$ and N$_2$O		mECU/kWh					
	low	3.6					
	mid 3%	17.0					
	mid 1%	43.5					
	high	131.5					

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11 DEFINITION OF THE NATURAL GAS FUEL CYCLE, DATA AND RESULTS

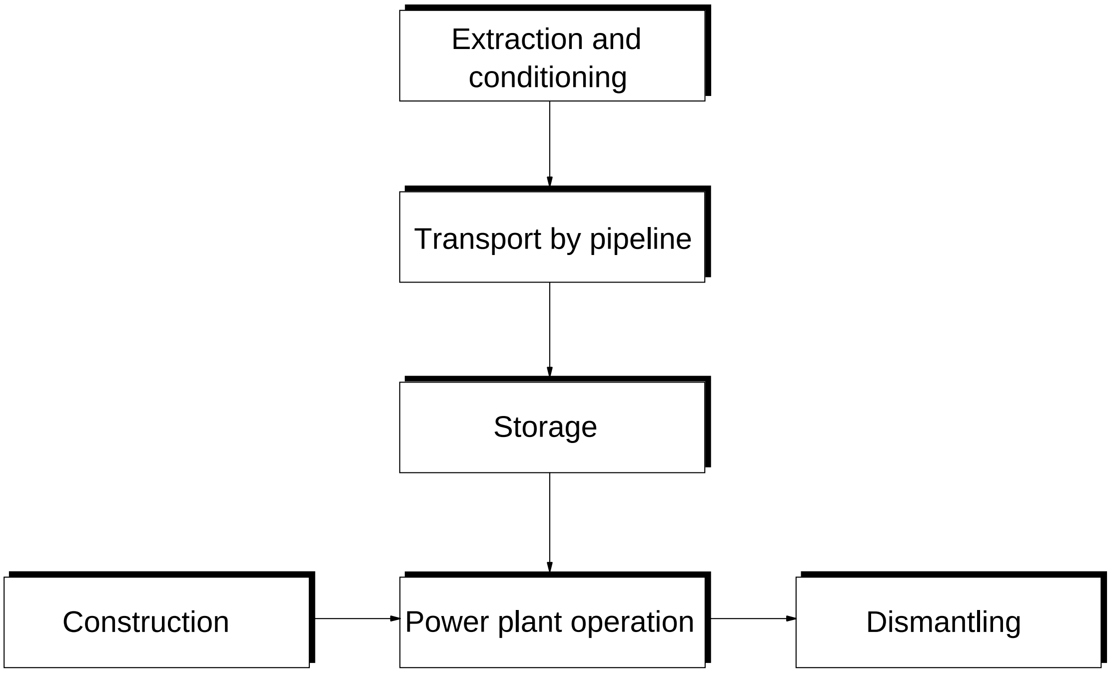

Figure 11.4 Process steps of the German gas fuel cycle

Table 11.10 Definition of the gas fuel cycle

Stage	Parameter	Value	Source
Fuel properties			
	Calorific value		
	MJ/kg	43.6	Pospischill (1993)
	Composition		
	S	0%	
1. Gas extraction			
	Location	15% Germany (D), 22% Netherlands (NL), 28% Norway (N), 32% GUS, 2,5% Denmark, 0.5% UK	FDE (1996)
	Gas field production	not specified	
	Composition of gas	D/NL/N/GUS	FDE (1996)
	Methane	86.6/86.6/92.8/96.0%	
	Ethane	1.1/3.0/4.6/1.7%	
	Propane	0.9/0.5/0.6/0.6%	
	Butane	0.6/0.1/0.2/0.2%	
	Nitrogen	3.5/8.7/0.9/1.0%	
	Carbon dioxide	3.9/1.0/1.0/0.1%	
	Hydrogen sulphide	3.6/0.0/0.0/0.5%	
	Heating value	41/42/48/49 MJ/kg	FDE (1996)
2. Gas transport			
	Mode of transport	Pipeline	FDE (1996)
	Pipeline length		FDE (1996)
	Germany	250 km	
	Netherlands	600 km	
	Norway	1700 km	
	GUS	7000 km	
	Pipeline diameter	not specified	
	Gas volume transported	not specified	
	Gas leakages		FDE (1996)
	Germany, Netherlands, Norway	0.001%	
	GUS	0.011%	
	Number of compressor stations	not specified	
	Compression station	not specified	
	Air emissions		FDE (1996)
	NO_x	*6690 kg/yr*	
	CH_4	*58 t/yr*	
	CO_2	*1130 t/yr*	
	Labour	24.6 person-years/TWh	
2a. Construction of pipeline		not specified	
3. Power generation			
	Fuel	Natural gas	
	Technology	Gas turbine	
	Location	Lauffen, Germany	
	Installed power	146.6 MW	Wehovsky *et al.*

Stage	Parameter	Value	Source
			(1994)
	Efficiency	33.2%	Wehovsky *et al.* (1994)
	Gas consumption	*12.6 Nm^3/s*	Wehovsky *et al.* (1994)
	Full load hours	675 h/yr	Wehovsky *et al.* (1994)
	Lifetime	35 years	Wehovsky *et al.* (1994)
	Pollution control	none	Wehovsky *et al.* (1994)
	Size of the plant		
	land area required	0.5 ha	Wehovsky *et al.* (1994)
	cooling system	/	Wehovsky *et al.* (1994)
	reservoir volume	not relevant	
	stack height	170 m	
	stack diameter	6 m	
	Labour	10 person-years/TWh	
	Air emissions		
	flue gas volume	*1681592 Nm^3/h*	Wehovsky *et al.* (1994)
	flue gas temperature	433 K	
	CO_2	604 g/kWh	Wehovsky *et al.* (1994)
	TSP	negligible	Wehovsky *et al.* (1994)
	SO_2	negligible	Wehovsky *et al.* (1994)
	NO_x	50 mg/Nm^3	Wehovsky *et al.* (1994)
	Waste products	negligible	Wehovsky *et al.* (1994)
3a. Construction of power plant			
	Material demands		Wehovsky *et al.* (1994)
	concrete, etc.	2200 t	
	metals	1500 t	
	Labour	33 person-years/TWh	
	Construction period	not specified	

Table 11.11 Burdens of the gas fuel cycle

Stage	Burden	Quantity	Source of data	Impact assessed?
1. Gas extraction	Occupational health			
	accidents - fatal	3.1e-5/Mill m^3		✓
	accidents - major injury	3.7e-4/Mill m^3		✓
	accidents - minor injury	3.4e-3/Mill m^3		✓
	noise levels	nq		x - no data
	exposure to physical stress	nq		x - no data
	Air emissions			
	CO_2	14.0 kg/MWh	FDE (1996)	✓
	SO_2	5.6 g/MWh	FDE (1996)	✓
	NO_x	52.2 g/MWh	FDE (1996)	✓
	PM_{10}	30.1 g/MWh	FDE (1996)	✓
	CH_4	2257 g/MWh	FDE (1996), Frischknecht *et al.* (1996)	✓
	Other burdens			
	noise	nq		x - negligible
2. Gas transport	Occupational health			
	accidents - fatal	nq		x - negligible
	accidents - major injury	nq		x - negligible
	accidents - minor injury	nq		x - negligible
	Public health			
	accidents - fatal	nq		x - negligible
	accidents - injury	nq		x - negligible
	Air emissions			
	CO_2	11.5 kg/MWh	FDE (1996)	✓
	SO_2	0.1 g/MWh	FDE (1996)	✓
	NO_x	68.0 g/MWh	FDE (1996)	✓
	PM_{10} - combustion	0.9 g/MWh	FDE (1996)	✓
	CH_4	584.8 g/MWh	FDE (1996), Frischknecht *et al.* (1996)	✓
	Other burdens			
	noise	nq		x - negligible
	burden on infrastructure	nq		x - negligible
3. Power generation	Occupational health			
	accidents - fatal	0.00024 /TWh		✓
	accidents - major injury	0.0053 /TWh		✓
	accidents - minor injury	0.25 /TWh		✓
	noise levels	nq		x - negligible
	exposure to physical stress	nq		x - negligible
	Air emissions			
	CO_2	26 kg/MWh	Wehovsky *et al.* (1994)	✓
	SO_2	negligible	Wehovsky *et al.* (1994)	✓

Stage	**Burden**	**Quantity**	**Source of data**	**Impact assessed?**
	NO_x	577 g/MWh	Wehovsky *et al.* (1994)	✓
	PM_{10}	negligible	Wehovsky *et al.* (1994)	✓
	trace elements	nq		x - negligible
	evaporated water from cooling system	nq		x - negligible
	Noise emissions	nq		x - negligible
	Solid waste production			
	ashes	negligible	Wehovsky *et al.* (1994)	x - negligible
	gypsum	none		
	Water abstraction			
	Emissions to water from.			
	cooling system	nq		x - negligible
	temperature of cooling water on return	nq		x - negligible
	chloride	nq		x - negligible
	FGD plant	nq		x - negligible
4. Transmission	No additional burdens			
5. Construction	Occupational health			
	accidents - fatal	0.0020 /TWh		✓
	accidents - major injury	0.060 /TWh		✓
	accidents - minor injury	2.4 /TWh		✓
	Air emissions from materials transport			
	CO_2	nq		x - negligible
	SO_2	nq		x - negligible
	NO_x	nq		x - negligible
	PM_{10} - combustion	nq		x - negligible
	Noise	nq		
	Road use	nq		
6. Demolition	Occupational health			
	accidents - fatal	9.5e-5 /TWh		✓
	accidents - major injury	0.0023 /TWh		✓
	accidents - minor injury	0.086 /TWh		✓
	Noise	nq		x - negligible
	Road use	nq		x - negligible

Table 11.12 Impacts and damages of the gas fuel cycle

			Impacts		Damages		
Receptor	**ReceptorSubGroup**	**Impact**	**per TWh**	**Units**	**mECU/kWh**	**ECU/tpoll**	**s_g**
1. Gas extraction							
Occupational accidents							
human	workers	occupational accidents	0.0049	deaths		na	A
human	workers	occupational accidents	0.056	major injuries		na	A
human	workers	occupational accidents	0.53	minor injuries		na	A
Air Pollution Effects							
		Impacts and damages assessed together with other upstream processes					
Global warming x CO_2, CH_4 and N_2O							
		Damages assessed together with all other process steps					
2. Gas transport							
Occupational accidents							
human	workers	occupational accidents	nq	deaths		na	A
human	workers	occupational accidents	nq	major injuries		na	A
human	workers	occupational accidents	nq	minor injuries		na	A
Public accidents							
human	total	public accidents	nq	deaths		na	A
human	total	public accidents	nq	major injuries		na	A
human	total	public accidents	nq	minor injuries		na	A
Air Pollution Effects							
		Impacts and damages assessed together with other upstream processes					
Global warming x CO_2, CH_4 and N_2O							
		Damages assessed together with all other process steps					
3. Power generation							
Air pollution x crops							
Acidity							
crops	total	add. lime needed in kg	1.0E+05	[kg] per TWh	0.002		A
crops	total	add. fertil. needed [kg]	-2.8E+04	[kg] per TWh	-0.01		A
SO_2							
crops	barley	yield loss [dt]	0	[dt] per TWh	0		A
crops	potato	yield loss [dt]	0	[dt] per TWh	0		A
crops	wheat	yield loss [dt]	0	[dt] per TWh	0		A
crops	sugar beet	yield loss [dt]	0	[dt] per TWh	0		A
crops	oats	yield loss [dt]	0	[dt] per TWh	0		A
crops	rye	yield loss [dt]	0	[dt] per TWh	0		A
Ozone							
crops	total	yield loss [dt]			0.01	490	B
Air pollution x ecosystems							
ecosystems	alk. unimpr. grass	Relative exceedance	0.6	[km2] per TWh	na		B
ecosystems	alpine meadows	weighted N deposition	2.1	[km2] per TWh	na		B
ecosystems	beech, various oaks	exceedance area	3.9	[km2] per TWh	na		B
ecosystems	birch, pine, ... mix		21.0	[km2] per TWh	na		B
ecosystems	mediterranean scrub		0.03	[km2] per TWh	na		B
ecosystems	non-alk.unimpr.grass		1.3	[km2] per TWh	na		B
ecosystems	peat bog		0.7	[km2] per TWh	na		B
ecosystems	swamp marsh		0.05	[km2] per TWh	na		B
ecosystems	tundra/rock/ice		0.5	[km2] per TWh	na		B
ecosystems	total	Relative exceedance weighted NOx exceedance area	0	[km2] per TWh	na		B
ecosystems	total	Relative exceedance weighted SO2 exceedance area	0	[km2] per TWh	na		B
Air pollution x human health							
NOx-all from nitrate aerosol							
Acute effects							
human	above_65_yrs	congestive heart failure	0.18	[case] per TWh	0.0013		B

			Impacts		Damages		
Receptor	**ReceptorSubGroup**	**Impact**	**per TWh**	**Units**	**mECU/kWh**	**ECU/tpoll**	**s_g**
human	adults	Restr. activity days	1056	[days] per TWh	0.076		B
human	asthma_adults	Bronchodilator usage	241	[case] per TWh	0.0085		B
human	asthma_adults	cough	248	[day] per TWh	0.0017		A
human	asthma_adults	Lower resp. symptoms	90	[days] per TWh	0.00064		A
human	asthma_children	Bronchodilator usage	48	[case] per TWh	0.0017		B
human	asthma_children	cough	83	[day] per TWh	0.00056		A
human	asthma_children	Lower resp. symptoms	64	[days] per TWh	0.00046		A
human	total	resp. hosp. admission	0.15	[case] per TWh	0.0012		A
human	total	cerebrovascular hosp. adm	0.37	[case] per TWh	0.0028		B
Chronic effects							
human	adults	’chronic’ mortality	3.0	[deaths] per TWh			B
human	adults	’chronic’ YOLL	30	[years] per TWh	2.4		B
human	adults	chronic bronchitis	2.1	[cases] per TWh	0.21		A
human	children	chronic cough	37	[episode] per TWh	0.0079		B
human	children	case of chr. bronchitis	29	[case] per TWh	0.0062		B
NOx-via ozone							
Acute effects							
human	total	mortality			7.01E-01	4.12E+02	B
human	total	morbidity			1.25E+00	7.32E+02	B
SO2-all from sulphate, unless marked SO_2							
Acute effects							
human	total	acute’ mortality SO_2		[deaths] per TWh			B
human	total	acute’ YOLL SO_2		[years] per TWh			B
human	total	resp. hosp. admission		[case] per TWh			A
human	above_65_yrs	congestive heart failure		[case] per TWh			B
human	adults	Restr. activity days		[days] per TWh			B
human	asthma_adults	Bronchodilator usage		[case] per TWh			B
human	asthma_adults	cough		[day] per TWh			A
human	asthma_adults	Lower resp. symptoms		[days] per TWh			A
human	asthma_children	Bronchodilator usage		[case] per TWh			B
human	asthma_children	cough		[day] per TWh			A
human	asthma_children	Lower resp. symptoms		[days] per TWh			A
human	total	cerebrovascular hosp. adm		[case] per TWh			B
Chronic effects							
human	adults	’chronic’ mortality		[deaths] per TWh			B
human	adults	’chronic’ YOLL		[years] per TWh			B
human	adults	chronic bronchitis		[cases] per TWh			A
human	children	chronic cough		[episode] per TWh			B
human	children	case of chr. bronchitis		[case] per TWh			B
Primary PM_{10}							
Acute effects							
human	above_65_yrs	congestive heart failure		[case] per TWh			B
human	adults	Restr. activity days		[days] per TWh			B
human	asthma_adults	Bronchodilator usage		[case] per TWh			B
human	asthma_adults	cough		[day] per TWh			A
human	asthma_adults	Lower resp. symptoms		[days] per TWh			A
human	asthma_children	Bronchodilator usage		[case] per TWh			B
human	asthma_children	cough		[day] per TWh			A
human	asthma_children	Lower resp. symptoms		[days] per TWh			A
human	total	resp. hosp. admission		[case] per TWh			A
human	total	cerebrovascular hosp. adm		[case] per TWh			B
Chronic effects							
human	adults	’chronic’ mortality		[deaths] per TWh			B
human	adults	’chronic’ YOLL		[years] per TWh			B
human	adults	chronic bronchitis		[cases] per TWh			A
human	children	chronic cough		[episode] per TWh			B
human	children	case of chr. bronchitis		[case] per TWh			B
Air pollution x materials							
SO_2 and acid deposition							
material	galvanised st.	maintenance surface (m2)	228	[m2] per TWh	0.007		B

			Impacts		Damages		
Receptor	**ReceptorSubGroup**	**Impact**	**per TWh**	**Units**	**mECU/kWh**	**ECU/tpoll**	**s_g**
material	limestone	maintenance surface (m2)	0.5	[m2] per TWh	0.0001		B
material	mortar	maintenance surface (m2)	2.1	[m2] per TWh	0.00006		B
material	natural stone	maintenance surface (m2)	0.4	[m2] per TWh	0.0001		B
material	paint	maintenance surface (m2)	5664	[m2] per TWh	0.07		B
material	rendering	maintenance surface (m2)	60.7	[m2] per TWh	0.002		B
material	sandstone	maintenance surface (m2)	0.6	[m2] per TWh	0.0002		B
material	zinc	maintenance surface (m2)	28.5	[m2] per TWh	0.0007		B
Occupational accidents							
human	workers	occupational accidents	0.00024	deaths	5.3E-02	na	A
human	workers	occupational accidents	0.0053	major injuries	5.6E-02	na	A
human	workers	occupational accidents	0.25	minor injuries	3.2E-02	na	A
Global warming x CO_2, CH_4 and N_2O							
		Damages assessed together with all other process steps					
1.+2. Upstream processes together							
Air pollution x crops							
Acidity							
crops	total	add. lime needed in kg	0.2E+05	[kg] per TWh	0.0004		A
crops	total	add. fertil. needed [kg]	-0.6E+04	[kg] per TWh	-0.003		A
SO_2							
crops	barley	yield loss [dt]	-0.6	[dt] per TWh	-0.000004		A
crops	potato	yield loss [dt]	-5.1	[dt] per TWh	-0.00005		A
crops	wheat	yield loss [dt]	18.5	[dt] per TWh	0.0002		A
crops	sugar beet	yield loss [dt]	-2.8	[dt] per TWh	-0.00001		A
crops	oats	yield loss [dt]	0.4	[dt] per TWh	0.000003		A
crops	rye	yield loss [dt]	-1.0	[dt] per TWh	-0.00002		A
Ozone							
crops	total	yield loss [dt]			0.002	490	B
Air pollution x human health							
NOx-all from nitrate aerosol							
Acute effects							
human	above_65_yrs	congestive heart failure	0.072	[case] per TWh	5.4e-4		B
human	adults	Restr. activity days	427	[days] per TWh	3.1e-2		B
human	asthma_adults	Bronchodilator usage	98	[case] per TWh	3.5e-3		B
human	asthma_adults	cough	101	[day] per TWh	6.7e-4		A
human	asthma_adults	Lower resp. symptoms	36	[days] per TWh	2.6e-4		A
human	asthma_children	Bronchodilator usage	77	[case] per TWh	2.7e-3		B
human	asthma_children	cough	126	[day] per TWh	8.4e-4		A
human	asthma_children	Lower resp. symptoms	94	[days] per TWh	6.7e-4		A
human	total	resp. hosp. admission	0.062	[case] per TWh	4.7e-4		A
human	total	cerebrovascular hosp. adm	0.15	[case] per TWh	1.1e-3		B
Chronic effects							
human	adults	’chronic’ mortality	1.2	[deaths] per TWh			B
human	adults	’chronic’ YOLL	12	[years] per TWh	9.9e-1		B
human	adults	chronic bronchitis	0.84	[cases] per TWh	8.4e-2		A
human	children	chronic cough	15	[episode] per TWh	3.2e-3		B
human	children	case of chr. bronchitis	12	[case] per TWh	2.5e-3		B
NOx-via ozone							
Acute effects							
human	total	mortality			7.01E-01	4.12E+02	B
human	total	morbidity			1.25E+00	7.32E+02	B
SO2-all from sulphate, unless marked SO_2							
Acute effects							
human	total	acute’ mortality SO_2	x-negligible	[deaths] per TWh			B
human	total	acute’ YOLL SO_2	x-negligible	[years] per TWh			B
human	total	resp. hosp. admission	x-negligible	[case] per TWh			A
human	above_65_yrs	congestive heart failure	x-negligible	[case] per TWh			B
human	adults	Restr. activity days	x-negligible	[days] per TWh			B
human	asthma_adults	Bronchodilator usage	x-negligible	[case] per TWh			B
human	asthma_adults	cough	x-negligible	[day] per TWh			A
human	asthma_adults	Lower resp. symptoms	x-negligible	[days] per TWh			A

			Impacts		**Damages**		
Receptor	**ReceptorSubGroup**	**Impact**	**per TWh**	**Units**	**mECU/kWh**	**ECU/tpoll**	**s_g**
human	asthma_children	Bronchodilator usage	x-negligible	[case] per TWh			B
human	asthma_children	cough	x-negligible	[day] per TWh			A
human	asthma_children	Lower resp. symptoms	x-negligible	[days] per TWh			A
human	total	cerebrovascular hosp. adm	x-negligible	[case] per TWh			B
Chronic effects							
human	adults	’chronic’ mortality	x-negligible	[deaths] per TWh			B
human	adults	’chronic’ YOLL	x-negligible	[years] per TWh			B
human	adults	chronic bronchitis	x-negligible	[cases] per TWh			A
human	children	chronic cough	x-negligible	[episode] per TWh			B
human	children	case of chr. bronchitis	x-negligible	[case] per TWh			B
Primary PM_{10}							
Acute effects							
human	above_65_yrs	congestive heart failure	0.023	[case] per TWh	1.7e-4		B
human	adults	Restr. activity days	135	[days] per TWh	9.7e-3		B
human	asthma_adults	Bronchodilator usage	31	[case] per TWh	1.1e-3		B
human	asthma_adults	cough	32	[day] per TWh	2.1e-4		A
human	asthma_adults	Lower resp. symptoms	12	[days] per TWh	8.2e-5		A
human	asthma_children	Bronchodilator usage	6.2	[case] per TWh	2.2e-4		B
human	asthma_children	cough	11	[day] per TWh	7.1e-5		A
human	asthma_children	Lower resp. symptoms	8.2	[days] per TWh	5.9e-5		A
human	total	resp. hosp. admission	0.020	[case] per TWh	1.5e-4		A
human	total	cerebrovascular hosp. adm	0.048	[case] per TWh	3.6e-4		B
Chronic effects							
human	adults	’chronic’ mortality	0.39	[deaths] per TWh			B
human	adults	’chronic’ YOLL	3.9	[years] per TWh	3.1e-1		B
human	adults	chronic bronchitis	0.27	[cases] per TWh	2.7e-2		A
human	children	chronic cough	4.7	[episode] per TWh	1.0e-3		B
human	children	case of chr. bronchitis	3.7	[case] per TWh	7.9e-4		B
Air pollution x materials							
SO_2 and acid deposition							
material	galvanised st.	maintenance surface (m2)	56	[m2] per TWh	0.0005		B
material	limestone	maintenance surface (m2)	0.1	[m2] per TWh	0.00004		B
material	mortar	maintenance surface (m2)	0.6	[m2] per TWh	0.00002		B
material	natural stone	maintenance surface (m2)	0.1	[m2] per TWh	0.00004		B
material	paint	maintenance surface (m2)	1311	[m2] per TWh	0.02		B
material	rendering	maintenance surface (m2)	15	[m2] per TWh	0.0005		B
material	sandstone	maintenance surface (m2)	0.2	[m2] per TWh	0.0005		B
material	zinc	maintenance surface (m2)	7	[m2] per TWh	0.0002		B
1.+2.+3. All processes together							
Global warming x CO_2, CH_4 and N_2O		mECU/kWh					
	low	1.5					
	mid 3%	7.2					
	mid 1%	18.3					
	high	55.5					

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12 DEFINITION OF THE BIOMASS FUEL CYCLE, DATA AND RESULTS

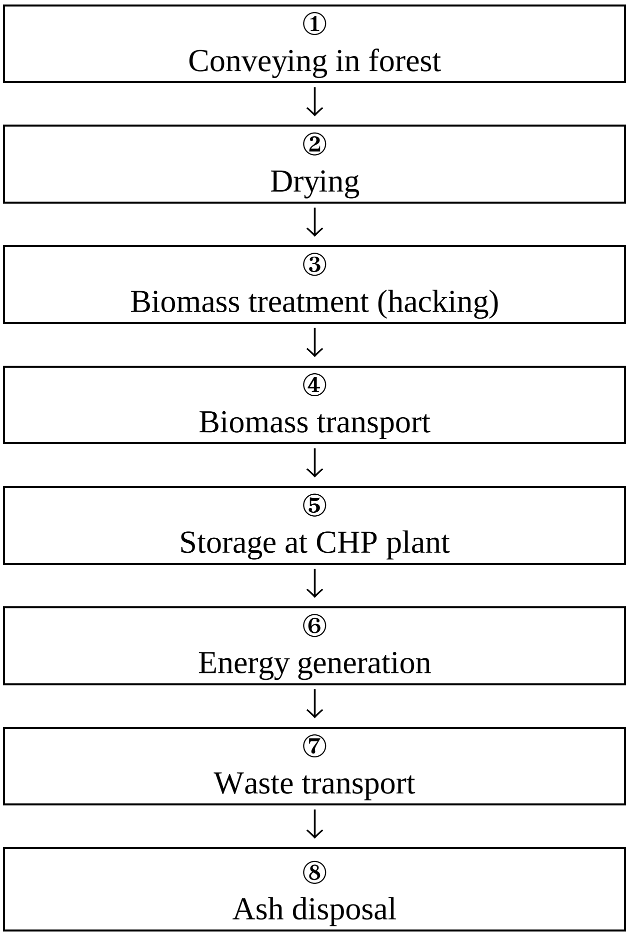

Figure AVIII.5 Biomass fuel cycle

Table 12.13 Definition of the biomass fuel cycle

Stage	Parameter	Quantity / Characteristic	Source of data
Fuel properties			
	Tree species	Norway Spruce	Kaltschmitt, Reinhardt (1997)
	Calorific value		Hartmann, Strehler (1995), Vetter *et al.* (1995), Hofbauer *et al.* (1994), Fritsche *et al.* (1994), Strehler, Gessner (1991), Kaltschmitt, Reinhardt (1997)
	MJ/kg dry mass	18.7	
	MJ/kg	10.2 (67 % humidity)	
	Composition		
	C	50.9%	
	H	6.6%	
	O	42.0%	
	N	0.2%	
	S	0.01%	
	Cl	0.01%	
	Ash	0.3%	
1. Conveying in forest			
	Mode of transport	by tractor, mostly on forest roads	Kaltschmitt, Reinhardt (1997)
	Distance to storage site	2 km	Kaltschmitt, Reinhardt (1997)
2. Drying			
	Mode of operation	drying while stored at edge of forest	Kaltschmitt, Reinhardt (1997)
3. Hacking			
	Mode of operation	Mobile hacker	Kaltschmitt, Reinhardt (1997)
	Number of loads per year	not specified	
	Quantity transported per year	not specified	
4. Biomass transport			
	Distance to power station	20 km	Kaltschmitt, Reinhardt (1997)
	Mode of transport	100% road, trucks class D	Kaltschmitt, Reinhardt (1997)
	Number of loads per year		
	Quantity transported per year		
	Characteristics of biomass transported	Chopped wood	
5. Storage at CHP plant			
	Storage capacity	1 week of energy consumption	Kaltschmitt, Reinhardt (1997)
6. Energy generation			
	Fuel	Wood chips	

Stage	Parameter	Quantity / Characteristic	Source of data
	Type of plant	Cogeneration unit	
	Location	Tübingen, Germany	
	Power generation capacity:		
	heat	12.8 MWth	Suttor (1995)
	net electric	3.6 MWe	Suttor (1995)
	Thermal net efficiency	64.0 %	Suttor (1995)
	Electric net efficiency	18.0 %	Suttor (1995)
	Total net efficiency	85.0 %	Suttor (1995)
	Full load hours per year	3000 h/year	
	Energy sent out:		
	thermal (GJ/yr)	138 240	
	electric (GWh/yr)	10.8	
	Lifetime (years)	30	
	Pollution control:		
	Multicyclone, fibrous filter		
	Plant characteristics:		
	land area required		
	height of stack	40 m	
	diameter of stack	4 m	
	surface elevation at site		
	Consumables:		
	wood chips (t dry mass /yr)	11 551	
	other		
	Other characteristics:		
	flue gas temperature (K)	373.15	
	flue gas volume (Nm^3/h)	23 730	
7. Transport of waste		Ashes	
	Type of waste	Cyclone and filter ash	
	Distance to energy generation unit (km)	20 km (cyclone ash) 100 km (filter ash)	Kaltschmitt, Reinhardt (1997)
	Mode of transport	100% road, trucks class E (cyclone ash) 100% road, trucks class B (filter ash)	Kaltschmitt, Reinhardt (1997)
	Number of loads per year		
	Quantity transported per year	35 t/yr cyclone ash 3 t/yr filter ash	Kaltschmitt, Reinhardt (1997)
8. Waste disposal			
	Type	Landfill (cyclone ash) Agricultural area (filter ash)	Kaltschmitt, Reinhardt (1997)
	Site		

Table 12.14 Burdens of the biomass fuel cycle

Stage	Burden	Quantity	Source of data	Impact assessed?
1. Conveying in forest				
	Occupational health			
	accidents - fatal	0.32/Mm^3 timber	BMELF (1993),	✓
	accidents - major injury	8.6//Mm^3 timber	BMA (several	✓
	accidents - minor injury	160//Mm^3 timber	years)	✓
	Air emissions			
	CO_2	53.2 t/yr	Kaltschmitt, Reinhardt (1997)	✓
	CO	193.2 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	SO_2	16.7 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	NO_x	552.1 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	Particulates	0.0 kg/yr	Kaltschmitt, Reinhardt (1997)	negligible
	Diesel particulates	49.2 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	CH_4	2.1 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	NMHC	87.8 kg/yr	Kaltschmitt, Reinhardt (1997)	
	Benzene	1.7 kg/yr	Kaltschmitt, Reinhardt (1997)	
	Benzo(*a*)pyrene	102.2 mg/yr	Kaltschmitt, Reinhardt (1997)	✓
	N_2O	2.4 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	NH_3	1.9 kg/yr	Kaltschmitt, Reinhardt (1997)	
	HCl	0.3 kg/yr	Kaltschmitt, Reinhardt (1997)	
	Formaldehyde	7.1 kg/yr	Kaltschmitt,	

Stage	Burden	Quantity	Source of data	Impact assessed?
			Reinhardt (1997)	
	TCDD-Equivalent	1.0 µg/yr	Kaltschmitt, Reinhardt (1997)	✓
	Other burdens			
	noise			x - no data
	visual intrusion			x - no data
	soil loss	t/yr		negligible
3. Hacking				
	Air emissions			
	CO_2	201.2 t/yr	Kaltschmitt, Reinhardt (1997)	✓
	CO	355.0 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	SO_2	63.4 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	NO_x	2210.2 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	Particulates	0.0 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	Diesel particulates	143.4 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	CH_4	5.6 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	NMHC	231.6 kg/yr	Kaltschmitt, Reinhardt (1997)	
	Benzene	4.4 kg/yr	Kaltschmitt, Reinhardt (1997)	
	Benzo(*a*)pyrene	500.2 mg/yr	Kaltschmitt, Reinhardt (1997)	✓
	N_2O	9.1 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	NH_3	7.4 kg/yr	Kaltschmitt, Reinhardt (1997)	
	HCl	1.2 kg/yr	Kaltschmitt, Reinhardt (1997)	
	Formaldehyde	18.8 kg/yr	Kaltschmitt, Reinhardt (1997)	

Stage	Burden	Quantity	Source of data	Impact assessed?
	TCDD-Equivalent	3.8 µg/yr	Kaltschmitt, Reinhardt (1997)	
	Other burdens			
	noise			x - no data
4. Biomass transport				
	Occupational health			
	accidents - fatal	0.86/Gtkm	BMV (1992), BMA (several years)	✓
	accidents - major injury	10.9/Gtkm		✓
	accidents - minor injury	345/Gtkm		✓
	Air emissions			
	CO_2	32.2 t/yr	Kaltschmitt, Reinhardt (1997)	✓
	CO	101.5 kg/yr	Kaltschmitt, Reinhardt (1997)	
	SO_2	10.1 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	NO_x	405.9 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	Particulates	0.0 kg/yr	Kaltschmitt, Reinhardt (1997)	
	Diesel particulates	22.3 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	CH_4	1.2 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	VOC	50.7 kg/yr	Kaltschmitt, Reinhardt (1997)	
	Benzene	1.0 kg/yr	Kaltschmitt, Reinhardt (1997)	
	Benzo(*a*)pyrene	78.3 mg/yr	Kaltschmitt, Reinhardt (1997)	
	N_2O	1.5 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	NH_3	1.2 kg/yr	Kaltschmitt, Reinhardt (1997)	
	HCl	0.2 kg/yr	Kaltschmitt, Reinhardt (1997)	
	Formaldehyde	4.1 kg/yr	Kaltschmitt, Reinhardt (1997)	

Stage	Burden	Quantity	Source of data	Impact assessed?
	TCDD-Equivalent	0.6 µg/yr	Kaltschmitt, Reinhardt (1997)	
	Other burdens			
	noise			x - no data
	road use	km/yr		negligible
5. Storage at CHP plant				
	Air emissions			
	CO_2	3.9 t/yr	Kaltschmitt, Reinhardt (1997)	✓
	CO	14.2 kg/yr	Kaltschmitt, Reinhardt (1997)	
	SO_2	1.2 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	NO_x	40.5 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	Particulates	0.0 kg/yr	Kaltschmitt, Reinhardt (1997)	
	Diesel particulates	3.6 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	CH_4	0.2 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	VOC	6.5 kg/yr	Kaltschmitt, Reinhardt (1997)	
	Benzene	0.1 kg/yr	Kaltschmitt, Reinhardt (1997)	
	Benzo(*a*)pyrene	7.5 mg/yr	Kaltschmitt, Reinhardt (1997)	
	N_2O	0.2 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	NH_3	0.1 kg/yr	Kaltschmitt, Reinhardt (1997)	
	HCl	0.0 kg/yr	Kaltschmitt, Reinhardt (1997)	
	Formaldehyde	0.5 kg/yr	Kaltschmitt, Reinhardt (1997)	
	TCDD-Equivalent	0.1 µg/yr	Kaltschmitt, Reinhardt (1997)	

Stage	Burden	Quantity	Source of data	Impact assessed?
	Other burdens			
	noise			x - no data
6. Energy generation				
	Occupational health			
	accidents - fatal	5.9/PWh	Wehovsky *et al.* (1994), BMA (several years)	✓
	accidents - major injury	16.2/PWh		✓
	accidents - minor injury	750/PWh		✓
	Air emissions			
	CO_2	22874.4 t/yr	Kaltschmitt, Reinhardt (1997)	✓
	CO	12005.9 kg/yr	Bobik (1991), Gernhardt *et al.* (1994), Stanzel *et al.* (1995), Kaltschmitt, Reinhardt (1997)	✓
	SO_2	784.6 kg/yr	Obernberger, (1994), Kaltschmitt, Reinhardt (1997)	✓
	NO_x	21010.3 kg/yr	Obernberger, (1994), Nussbaumer (1989), Gernhardt *et al.* (1994), Kaltschmitt, Reinhardt (1997)	✓
	Particulates	618.0 kg/yr	Nussbaumer *et al.* (1994), Kaltschmitt, Reinhardt (1997)	✓
	Diesel particulates	0.0 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	CH_4	120.1 kg/yr	Bobik (1991), Gernhardt *et al.* (1994), Stanzel *et al.* (1995), Kaltschmitt, Reinhardt (1997)	✓
	NMHC	480.3 kg/yr	Bobik (1991), Gernhardt *et al.* (1994), Stanzel *et al.* (1995), Nussbaumer (1989), Kaltschmitt, Reinhardt (1997)	✓
	Benzene	40.3 kg/yr	Bobik (1991),	

Stage	**Burden**	**Quantity**	**Source of data**	**Impact assessed?**
			Gernhardt *et al.* (1994), Stanzel *et al.* (1995), Obermeier (1995), Kaltschmitt, Reinhardt (1997)	
	Benzo(*a*)pyrene	1081.5 mg/yr	Bobik (1991), Kaltschmitt, Reinhardt (1997)	✓
	N_2O	1235.5 kg/yr	Bobik (1991), Gernhardt *et al.* (1994), Stanzel *et al.* (1995), Vitovec (1991), Kaltschmitt, Reinhardt (1997)	✓
	NH_3	0.0 kg/yr	Good, Nussbaumer (1994), Kaltschmitt, Reinhardt (1997)	
	HCl	706.1 kg/yr	Obernberger (1994), Kaltschmitt, Reinhardt (1997)	
	Formaldehyde	kg/yr		x - no data
	TCDD-Equivalent	1544.9 µg/yr	Weber *et al.* (1995), Wurst *et al.* (1995), Wilken *et al.* (1993), Bobik (1991), BUWAL (1993), Kaltschmitt, Reinhardt (1997)	✓
	Solid waste emissions			
	Cyclone ash	35 t/yr	Kaltschmitt, Reinhardt, 1997	
	Filter ash	3 t/yr	Kaltschmitt, Reinhardt (1997)	
	Other burdens			
	noise			x - no data
7. Transport of waste				
	Air emissions			
	CO_2	0.1 t/yr	Kaltschmitt, Reinhardt (1997)	✓

Stage	Burden	Quantity	Source of data	Impact assessed?
	CO	0.3 kg/yr	Kaltschmitt, Reinhardt (1997)	
	SO_2	0.0 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	NO_x	1.0 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	Particulates	0.0 kg/yr	Kaltschmitt, Reinhardt (1997)	
	Diesel particulates	0.1 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	CH_4	0.0 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	VOC	0.1 kg/yr	Kaltschmitt, Reinhardt (1997)	
	Benzene	0.0 kg/yr	Kaltschmitt, Reinhardt (1997)	
	Benzo(*a*)pyrene	0.2 mg/yr	Kaltschmitt, Reinhardt (1997)	
	N_2O	0.0 kg/yr	Kaltschmitt, Reinhardt (1997)	✓
	NH_3	0.0 kg/yr	Kaltschmitt, Reinhardt (1997)	
	HCl	0.0 kg/yr	Kaltschmitt, Reinhardt (1997)	
	Formaldehyde	0.0 kg/yr	Kaltschmitt, Reinhardt (1997)	
	TCDD-Equivalent	0.0 µg/yr	Kaltschmitt, Reinhardt (1997)	
	Other burdens			
	noise			x - no data
	road use	km/yr		negligible

Table 12.15 Impacts and damages of the biomass fuel cycle

			Impacts		Damages		
Receptor	**ReceptorSubGroup**	**Impact**	**per year**	**Units**	**ECU/year**	**ECU/tpoll**	**s_g**
1.+2.+3. Harvest							
Occupational accidents							
human	workers	occupational accidents	0.3	deaths	636750	na	A
human	workers	occupational accidents	7.9	major injuries	227580	na	A
human	workers	occupational accidents	148.4	minor injuries	216740	na	A
Air Pollution Effects							
		Impacts and damages assessed together with other upstream processes					
Global warming x CO_2, CH_4 and N_2O							
		Damages assessed together with all other process steps					
4. Biomass transport							
Occupational accidents							
human	workers	occupational accidents	0.0004	deaths	608.3	na	A
human	workers	occupational accidents	0.005	major injuries	51.8	na	A
human	workers	occupational accidents	0.1	minor injuries	49.6	na	A
Public accidents							
human	total	public accidents	na	deaths	na	na	A
human	total	public accidents	na	major injuries	na	na	A
human	total	public accidents	na	minor injuries	na	na	A
Air Pollution Effects							
		Impacts and damages assessed together with other upstream processes					
Global warming x CO_2, CH_4 and N_2O							
		Damages assessed together with all other process steps					
6. Energy generation							
Air pollution x crops							
Acidity							
crops	total	add. lime needed in kg	399.0	[kg]	6.9		A
crops	total	add. fertil. needed [kg]	-107.1	[kg]	-525		A
SO_2							
crops	barley	yield loss [dt]	-0.07	[dt]	-0.4		A
crops	potato	yield loss [dt]	-0.5	[dt]	-4.7		A
crops	wheat	yield loss [dt]	-0.04	[dt]	-0.4		A
crops	sugar beet	yield loss [dt]	-0.3	[dt]	-1.5		A
crops	oats	yield loss [dt]	0.02	[dt]	0.1		A
crops	rye	yield loss [dt]	-0.09	[dt]	-1.6		A
Ozone							
crops	total	yield loss [dt]			7427		B
Air pollution x ecosystems							
ecosystems	alk. unimpr. grass	Relative exceedance	29430	[km2]	na		B
ecosystems	alpine meadows	weighted N deposition	100350	[km2]	na		B
ecosystems	beech, various oaks	exceedance area	149880	[km2]	na		B
ecosystems	birch, pine, ... mix		879690	[km2]	na		B
ecosystems	mediterranean scrub		951	[km2]	na		B
ecosystems	non-alk.unimpr.grass		74490	[km2]	na		B
ecosystems	peat bog		25710	[km2]	na		B
ecosystems	swamp marsh		3930	[km2]	na		B
ecosystems	tundra/rock/ice		16740	[km2]	na		B
ecosystems	total	Relative exceedance weighted NOx exceedance area	0	[km2]	na		B
ecosystems	total	Relative exceedance weighted SO2 exceedance area	16170	[km2]	na		B
Air pollution x human health							
NOx-all from nitrate aerosol							
Acute effects							
human	above_65_yrs	congestive heart failure	0.02	[case]	171.9		B

			Impacts		Damages		
Receptor	**ReceptorSubGroup**	**Impact**	**per year**	**Units**	**ECU/year**	**ECU/tpoll**	**s_g**
human	adults	Restr. activity days	129.2	[days]	9684.0		B
human	asthma_adults	Bronchodilator usage	29.5	[case]	1092.0		B
human	asthma_adults	cough	30.4	[day]	212.5		A
human	asthma_adults	Lower resp. symptoms	11.0	[days]	82.4		A
human	asthma_children	Bronchodilator usage	5.9	[case]	218.7		B
human	asthma_children	cough	10.2	[day]	71.3		A
human	asthma_children	Lower resp. symptoms	7.8	[days]	58.9		A
human	total	resp. hosp. admission	0.02	[case]	147.9		A
human	total	cerebrovascular hosp. adm	0.05	[case]	360.3		B
Chronic effects							
human	adults	’chronic’ mortality	0.4	[deaths]	1155745	55008	B
human	adults	’chronic’ YOLL	3.7	[years]	314400	14964	B
human	adults	chronic bronchitis	0.3	[cases]	26631	1268	A
human	children	chronic cough	4.5	[episode]	1014.9		B
human	children	case of chr. bronchitis	3.5	[case]	789.6		B
NOx-via ozone							
Acute effects							
human	total	mortality			8933		B
human	total	morbidity			15380		B
SO2-all from sulphate, unless marked SO_2							
Acute effects							
human	total	acute’ mortality SO_2	na	[deaths]	na		B
human	total	acute’ YOLL SO_2	0.002	[years]	351.0		B
human	total	resp. hosp. admission	0.001	[case]	4.2		A
human	above_65_yrs	congestive heart failure	0.001	[case]	4.8		B
human	adults	Restr. activity days	3.6	[days]	270.8		B
human	asthma_adults	Bronchodilator usage	0.8	[case]	30.5		B
human	asthma_adults	cough	0.9	[day]	6.0		A
human	asthma_adults	Lower resp. symptoms	0.3	[days]	2.3		A
human	asthma_children	Bronchodilator usage	0.2	[case]	6.1		B
human	asthma_children	cough	0.3	[day]	2.0		A
human	asthma_children	Lower resp. symptoms	0.2	[days]	1.7		A
human	total	cerebrovascular hosp. adm	0.001	[case]	10.1		B
Chronic effects							
human	adults	’chronic’ mortality	0.01	[deaths]	na		B
human	adults	’chronic’ YOLL	0.1	[years]	8793	11207	B
human	adults	chronic bronchitis	0.007	[cases]	711.6		A
human	children	chronic cough	0.1	[episode]	28.5		B
human	children	case of chr. bronchitis	0.1	[case]	22.1		B
Primary PM_{10}							
Acute effects							
human	above_65_yrs	congestive heart failure	0.0008	[case]	6.6		B
human	adults	Restr. activity days	4.9	[days]	371.1		B
human	asthma_adults	Bronchodilator usage	1.1	[case]	41.8		B
human	asthma_adults	cough	1.2	[day]	8.1		A
human	asthma_adults	Lower resp. symptoms	0.4	[days]	3.2		A
human	asthma_children	Bronchodilator usage	0.2	[case]	8.4		B
human	asthma_children	cough	0.4	[day]	2.7		A
human	asthma_children	Lower resp. symptoms	0.3	[days]	2.3		A
human	total	resp. hosp. admission	0.0007	[case]	5.7		A
human	total	cerebrovascular hosp. adm	0.002	[case]	13.8		B
Chronic effects							
human	adults	’chronic’ mortality	0.01	[deaths]	na		B
human	adults	’chronic’ YOLL	0.1	[years]	12039	25014	B
human	adults	chronic bronchitis	0.01	[cases]	1020.3		A
human	children	chronic cough	0.2	[episode]	38.9		B
human	children	case of chr. bronchitis	0.1	[case]	30.2		B
Air pollution x materials							
SO_2 and acid deposition							
material	galvanised st.	maintenance surface (m2)	0.9	[m2]	28.8		B

			Impacts		Damages		
Receptor	**ReceptorSubGroup**	**Impact**	**per year**	**Units**	**ECU/year**	**ECU/tpoll**	s_g
material	limestone	maintenance surface (m2)	0.003	[m2]	0.8		B
material	mortar	maintenance surface (m2)	0.008	[m2]	0.3		B
material	natural stone	maintenance surface (m2)	0.003	[m2]	0.8		B
material	paint	maintenance surface (m2)	12.8	[m2]	161.1		B
material	rendering	maintenance surface (m2)	0.3	[m2]	10.5		B
material	sandstone	maintenance surface (m2)	0.004	[m2]	1.2		B
material	zinc	maintenance surface (m2)	0.1	[m2]	3.1		B
Occupational accidents							
human	workers	occupational accidents	0.00003	deaths	-139.6	na	A
human	workers	occupational accidents	0.0008	major injuries	-35.3	na	A
human	workers	occupational accidents	0.04	minor injuries	-123.8	na	A
Global warming x CO_2, CH_4 and N_2O							
		Damages assessed together with all other process steps					
7. Waste transport							
Air Pollution Effects							
		Impacts and damages assessed together with other upstream processes					
Global warming x CO_2, CH_4 and N_2O							
		Damages assessed together with all other process steps					
1.+2.+3.+4.+5.+7. Upstream processes together							
Air pollution x crops							
Acidity							
crops	total	add. lime needed in kg	606.3	[kg]	10.4		A
crops	total	add. fertil. needed [kg]	-165.4	[kg]	81.3		A
SO_2							
crops	barley	yield loss [dt]	-0.1	[dt]	-0.7		A
crops	potato	yield loss [dt]	-0.2	[dt]	-2.0		A
crops	wheat	yield loss [dt]	-0.2	[dt]	-2.1		A
crops	sugar beet	yield loss [dt]	-0.2	[dt]	-1.2		A
crops	oats	yield loss [dt]	-0.004	[dt]	-0.02		A
crops	rye	yield loss [dt]	-0.02	[dt]	-0.3		A
Ozone							
crops	total	yield loss [dt]			1196	490	B
Air pollution x human health							
NOx-all from nitrate aerosol							
Acute effects							
human	above_65_yrs	congestive heart failure	0.003	[case]	26.7		B
human	adults	Restr. activity days	20.1	[days]	1505.1		B
human	asthma_adults	Bronchodilator usage	4.6	[case]	170.0		B
human	asthma_adults	cough	4.7	[day]	33.0		A
human	asthma_adults	Lower resp. symptoms	1.7	[days]	13.0		A
human	asthma_children	Bronchodilator usage	0.9	[case]	34.0		B
human	asthma_children	cough	1.6	[day]	11.1		A
human	asthma_children	Lower resp. symptoms	1.2	[days]	9.1		A
human	total	resp. hosp. admission	0.003	[case]	23.0		A
human	total	cerebrovascular hosp. adm	0.007	[case]	56.0		B
Chronic effects							
human	adults	’chronic’ mortality	0.06	[deaths]	na		B
human	adults	’chronic’ YOLL	0.6	[years]	48840		B
human	adults	chronic bronchitis	0.04	[cases]	4137		A
human	children	chronic cough	0.7	[episode]	157.7		B
human	children	case of chr. bronchitis	0.5	[case]	122.7		B
NOx-via ozone							
Acute effects							
human	total	mortality			1322		B
human	total	morbidity			2621		B
SO2-all from sulphate, unless marked SO_2							
Acute effects							
human	total	acute’ mortality SO_2	na	[deaths]	na		B
human	total	acute’ YOLL SO_2	0.0002	[years]	34.4		B
human	total	resp. hosp. admission	0.00006	[case]	0.5		A

			Impacts		Damages		
Receptor	ReceptorSubGroup	Impact	per year	Units	ECU/year	ECU/tpoll	s_g
human	above_65_yrs	congestive heart failure	0.00007	[case]	0.5		B
human	adults	Restr. activity days	0.4	[days]	29.4		B
human	asthma_adults	Bronchodilator usage	0.09	[case]	3.3		B
human	asthma_adults	cough	0.09	[day]	0.6		A
human	asthma_adults	Lower resp. symptoms	0.03	[days]	0.3		A
human	asthma_children	Bronchodilator usage	0.02	[case]	0.7		B
human	asthma_children	cough	0.03	[day]	0.2		A
human	asthma_children	Lower resp. symptoms	0.02	[days]	0.2		A
human	total	cerebrovascular hosp. adm	0.0001	[case]	1.1		B
Chronic effects							
human	adults	’chronic’ mortality	0.001	[deaths]			B
human	adults	’chronic’ YOLL	0.01	[years]	954.6		B
human	adults	chronic bronchitis	0.0007	[cases]	77.3		A
human	children	chronic cough	0.01	[episode]	3.1		B
human	children	case of chr. bronchitis	0.01	[case]	2.4		B
Primary PM_{10}							
Acute effects							
human	above_65_yrs	congestive heart failure	0.0005	[case]	3.8		B
human	adults	Restr. activity days	2.9	[days]	215.6		B
human	asthma_adults	Bronchodilator usage	0.7	[case]	24.3		B
human	asthma_adults	cough	0.7	[day]	4.7		A
human	asthma_adults	Lower resp. symptoms	0.2	[days]	1.8		A
human	asthma_children	Bronchodilator usage	0.1	[case]	4.9		B
human	asthma_children	cough	0.2	[day]	1.6		A
human	asthma_children	Lower resp. symptoms	0.2	[days]	1.3		A
human	total	resp. hosp. admission	0.0004	[case]	3.3		A
human	total	cerebrovascular hosp. adm	0.001	[case]	8.0		B
Chronic effects							
human	adults	’chronic’ mortality	0.008	[deaths]	na		B
human	adults	’chronic’ YOLL	0.08	[years]	7002		B
human	adults	chronic bronchitis	0.005	[cases]	566.7		A
human	children	chronic cough	0.1	[episode]	22.7		B
human	children	case of chr. bronchitis	0.08	[case]	17.6		B
Air pollution x materials							
SO_2 and acid deposition							
material	galvanised st.	maintenance surface (m2)	1.5	[m2]	43.9		B
material	limestone	maintenance surface (m2)	0.003	[m2]	1.1		B
material	mortar	maintenance surface (m2)	0.02	[m2]	0.5		B
material	natural stone	maintenance surface (m2)	0.003	[m2]	0.9		B
material	paint	maintenance surface (m2)	38.8	[m2]	487.8		B
material	rendering	maintenance surface (m2)	0.4	[m2]	13.5		B
material	sandstone	maintenance surface (m2)	0.005	[m2]	1.3		B
material	zinc	maintenance surface (m2)	0.2	[m2]	5.7		B
1.+2.+5.+6.+8. All processes together							
Global warming x CO_2, CH_4 and N_2O		ECU/year					
	low		2585				
	mid 3%		12246				
	mid 1%		31293				
	high		94558				

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13 DEFINITION OF THE NUCLEAR FUEL CYCLE, DATA AND RESULTS

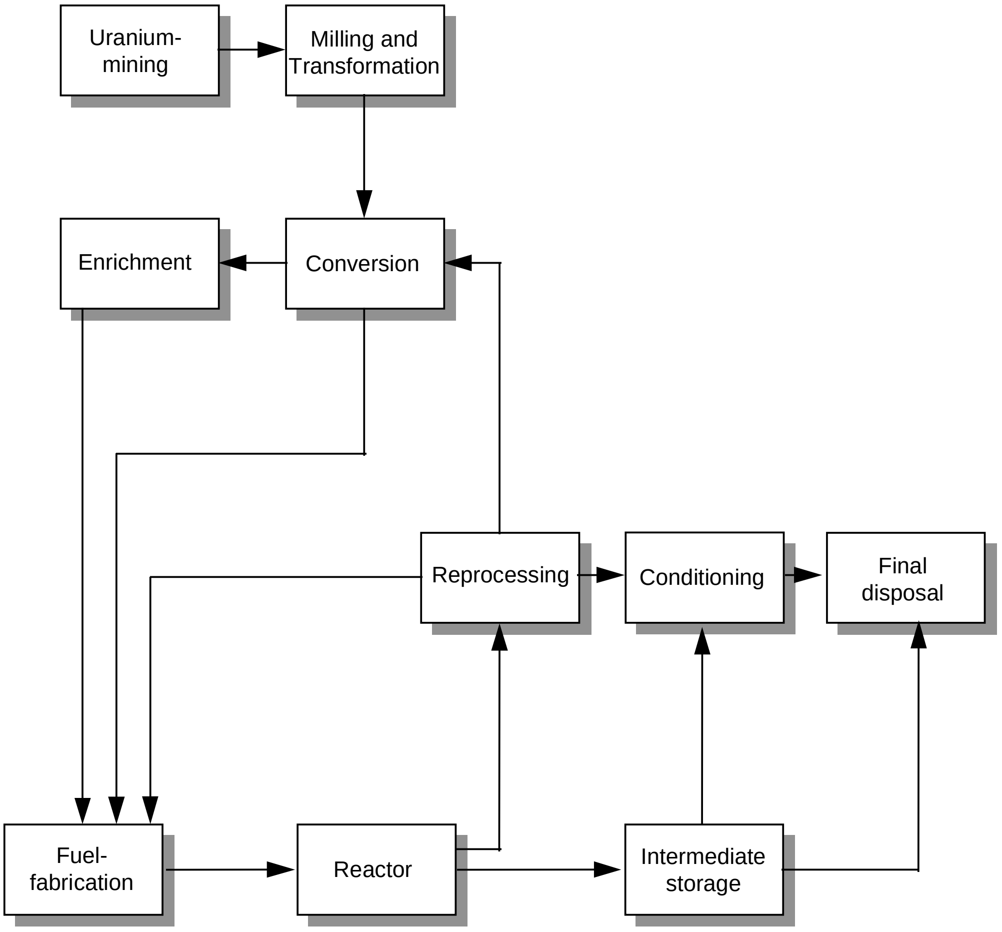

Figure 13.6 Process steps of the German nuclear fuel cycle

Table 13.16 Fuel cycle characteristics of the nuclear fuel cycle

Stage	Parameter	Value	Source
1. Mining and milling			
	Power plant requirements:		
	Uranium ore mined	23.7 t/TWh	based on (Wehowsky et al., 1994)
	Origin of the uranium		
	Canada		
	Ore grade	0.84 %	(UNSCEAR, 1993)
	Type of mining	open pit	
2. Conversion			
	Operated by	COMHUREX, France	(CEPN, 1995)
	Conversion to UF_4		
	location	Malvesi, France	
	capacity	11 000 t/yr	
	Conversion to UF_6		
	location	Pierrelatte, France	
	capacity	8 700 t/yr	
	Power plant requirements:		
	UF_6	20.03 t/TWh	based on (Wehowsky et al., 1994)
3. Enrichment			
	Gasdiffusion		(CEPN, 1995)
	operated by	EURODIF, France	
	location	Pierrelatte, France	
	electricity use	nuclear power plant Tricastin, France	
4. Fuel fabrication			
	UO_2 - fuel		(CEPN, 1995)
	operated by	FBFC	
	location	Pierrelatte, France	
	capacity	600 t_{UO2}/yr	
	Power plant requirements:		
	UO_2	2.29 t/TWh (24.6 t/yr)	(Wehowsky et al., 1994)
5. Power generation			
	Fuel	UO_2	(Wehowsky et al., 1994)
	Technology	PWR	
	Location	Southwest of Germany	
	Installed power	1400 MWe	
	Load factor	89%	
	Burn-up	50 MWd/kg	
6. Reprocessing			
	Operated by	COGEMA	(CEPN, 1995)
	Location	La Hague, France	
	Procedure	PUREX	
	Capacatity of UP3 plant	800 t/yr	
	Power plant requirements	2.29 t/TWh	
7. Waste disposal			
	Underground		
	Surface		
8. Transportation	all transportation steps	road, rail	(CEPN, 1995)

Table 13.17 Quantification of burdens from the nuclear fuel cycle

Stage	**Burden**	**Quantity**	**Source**	**Impact assessed**
1. Mining and milling				
	Radioactive emissions			
	liquid	n. q.		
	U-238			
	Ra-222			
	gaseous			
	U-238			
	Ra-222		UNSCEAR,1993	✔
	mining	18.8 TBq/TWh		
	milling	0.11 TBq/TWh		
	mill tailings in operation	1.1 TBq/TWh		
	abandoned mill tailings	1.1e3 TBq/TWh		
	Occupational health			
	accidents - fatal	3.1e-4/TWh		✔
	accidents - major injury	6.8e-3/TWh		✔
	accidents - minor injury	1.4e-1/TWh		✔
	Other burdens			
2. Conversion				
	Radioactive emissions			
	liquid	n. q.		
	U-234			
	U-225			
	U-238			
	gaseous			
	U-234	3.4e-7 TBq/TWh	(CEPN, 1995)	✔
	U-225	1.5e-8 TBq/TWh	(CEPN, 1995)	✔
	U-238	3.2e-7 TBq/TWh	(CEPN, 1995)	✔
	Occupational health			
	accidents - fatal	1.3e-4/TWh		✔
	accidents - major injury	1.7e-3/TWh		✔
	accidents - minor injury	5.0e-2/TWh		✔
	Other burdens			
3. enrichment				
	Radioactive emissions			
	liquid	n. q.		
	U-234			
	U-225			
	U-238			
	gaseous			
	U-234	1.7e-7 TBq/TWh	(CEPN, 1995)	✔
	U-225	8.9e-9 TBq/TWh	(CEPN, 1995)	✔
	U-238	1.3e-10 TBq/TWh	(CEPN, 1995)	✔
	Occupational health			
	accidents - fatal	2.6e-4/TWh		✔
	accidents - major injury	3.6e-3/TWh		✔
	accidents - minor injury	1.0e-1/TWh		✔

Stage	**Burden**	**Quantity**	**Source**	**Impact assessed**
	Other burdens			
4. Fuel fabrication				
UO_2	Radioactive emissions			
	liquid	n. q.		
	U-234			
	U-225			
	U-238			
	gaseous			
	U-234	1.8e-9 TBq/TWh	(CEPN, 1995)	✔
	U-225	1.3e-10 TBq/TWh	(CEPN, 1995)	✔
	U-238	4.4e-10 TBq/TWh	(CEPN, 1995)	✔
	Occupational health			
	accidents - fatal	1.3e-4/TWh		✔
	accidents - major injury	1.7e-3/TWh		✔
	accidents - minor injury	5.0e-2/TWh		✔
	Other burdens			
5. Power generation				
	Radioactive emissions			
	liquid	n. q.		
	H-3			
	gaseous		(UNSCEAR, 1993)	
	C-14	7.3e-3 TBq/TWh		✔
	H-3	7.9e-2 TBq/TWh		✔
	noble gases	1.5 TBq/TWh		✔
	I-131	9.5e-7 TBq/TWh		✔
	aerosols	3.5e-7 TBq/TWh		✔
	Occupational health			
	accidents - fatal	7.8e-4/TWh		✔
	accidents - major injury	1.7e-2/TWh		✔
	accidents - minor injury	8.1e-1/TWh		✔
	Other burdens			
	major accident	(see Table ???)		✔
6. Reprocessing				
	Radioactive emissions			
	liquid	n. q.		
	H-3			
	C-14			
	I-129			
	Pu-238			
	Pu-239			
	U-238			
	Am-241			
	gaseous			
	C-14	3.8e-2 TBq/TWh	(CEPN, 1995)	✔
	H-3	2.4e-2 TBq/TWh	(CEPN, 1995)	✔
	noble gases	3.8e+2 TBq/TWh	(CEPN, 1995)	✔
	I-129	2.7e-5 TBq/TWh	(CEPN, 1995)	✔
	I-131	3.8e-7 TBq/TWh	(CEPN, 1995)	✔
	I-133	1.7e-7 TBq/TWh	(CEPN, 1995)	✔
	Pu-238	5.4e-12 TBq/TWh	(CEPN, 1995)	✔

Stage	Burden	Quantity	Source	Impact assessed
	Pu-239	1.2e-11 TBq/TWh	(CEPN, 1995)	✔
	Occupational health			
	accidents - fatal	4.0e-4/TWh		✔
	accidents - major injury	5.4e-3/TWh		✔
	accidents - minor injury	1.4e-2/TWh		✔
	Other burdens			
7. Waste disposal				
	Radioactive emissions			
	liquid	n. q.		
	C-14			
	I-129			
	Occupational health	n. q.		
	accidents - fatal			
	accidents - minor injury			
	accidents - major injury			
	Other burdens	n. q.		
8. Transportation				
	Radioactive emissions	n. q.		
	liquid			
	gaseous			
	Occupational health	n. q.		
	accidents - fatal			
	accidents - major injury			
	accidents - minor injury			
9. Construction and dismantling				
	Radioactive emissions	n. q.		
	liquid			
	gaseous			
	Occupational health			
	accidents - fatal	5.7e-3/TWh		✔
	accidents - major injury	1.6e-1/TWh		✔
	accidents - minor injury	6.5/TWh		✔
All stages				
	non-radioactive emissions		(Wiese et al., 1995)	
	SO_2	32 g/MWh		✔
	NO_x	70 g/MWh		✔
	PM_{10}	7 g/MWh		✔
	CO_2	19700 g/MWh		✔

Table 13.18 Fraction of core inventory released for several beyond design accident categories according to German Reactor Safety Study (GRS, 1989). Frequency of occurrence estimated based on (Keßler, 1994).

Accident category	fraction of core inventory released							Frequency of occurrence per year
	Noble gases	Iodines	Alkali metals	Tellurium group	Alkaline earth metals	Noble metals	Metal oxides	
DRSB 1	1		(0.5 - 0.9)		3.6 E-1	1.0 E-5	3.4 E-2	10^{-7}
DRSB 2	1	3.7 E-1	3.7 E-1	2.3 E-1	1.4 E-1	2.5 E-6	1.2 E-2	10^{-7}
DRSB 3	1.7 E-1	1.5 E-1	1.5 E-1	5.0 E-2	6.4 E-4	8.8 E-8	2.1 E-9	10^{-8}
DRSB 4	1.7 E-1	2.5 E-2	2.5 E-2	1.5 E-2	1.2 E-4	1.7 E-8	3.8 E-10	10^{-8}
DRSB 5	1	7.8 E-3	7.8 E-3	2.1 E-3	1.4 E-4	3.6 E-7	1.1 E-5	10^{-6}
DRSB6	9 E-1	2.0 E-3	2.0 E-3	3.5 E-6	1.9 E-7	6.4 E-10	3.3 E-8	10^{-6}

Table 13.19 Quantification of impacts from the nuclear fuel cycle

Stage	Impact	Impact-units	Impact per TWh	Damages mECU/kWh 0% DR	Damages mECU/kWh 3% DR	error estimation
1. Mining and milling						
	Public health					
	collective dose	manSv	16.3			C
	fatal cancers	-	0.82			
	Yoll-approach			1.5	4.5e-3	
	VSL-approach			2.5	8.6e-3	
	non fatal cancers	-	1.9	8.6e-1	2.6e-3	
	hereditary effects	-	0.16	5.0e-1	1.5e-3	
	Occupational health					
	collective dose	manSv	5.8e-3			?
	fatal cancers	-	2.3e-4			
	Yoll-approach			4.2e-4	3.1e-4	
	VSL-approach			7.1e-4	5.3e-4	
	non fatal cancers	-	7.0e-4	3.2e-4	3.2e-4	
	hereditary effects	-	3.5e-5	1.1e-4	1.1e-4	
	accidents - fatal	deaths	3.1e-4	9.6e-4	9.6e-4	
	accidents - major injury		6.8e-3	2.6e-4	2.6e-4	
	accidents - minor injury		1.4e-1	4.6e-4	4.6e-4	
2. Conversion						
	Public health					
	collective dose	manSv	2.9e-5			
	fatal cancers	-	1.5e-6			
	Yoll-approach			2.8e-6	8.2e-9	
	VSL-approach			4.7e-6	1.6e-8	
	non fatal cancers	-	3.5e-6	1.6e-6	4.7e-9	
	hereditary effects	-	2.9e-7	9.0e-7	2.7e-9	
	Occupational health					
	collective dose	manSv	1.9e-3			
	fatal cancers	-	7.5e-5			
	Yoll-approach			1.4e-4	1.0e-4	
	VSL-approach			2.3e-4	1.7e-4	
	non fatal cancers	-	2.2e-4	9.9e-5	9.9e-5	
	hereditary effects	-	1.1e-5	3.4e-5	3.4e-5	
	accidents - fatal		1.3e-4	4.0e-4	4.0e-4	
	accidents - major injury		1.7e-3	6.4e-5	6.4e-5	
	accidents - minor injury		5.0e-2	1.7e-4	1.7e-4	
3. Enrichment						
	Public health					
	collective dose	manSv	2.4e-5			
	fatal cancers	-	1.2e-6			
	Yoll-approach			2.2e-6	6.5e-9	
	VSL-approach			3.7e-6	1.3e-8	
	non fatal cancers	-	2.9e-6	1.3e-6	3.9e-9	
	hereditary effects	-	2.4e-7	7.4e-7	2.2e-9	
	Occupational health					
	collective dose	manSv	7.6e-6			
	fatal cancers	-	3.0e-7			
	Yoll-approach			5.5e-7	4.1e-7	

Stage	**Impact**	**Impact-units**	**Impact per TWh**	**Damages mECU/kWh 0% DR**	**Damages mECU/kWh 3% DR**	**error estimation**
	VSL-approach			9.3e-7	6.9e-7	
	non fatal cancers	-	9.1e-7	4.1e-7	4.1e-7	
	hereditary effects	-	4.6e-9	1.4e-8	1.4e-8	
	accidents - fatal	deaths	2.6e-4	8.1e-4	8.1e-4	
	accidents - major injury		3.6e-3	1.4e-4	1.4e-4	
	accidents - minor injury		1.0e-1	3.3e-4	3.3e-4	
4. Fuel fabrication						
	Public health					
	collective dose	manSv	5.7e-6			
	fatal cancers	-	2.9e-7			
	Yoll-approach			5.3e-7	1.6e-9	
	VSL-approach			9.0e-7	3.0e-9	
	non fatal cancers	-	6.8e-7	3.1e-7	9.2e-10	
	hereditary effects	-	5.7e-8	1.8e-7	5.3e-10	
	Occupational health					
	collective dose	manSv	4.4e-3			
	fatal cancers	-	1.8e-4			
	Yoll-approach			3.3e-4	2.5e-4	
	VSL-approach			5.6e-4	4.1e-4	
	non fatal cancers	-	5.3e-4	2.4e-4	2.4e-4	
	hereditary effects	-	2.6e-5	8.1e-5	8.1e-5	
	accidents - fatal	deaths	1.3e-4	4.0e-4	4.0e-4	
	accidents - major injury		1.7e-3	6.4e-5	6.4e-5	
	accidents - minor injury		5.0e-2	1.7e-4	1.7e-4	
5. Power generation						
5.1 Normal operation						
	Public health					
	collective dose	manSv	6.3e-1			
	fatal cancers	-	3.2e-2			
	Yoll-approach			5.9e-2	1.7e-4	
	VSL-approach			9.9e-2	3.4e-4	
	non fatal cancers	-	7.6e-2	3.4e-2	1.0e-4	
	hereditary effects	-	6.4e-3	2.0e-2	6.0e-5	
	Occupational health					
	collective dose	manSv	3.9e-1			
	fatal cancers	-	1.6e-2			
	Yoll-approach			2.9e-2	2.2e-2	
	VSL-approach			5.0e-2	3.7e-2	
	non fatal cancers	-	4.7e-2	2.1e-2	2.1e-2	
	hereditary effects	-	2.3e-3	7.1e-3	7.1e-3	
	accidents - fatal	deaths	7.8e-4	2.4e-3	2.4e-3	
	accidents - major injury		1.7e-2	6.4e-4	6.4e-4	
	accidents - minor injury		8.1e-1	2.7e-3	2.7e-3	
5.2 Beyond design accidents						
	Public health					
	fatal cancers	-	9.5e-4			
	Yoll-approach			1.7e-3	2.6e-4	
	VSL-approach			2.9e-3	5.1e-5	
	non fatal cancers	-	2.3e-3	1.0e-3	1.5e-4	
	hereditary effects	-	1.9e-4	5.9e-4	8.8e-5	
6. reprocessing						

Stage	Impact	Impact-units	Impact per TWh	Damages mECU/kWh 0% DR	Damages mECU/kWh 3% DR	error estimation
	Public health					
	collective dose	manSv	3.3			
	fatal cancers	-	1.6e-1			
	Yoll-approach			2.9e-1	8.7e-4	
	VSL-approach			5.0e-1	1.7e-3	
	non fatal cancers	-	4.0e-1	1.8e-1	5.4e-4	
	hereditary effects	-	3.3e-2	1.0e-1	3.1e-4	
	Occupational health					
	collective dose	manSv	9.3e-4			
	fatal cancers	-	3.7e-5			
	Yoll-approach			6.8e-5	5.1e-5	
	VSL-approach			1.1e-4	8.5e-5	
	non fatal cancers	-	1.1e-4	5.0e-5	5.0e-5	
	hereditary effects	-	5.6e-6	1.7e-5	1.7e-5	
	accidents - fatal	deaths	4.0e-4	1.2e-3	1.2e-3	
	accidents - major injury		5.4e-3	2.0e-4	2.0e-4	
	accidents - minor injury		1.4e-2	4.6e-5	4.6e-5	
7. Waste disposal						
	Public health					
	collective dose	manSv	1.4e-1			C
	fatal cancers	-	7.0e-3			
	Yoll-approach			1.3e-2	3.8e-5	C
	VSL-approach			2.2e-2	7.3e-5	C
	non fatal cancers	-	1.7e-2	7.7e-3	2.3e-5	C
	hereditary effects	-	1.4e-3	4.3e-3	1.3e-5	C
	Occupational health					
	collective dose	manSv	1.2e-2			B
	fatal cancers	-	4.8e-4			
	Yoll-approach			8.8e-4	6.6e-4	B
	VSL-approach			1.5e-3	1.1e-3	B
	non fatal cancers	-	1.4e-3	6.3e-4	6.3e-4	B
	hereditary effects	-	7.2e-5	2.2e-4	2.2e-4	B
	accidents - fatal	deaths	n. q.	n. q.	n. q.	
	accidents - major injury		n. q.	n. q.	n. q.	
	accidents - minor injury		n. q.	n. q.	n. q.	
8. Transportation						
	Public health					
	collective dose	manSv	1.3e-3			
	fatal cancers	-	6.5e-5			
	Yoll-approach			1.2e-4	3.5e-7	
	VSL-approach			2.0e-4	6.8e-7	
	non fatal cancers	-	1.6e-4	7.2e-5	2.2e-7	
	hereditary effects	-	1.3e-5	4.0e-5	1.2e-7	
	accidents - fatal	deaths	n. q.			
	accidents - major injury		n. q.			
	accidents - minor injury		n. q.			
	Occupational health					
	collective dose	manSv	1.2e-3			
	fatal cancers	-	4.8e-5			
	Yoll-approach			8.8e-5	6.6e-5	
	VSL-approach			1.5e-4	1.1e-4	

Stage	**Impact**	**Impact-units**	**Impact per TWh**	**Damages mECU/kWh 0% DR**	**Damages mECU/kWh 3% DR**	**error estimation**
	non fatal cancers	-	1.4e-4	6.3e-5	6.3e-5	
	hereditary effects	-	7.2e-6	2.2e-5	2.2e-5	
	accidents - fatal	deaths	n. q.			
	accidents - major injury		n. q.			
	accidents - minor injury		n. q.			
9. Construction and dismantling						
	Public health					
	collective dose	manSv	n. q.			
	fatal cancers	-	n. q.			
	Yoll-approach					
	VSL-approach					
	non fatal cancers	-	n. q.			
	hereditary effects	-	n. q.			
	accidents - fatal	deaths	n. q.			
	accidents - major injury		n. q.			
	Occupational health					
	collective dose	manSv	2.2e-2			
	fatal cancers	-	8.6e-4			
	Yoll-approach			1.6e-3	1.2e-3	
	VSL-approach			2.7e-3	2.0e-3	
	non fatal cancers	-	2.6e-3	1.2e-3	1.2e-3	
	hereditary effects	-	1.3e-4	4.0e-4	4.0e-4	
	accidents - fatal	deaths	5.7e-3	1.8e-2	1.8e-2	
	accidents - major injury		1.6e-1	6.0e-3	6.0e-3	
	accidents - minor injury		6.5	2.2e-2	2.2e-2	
All stages						
	non-radioactive emissions					
	SO_2, NO_x , PM_{10}					
	Yoll-approach			0.57	0.44	
	VSL-apporach			2.7	2.1	
	global warming	mECU/kWh				
	low	0.075				
	mid 1%	0.35				
	mid 3%	0.91				
	high	2.7				

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