EXTERNAL COSTS OF ENERGY: APPLICATION OF THE EXTERNE METHODOLOGY IN FRANCE

Final Report for Contract JOS3-CT95-0010

J.V. Spadaro and A. Rabl
Centre d'Energetique
Ecole des Mines de Paris
60, boulevard Saint-Michel
F - 75272 Paris Cedex 06

rabl@cenerg.ensmp.fr
spadaro@cenerg.ensmp.fr

January 1998

Note:

This reports has some minor formatting mistakes due to conversion problems. Sorry for the inconvenience.
PR, IPTS

CONTENTS

GLOSSARY

acute	Near-term effect or impact
chronic	Long-term effect or impact
°C	Celsius degrees
CI	Confidence Interval (typically 68% or 95%)
DR	Discount Rate (typically 0%, 1%, 3% or 10%)
ECU	European Common Unit of currency (= $ 1.25 = 6.5 FF)
ER or f_{er}	Exposure-Response function in *cases/(yr-receptor-mg/m^3)*
g	gram
G	prefix - Giga (10^9)
IPA	Impact Pathways Analysis
k	prefix - kilo (10^3)
kWh_{el}	kilo-Watt-hour electric (= 10^3 Wh = 3600 kJ)
kWh_{th}	kilo-Watt-hour thermal
K	Kelvins (= 273 + °C)
m	meter
m	prefix - milli (10^{-3})
M	prefix - Mega (10^6)
MSW	Municipal Solid Waste (refers to incineration)
Nitrates	Secondary particulates (aerosols) derived from NOx emissions
Nm^3	Normal cubic meter (volume of air at 273K)
NMVOC	Non-Methane Volatile Organic Compounds
PM_{10}	Particulate Matter with an aerodynamic diameter less than 10 μm
$PM_{2.5}$	Particulate Matter with an aerodynamic diameter less than 2.5 μm
s	second
Sulfates	Secondary particulates (aerosols) derived from SO_2 emissions
t	ton (= 1000 kg)
T	prefix - Tera (10^{12})
TEQ	Toxic Equivalence 2,3,7,8-tetrachorodibenzo-p-dioxin (**TCDD** = dioxins)
TSP	Total Suspended Particles
VOC	Volatile Organic Compounds
VSL	Value of Statistical Life (= 3 100 000 ECU)
W	Watts, unit of power (= 1 Joule, **J**, per second)
YOLL	Years Of Life Lost (value depends on DR)
m	prefix - micro (10^{-6})
m_g	Geometric median for a lognormal distribution

$\mathbf{s_g}$ Geometric standard deviation for a lognormal distribution

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 ***France.***

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 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 France; and is published by J.V. Spadaro and A. Rabl, who are researchers at the Centre d'Energétique of the Ecole des Mines de Paris. It contains all the details of the application of the methodology to the Coal, Natural Gas, Oil, Nuclear, Hydroelectric, Biomass fuel cycle cases, waste incineration, aggregation, and Incinerators and Cars: A Comparison of Emissions and Damages as an illustration of the use of these results. 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 methodology publication (see above).

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 appendices.

1.4. THE FRENCH NATIONAL IMPLEMENTATION

1.4.1. Description of the country

France occupies a *central* location in the European continent. Namely, it not detached from it like the British Isles, nor is it too far west like the Iberian peninsula, nor is it located deep in its interior like Austria and other Central European countries, rather it is set in the heart of the European Union both geographically and commercially. It is surrounded by the Atlantic ocean to the west, Spain and the Mediterranean sea to the south, Italy, Switzerland, Germany and Belgium to the East and the Channel sea to the north. These seas together with the Pyrenees mountains to the south, the Alps to the east and the River Rhine to the north-east define the so called *hexagonal* outline of France.

The surface area of France is about 550,000 km^2, which is nearly equal to the combined sizes of Germany and England. Most of the surface to the north and west is relatively flat land, whereas to the south and south-east the area is much more mountainous. In 1996, the population of France was approximately 58 million people, of which 10.5 million or 18% lived in Paris and its nearest suburbs (Ile-de-France). It is worthwhile noting that although the Ile-de-France region covers only 2% of the area of France, a quarter (25%) of the economically active population lived there! Other major cities include Bordeaux, Dijon, LeHavre, Lille, Lyon, Marseilles, Metz, Nantes, Nice, Strasbourg and Toulouse. By contrast to its nearest neighbors, the population density across France is just over one hundred (105) inhabitants per square kilometer. This value is half as large as that for Italy, Germany, Belgium or the UK, and only two-thirds (66%) of the European average population density (158 persons/km^2).

1.4.2. Overview of the French energy sector

According to the *1995 Pétrole et Energies* report, published by the Comite Professionnel Du Pétrol [CPDP, 1996], the annual gross electricity production in France for 1995 was approximately 500 Tera-Watt-hours (TWh_{el}) [1]. Nearly 95% of the electricity demand was produced by the French state-owed utility company Electricité de France (EdF), either directly or through several working-partnerships with smaller firms, including, for instance, the Compagnie National du Rhone (CNR) in the case of hydroelectric power. The remaining 5% was generated by several Independent Power Producers (IPP). The national energy mix (distribution by fuel

[1] 1 TWh_{el} = 1000 GWh_{el} = 10^{12} Watt-hours (Wh).

type) in 1995 was, in descending order: 76.1% nuclear (58400 MW installed power), 16% hydro (23300 MW), 4.4% coal (8670 MW), 1.8% coke and natural gas, 1% fuel oil (8165 MW) and 0.6% other. Nuclear and hydro components are part of baseload supply, whereas coal, gas and oil power plants are used as needed to meet peak demand, particularly during winter months (heating load). Presently, in France, the summer-time cooling load is small, although EdF has been more and more actively involved in trying to expand the use of air-conditioning in the public, commercial and private sectors. The current production cost and average retail price of electricity in France are 40 mECU/kWh and 65 mECU/kWh, respectively.

The contribution to the electricity grid by the individual IPPs was about 19 TWh_{el} in 1995, which was generated entirely by using fossil fuels. The IPP energy mix consisted of 35% coal, 20% fuel oil and 45% natural gas [DGEMP, 1995]. It is worth noting that all of the electricity derived from natural gas in France is generated entirely from power plants owned and operated by IPPs. Currently, EdF has no natural gas or cogeneration plants in operation although some interest in these technologies is beginning to develop, particularly in the use of natural gas for new power stations.

1.4.3. Justification of the selection of fuel cycles

For France, the choice of which fuel cycle to analyze is clearly motivated by present and future electricity needs. As already pointed out, the present electricity load in France is provided primarily (98%) by nuclear, hydroelectric, coal and fuel oil sources. Hence, the need to estimate the external costs is of paramount importance, not only for the sake in determining the environmental burdens themselves, but more importantly to consider the overall pros and cons associated with each fuel-to-electricity technology. A fair comparison ought to depend on both economic and environmentally related issues. Natural gas, on the other hand, is increasingly becoming the fuel of choice for *new* power plants, i.e., those which will be coming on line in the not too distant future. Finally, in light of the fact that fossil fuel reserves may not last forever, the choice of using renewable energy resources, such as biomass, is a logical one; and could become very promising and competitive if the external costs for each fuel-cycle are fully internalized.

The analysis of the waste incineration cycle (it should be noted that this is not a fuel-cycle in the strictest sense of the word) is based on the need to better understand and evaluate the environmental costs and risks or *benefits* (heat recuperation, for example) of managing the disposal of municipal solid waste. This is an important issue, since all of the household waste produced in France will have to be thermally treated by the year 2004. Furthermore, a particularly sensitive issue has recently arisen and concerns dioxin releases to the air from the treatment of plastic waste products. This has become an important and controversial public concern which needs to be addressed.

1.4.4. Related national studies

Unfortunately, there are **no** major studies dealing with the environmental burdens or external costs of electricity production in France other than the current work. None of the existing studies, to the best of our knowledge, are as detailed or systematic as the ExternE Implementation study presented here.

We should point out that this work was in part funded by the French energy agency of ADEME (Agence De l'Environnement et de la Maitrise de l'Energie) and the French Ministry of the Environment. We are very grateful for their enthusiastic and financial support of this work.

1.5. REFERENCES

CPDP (1996) *1995 Pétrole et Énergies, Comite Professionnel Du Petrol,* Tour Corosa, B.P. 282, 92505 Rueil Malmaison Cedex, France.

DGEMP (1995) *Production-Distribution de l'énergie électrique en France, Statistiques 94,* Ministère de l'Industrie, de la Poste et des Télécommunications.

EC/OECD/IEA (1995) Proceedings of the First EC/OECD/IEA Workshop on Energy Externalities: The External Costs of Energy. Brussels 30-31 January 1995.

European Commission, DGXII, Science, Research and Development, JOULE (1995a). Externalities of Fuel Cycles 'ExternE' Project. Report 1, Summary.

European Commission, DGXII, Science, Research and Development, JOULE (1995b). Externalities of Fuel Cycles 'ExternE' Project. Report 2, Methodology.

European Commission, DGXII, Science, Research and Development, JOULE (1995c). Externalities of Fuel Cycles 'ExternE' Project. Report 3, Coal and Lignite Fuel Cycles.

European Commission, DGXII, Science, Research and Development, JOULE (1995d). Externalities of Fuel Cycles 'ExternE' Project. Report 4, Oil and Gas Fuel Cycles.

European Commission, DGXII, Science, Research and Development, JOULE (1995e). Externalities of Fuel Cycles 'ExternE' Project. Report 5, Nuclear Fuel Cycle.

European Commission, DGXII, Science, Research and Development, JOULE (1995f). Externalities of Fuel Cycles 'ExternE' Project. Report 6, Wind and Hydro Fuel Cycles.

European Commission, DGXII, Science, Research and Development, JOULE (1998a). 'ExternE' Project. Methodology Report, 2nd Edition. To be published.

European Commission, DGXII, Science, Research and Development, JOULE (1998b). 'ExternE' Project. Analysis of Global Warming Externalities. To be published.

European Commission, DGXII, Science, Research and Development, JOULE (1998c). 'ExternE' Project. Summary of the ExternE National Implementation Project. To be published.

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

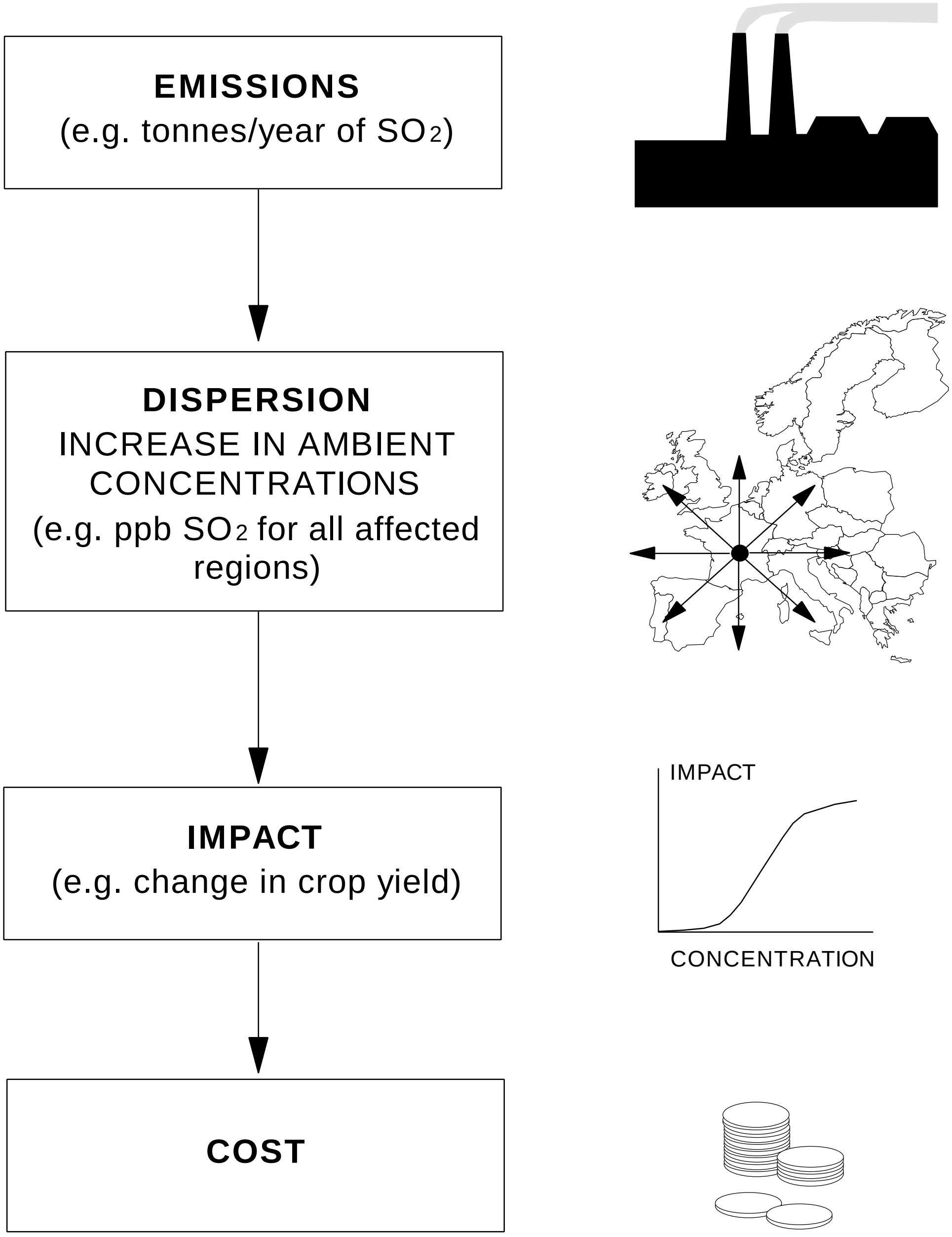


Figure 2.1 An illustration of the main steps of the impact pathways methodology applied to the consequences of pollutant emissions. Each step is analysed with detailed process models.

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.

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 labor 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.

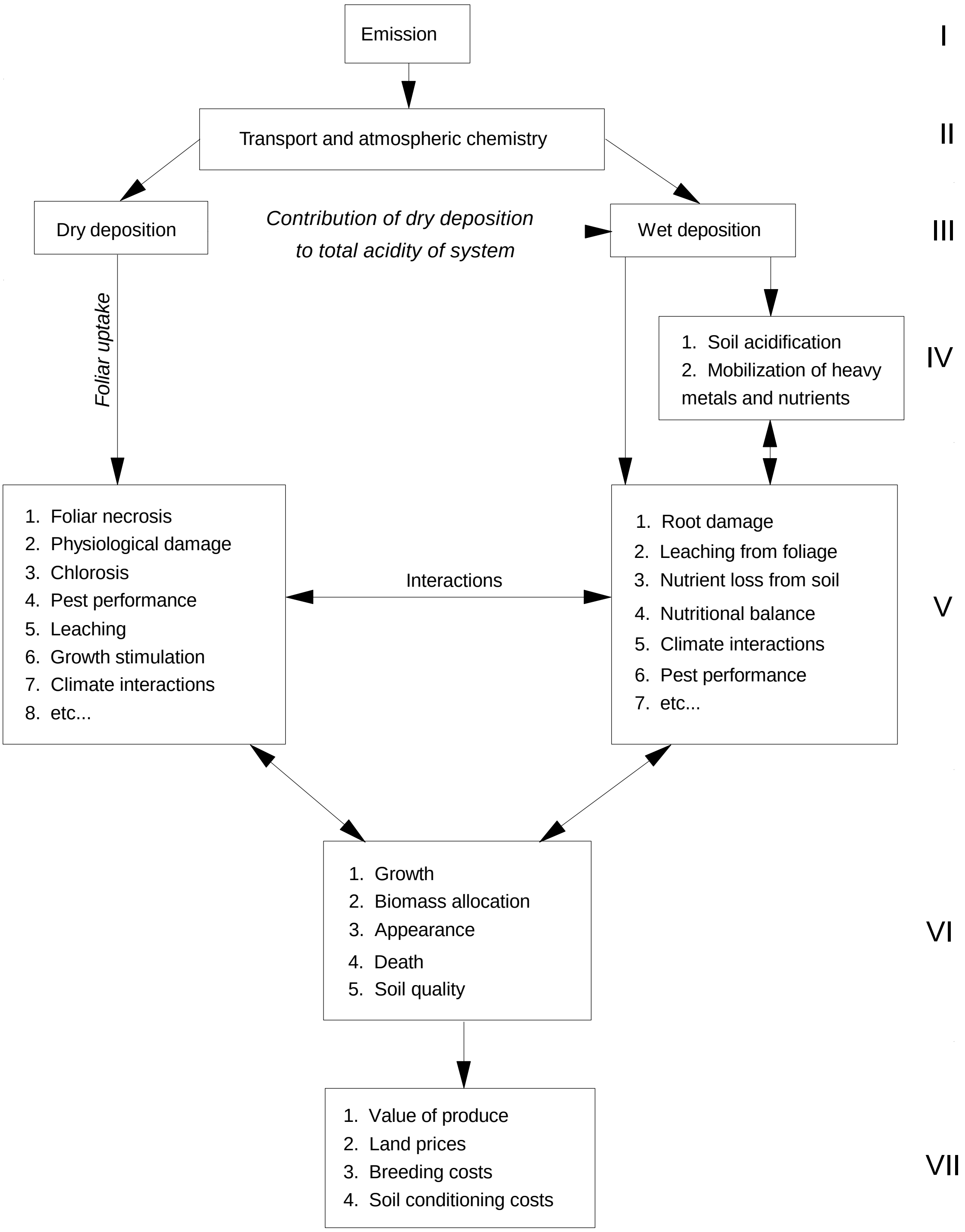


Figure 2.2 The impact pathway showing the series of linkages between emission of acidifying pollutants and ozone precursors and valuation of impacts on agricultural systems.

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.

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 modeling 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.

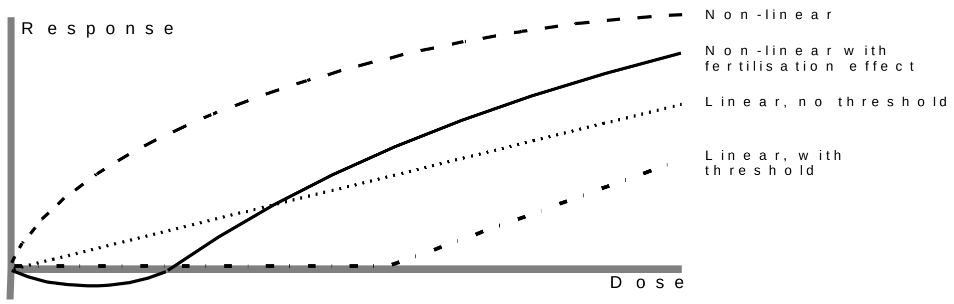


Figure 2.3 A variety of possible forms for dose-response functions.

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 fulfills 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.

2.7. References

European Commission, DGXII, Science, Research and Development, JOULE (1995a). Externalities of Fuel Cycles 'ExternE' Project. Report 1, Summary.

European Commission, DGXII, Science, Research and Development, JOULE (1995b). Externalities of Fuel Cycles 'ExternE' Project. Report 2, Methodology.

European Commission, DGXII, Science, Research and Development, JOULE (1995c). Externalities of Fuel Cycles 'ExternE' Project. Report 3, Coal and Lignite Fuel Cycles.

European Commission, DGXII, Science, Research and Development, JOULE (1995d). Externalities of Fuel Cycles 'ExternE' Project. Report 4, Oil and Gas Fuel Cycles.

European Commission, DGXII, Science, Research and Development, JOULE (1995e). Externalities of Fuel Cycles 'ExternE' Project. Report 5, Nuclear Fuel Cycle.

European Commission, DGXII, Science, Research and Development, JOULE (1995f). Externalities of Fuel Cycles 'ExternE' Project. Report 6, Wind and Hydro Fuel Cycles.

European Commission, DGXII, Science, Research and Development, JOULE (1998). Externalities of Fuel Cycles 'ExternE' Project. Updated Methodology Report (in prep.).

Fritsche, U., Leuchtner, J., Matthes, F.C., Rausch, L. and Simon, K.-H. (1992). Gesamt-Emissions-Model Intergrierter Systeme (GEMIS) Version 2.0. OKO-Institutt Buro Darmstadt, Bunsenstr. 14, D-6100 Darmstadt. An English version is distributed under the name TEMIS.

Heijungs, R., *et al* (1992). Environmental Life Cycle Assessment of Products. Part 1. Guide. Part 2. Backgrounds. Centre of Environmental Science, Garenmarkt 1, P.O. Box 9518, 2300 RA Leiden, the Netherlands.

Hohmeyer, O, (1988). Social Costs of Energy Consumption. Springer Verlag, Berlin.

ISET (1995) Externalities of photo-voltaics. In the ExternE National Implementation Report for Germany, written by IER (Universitat Stuttgart) and others. To be published in 1998.

Lindfors, L.-G., Christiansen, K., Hoffman, L., Virtanen, Y., Juntilla, V., Leskinen, A., Hanssen, O.-J., Ronning, A., Ekvall, T. and Finnveden, G. (1995). LCA-NORDIC Technical Report No. 10: Impact Assessment. TemaNord 1995:503, Nordic Council of Ministers, Copenhagen.

OECD (1992). Proceedings of an OECD Workshop on Life Cycle Analysis of Energy Systems. Paris, 21-22 May, 1992.

3. QUANTIFICATION OF EXTERNALITIES

3.1. IMPACT PATHWAYS ANALYSIS (IPA) PROCEDURE

The methodology adopted for evaluating the external costs of energy production and waste incineration consists of four main steps. These are illustrated in Figure 2.1 (Chapter 2). The IPA procedure begins by quantifying the airborne emissions, which are either measured or may be estimated by considering the fuel consumption and the power producing technology. Emission rates are reported for the classical pollutants, that is, PM, SO_2, NOx, CO_2, as well as for toxic species, including heavy metals (As, Cd, Cr, Ni,..) and dioxins and furlans. The latter, of course, are byproducts from waste combustion.

Next, we estimate the *marginal* increase in pollutant concentration level, that is, above the existing background value. Atmospheric dispersion is subdivided into *local* range dispersion, extending up to 50 kilometers from the emission source, and *regional* scale dispersion, extending across the European continent. Depending on the scale, different air transport algorithms (models) are employed in estimating the concentration fields. For the local range, the degree of pollutant dispersion is dependent primarily on meteorological parameters. Of these, certainly, the most important are wind speed and wind direction. For the regional domain, on the other hand, atmospheric chemistry and pollutant removal via dry (gravitational settling, for example) and wet deposition (rain) mechanisms are equally important as meteorological data in determining pollutant concentration levels.

Physical impacts are calculated next. These include, for example, the number of asthma attacks, hospital visits or admissions and mortality impacts, such as the number of Years Of Life Lost (YOLL). Impacts to health (morbidity and mortality), crops and materials (damages to building surfaces) are estimated by applying the *exposure-response* (ER) relationships. These functions relate an increase in pollutant concentration level (exposure) to an anticipated damage or negative effect (response) on a particular receptor [2]. Of course, a potential benefit of air pollution is also possible as in the case of crops exposed to higher atmospheric concentrations of SO_2 and/or NOx (fertilizer effect).

[2] A receptor is anything which is affected beneficially or adversely by an increase in air pollution.

Finally, the last step in the analysis is the valuation of external costs of air pollution. This involves multiplying the number of cases (responses) by the monetary unit cost per incidence. Unit costs are determined in a number of ways, including contingency studies (that is, willingness to pay, WTP, to avoid a particular impact), hedonic valuations, etc.

3.2. DISPERSION OF AIRBORNE EMISSIONS

3.2.1. Regional dispersion

The long-range or ***regional scale*** transport of airborne pollutants is modeled by ECOSENSE (see Appendix I), which was developed by IER at the University of Stuttgart, Germany for the European Community, DGXII, ExternE Project to quantify the externalities of electricity production. ECOSENSE calculates ground-level concentrations by using a windrose trajectory algorithm which is an adaptation of the Harwell dispersion model developed by Derwent and colleagues at AEA Technology, Harwell Laboratory in the UK. The program also estimates the concentration levels of nitrate and sulfate aerosols, also referred to as *secondary* pollutants or particulates, which form in the air via chemical transformations involving NOx and SO_2 species with ammonium particulates already present in the atmosphere (see Appendix II). In addition to pollutant concentrations, ECOSENSE also evaluates the physical damages and externalities of air pollution, thus, making the software a self-contained environmental impact pathways analysis (IPA) package.

Integrated to ECOSENSE are several databases, which include data on typical meteorological conditions across Europe (wind speed/direction and precipitation rates), inventories, broken-down by country, of forests, crops (barley, oats, etc.) and materials (galvanized steel, limestone, paint, etc.), population statistics on a 100 by 100 kilometer and 10 by 10 kilometer range, and background levels for different atmospheric pollutants, to name a few.

Presently, ECOSENSE can only model emissions from a *single point source* at a time, therefore, impacts from the different stages of electricity production, i.e., upstream, generation and downstream steps, must first be evaluated separately and then combined to obtain the overall effect. Damages from line and area source emissions, such as those arising from transportation vehicles or farming machinery, may be evaluated by aggregating the emissions over the appropriate road segment or surface and then assigning the value to a single point source situated somewhere in the region of concern. In reality, atmospheric concentration levels due to emissions from transportation vehicles are better estimated by using the ROADPOL software, which was developed for the ExternE Transport Project by the Greek transportation team [Vossiniotis, *et al.*, 1996]. On the negative side, however, impact calculations are tedious and slow since damages must be evaluated manually. That is, externally to ECOSENSE. In our experience, the improved accuracy is negligible when compared to the uncertainties involved at each step of the damage calculation, and, hence, do not justify the significant effort in obtaining improved concentrations near the transport route when impacts need to be evaluated over a much larger area.

Impact calculations on a regional level are carried out using the 100 by 100 kilometer Eurogrid Cells. The height of the emission source is not relevant for this range since the dispersion model assumes uniform mixing of the pollutant along the vertical direction throughout the *planetary* mixing layer (for a discussion of air pollution terminology, see Zannetti [1990]). For this study, we assume that the regional scale begins at a distance of 50 kilometers from the pollution source and extends throughout most of the European continent (except for the former Soviet Union).

3.2.2. Local dispersion

For the short range or ***local scale*** analysis, results are once again calculated by ECOSENSE through the use of the *Industrial Source Complex Short Term* transport model, version 2.0 (ISCLT2). This software, originally developed by the United States Environmental Protection Agency [Wackter and Foster, 1992], employs a steady state Gaussian dispersion algorithm for predicting local scale pollutant transport and concentration fields. The model uses site dependent meteorological data, which has to be entered into ECOSENSE prior to running the transport analysis. The pollutant removal rate by either chemical transformations or dry/wet deposition is negligibly small over this range. For the local scale, extending up to 50 kilometers from the source, ECOSENSE estimates the physical impacts and damage costs by using demographic results for the 10 by 10 kilometer *small* Eurogrid cells.

ECOSENSE was also used to predict impacts and damages from farming equipment and road transport. Since emissions tend to be very small, they have been scaled upwards by a factor of 10^7 to prevent erroneous data due to roundoff errors. Of course, in the end, impacts and damages are re-scaled by the same factor.

3.3. EXPOSURE-RESPONSE FUNCTIONS

The exposure-response (ER) functions used for evaluating externalities to public health, crops and building surfaces (materials) are presented in Appendices II, III and IV. Note that we distinguish between ER functions recommended for the ExternE National Implementation Project, also referred to as *Core Functions*, as well as those which should be used for *Sensitivity* analyses only.

In Table 3.1, we have listed the *Core* exposure-response functions which have been used in evaluating the public health impacts and damage costs shown in this report. With two exceptions, the list given here is nothing more than a subset of the ER functions summarized in Table 1 of

Appendix II (*Analysis of Health Effects*). First, we have added an additional column showing the monetary unit costs in ECU for each impact category or *endpoint* (Tables 10 and 11 in Appendix II). Second, for aerosols and particulates we have provided a single "*mortality*" ER function, which includes both the acute and chronic components. As noted in the table, this function applies only to adults older than 30 years, which account for 57% of the general population. It should be noted that the ER slopes have units of number of cases (for example, asthma attacks, YOLLs, etc.) per year per receptor (meaning asthmatic, elder over 65, child, etc.) per marginal concentration increase in $\mu g/m^3$. Finally, the last column in the table is uncertainty label for each endpoint (see Appendix VIII).

The exposure response functions for quantifying public health effects are compared graphically in Figure 3.1. For each of the pollutants considered in this study, we show the economic impact due to mortality and aggregated morbidity effect (summed over all the various endpoints for a particular pollutant) on the same scale so as to compare the relative importance of the different pollutants. Note that the abscissa is a logarithmic scale varying by nine (9) orders of magnitude!! Damage costs are expressed in mECU [3] per year per person for a marginal increase in ambient concentration level equal to (1 $\mu g/m^3$) [4]. In addition to the recommended ExternE *Core* Project functions (dark colored bars), we also show impacts due to some of the sensitivity functions (light colored bars).

Three observations are worth noting.

1. Of all the pollutants considered in this analysis, undoubtedly the most toxic per unit concentration (1 $\mu g/m^3$) or equivalently per ton of pollutant are dioxins, followed by benzo-a-pyrene (BaP), with an impact more than ten (10) times smaller, next come particulates and aerosols, whose impacts are at least three (3) orders of magnitude smaller for mortality and four (4) orders of magnitude lower for aggregated morbidity effects. Fatal cancers due to diesel particulates and SOx impacts are more than five (5) orders of magnitude smaller than dioxin damages. Of course, we must keep in mind that the "*real*" impact depends on the "*actual*" air emissions which take place. For a diesel vehicle, for example, the real particulate emissions are several orders of magnitude higher than BaP emissions, therefore, particulate damages will dominate the externality.

2. Mortality impacts exceed aggregated morbidity effects by about a factor of 6. That is, mortality costs represent 85% of the total cost to public health, with the remaining 15% attributed to morbidity.

---

[3] 1 mECU = 0.001 ECU.

[4] 1 $\mu g = 0.000001\ g = 10^{-6}\ g$.

3. Impacts due to the sensitivity ER functions are small. For example, the $PM_{2.5}$ sensitivity functions for morbidity are about 12 times *smaller* than the aggregated morbidity effects for particulates based on the ExternE Core functions. For NOx acute mortality, the situation is not so clear cut since local scale damages could be significant if the receptor density is very high. As it turns out, even for a ground-level emission source near a densely populated city like Paris (about 22300 inhabitants per square kilometer) the ratio of NOx acute mortality to the total damage cost is no more than 5% to 10%. Hence, we may conclude that impacts attributed to the *sensitivity* functions are negligible, especially when considering the uncertainties involved in the other steps of the damage calculation.

Table 3.1: Quantification of health impacts. The exposure-response slope, f_{er} , has units of cases / (yr-*receptor*-µg/m^3) and the cost is in 1995 ECU per case (see Appendix II for details).

Receptor	*Impact Category*	*Reference*	*Pollutant*	f_{er}	*Cost*	s_g [1]
ASTHMATICS *(3.5% of population)*						
adults	Bronchodilator usage	Dusseldorp et al., 95	Nitrates PM_{10} Sulfates $PM_{2.5}$	0.163 0.163 0.272 0.272	37	B? B B B
adults	Cough	Dusseldorp et al., 95	Nitrates PM_{10} Sulfates $PM_{2.5}$	0.168 0.168 0.280 0.280	7	A? A A A
adults	Lower respiratory symptoms (wheeze)	Dusseldorp et al., 95	Nitrates PM_{10} Sulfates $PM_{2.5}$	0.061 0.061 0.101 0.101	7.5	A? A A A
children	Bronchodilator usage	Roemer et al., 93	Nitrates PM_{10} Sulfates $PM_{2.5}$	0.078 0.078 0.129 0.129	37	B? B B B
children	Cough	Pope/Dockery, 92	Nitrates PM_{10} Sulfates $PM_{2.5}$	0.133 0.133 0.223 0.223	7	A? A A A
children	Lower respiratory symptoms (wheeze)	Roemer et al., 93	Nitrates PM_{10} Sulfates $PM_{2.5}$	0.103 0.103 0.172 0.172	7.5	A? A A A
ELDERLY 65+ (13% of population)						
	Congestive heart failure	Schwartz/Morris, 95	Nitrates PM_{10} Sulfates $PM_{2.5}$ CO	1.85E-5 1.85E-5 3.09E-5 3.09E-5 5.64E-7	7870	B? B B B B
CHILDREN (24% of population)						
	Chronic bronchitis	Dockery et al., 89	Nitrates PM_{10}	1.61E-3	225	B? B

			Sulfates $PM_{2.5}$	1.61E-3 2.69E-3 2.69E-3		B B
	Chronic cough	Dockery et al., 89	Nitrates PM_{10} Sulfates $PM_{2.5}$	2.07E-3 2.07E-3 3.46E-3 3.46E-3	225	B? B B B

Table 3.1 (cont)**:** Quantification of public health impacts (see Appendix II for details).

Receptor	*Impact Category*	*Reference*	*Pollutant*	f_{er}	*Cost*	s_g
ADULTS						
76% of population	Restricted activity days (RAD)	Ostro, 87	Nitrates PM_{10} Sulfates $PM_{2.5}$	0.025 0.025 0.042 0.042	75	B? B B B
76% of population	Chronic bronchitis	Abbey et al., 95	Nitrates PM_{10} Sulfates $PM_{2.5}$	4.9E-5 4.9E-5 7.8E-5 7.8E-5	105000	A? A A A
57% of population (> 30 yrs)	Mortality (*'chronic' Yoll*)	Pope et al., 95	Nitrates PM_{10} Sulfates $PM_{2.5}$	7.2E-4 7.2E-4 1.2E-3 1.2E-3	84330 [2]	B? B B B
ENTIRE POPULATION						
	Respiratory hospital admissions (RHA)	Dab et al., 96	Nitrates PM_{10} Sulfates $PM_{2.5}$	2.07E-6 2.07E-6 3.46E-6 3.46E-6	7870	A? A A A
		Ponce de Leon, 96	SO_2	2.04E-6	7870	A
	Cerebrovascular hospital admissions	Wordley et al., 97	Nitrates PM_{10} Sulfates $PM_{2.5}$	5.04E-6 5.04E-6 8.42E-6 8.42E-6	7870	B? B B B
	Acute Mortality (*'acute' Yoll*)	London/Athens, 96 (case studies)	SO_2	5.34E-6	155000 [3]	B
	Cancers [4]	Pilkington and Hurley, 1997	B[a]P (fatal) (non-fatal) Diesel part (fatal) (non-fatal)	1.29E-3 1.43E-4 4.37E-7 4.86E-8	1330000 450000 1330000 450000	B B B B

[1] Uncertainty rating: **A** = high confidence (σ_g = 2.5 - 4),
B = medium confidence (σ_g = 4 - 6),
? = effect could be zero!

[2] Value of a 'chronic' YOLL at a discount rate (DR) of 3%.

[3] Value of an 'acute' YOLL for DR = 3%.

[4] Value of a fatal cancer based on a YOLL evaluation (DR=3%) plus cost of illness.

Sources: [ExternE, European Commission, 1995b] and [Hurley et al., 1997].

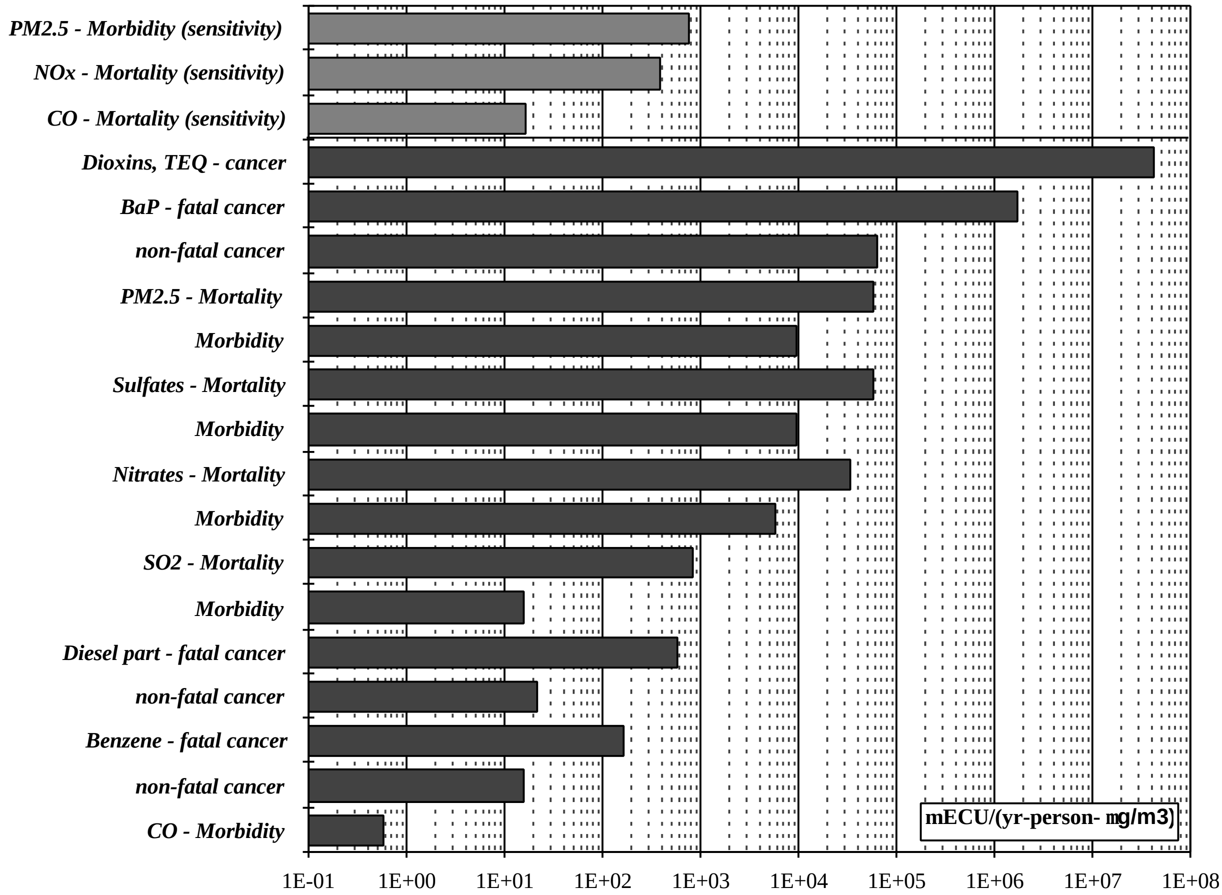


Figure 3.1: Comparison of air pollution health impacts in terms of cost per ambient concentration of the respective pollutant. The items labeled "*sensitivity*" correspond to ER functions that are considered less well established and that have not been used in the present work.

3.4. IMPACT EVALUATION

External costs are calculated using the procedures presented in Table 3.2. Although complete details regarding the ER functions, monetary valuation and uncertainty analysis have already been discussed in the Methodology chapter and more details may be found in the appendices, it is useful here to reiterate a few of the key assumptions implicit in our analyses.

1. For the marginal concentrations anticipated in this study, the ER functions for public health are assumed to vary linearly from zero, i.e., without a threshold value. The ER slope has units of

cases per year per *receptor* per concentration (typically in $\mu g/m^3$). A receptor is either an asthmatic, elder 65+ or the entire population. Adults (> 14 years old) represent 76% of the total population, with children (< 14 years of age) making up the remaining 24%. Asthmatics and elderly above 65 account for 3.5% and 14% of the total population, respectively.

2. From an epidemiological point of view, sulfates are treated the same as particles with an aerodynamic diameter of 2.5 microns ($PM_{2.5}$), whereas nitrates are assumed to be like PM_{10} (at the present time, these classifications are only tentative since there aren't many epidemiological studies to verify or disprove these claims). Furthermore, diesel particulates have aerodynamic diameters which are much smaller than 0.1 µm [5]. Typically, the average particle diameter is around 0.01 µm. Therefore, the use of the ER function for $PM_{2.5}$ particulates is only an approximation. No ER relationship for smaller sized particulates is available at the present time.

3. Mortality costs for either '*acute*' (near term) or '*chronic*' (long term) YOLL are discounted at a rate of 3% over the appropriate time interval. With respect to '*chronic*' YOLLs, only those persons above 30 years of age are at risk. These individuals represent about 60% of the total population.

4. Damage costs due to cancers are evaluated by using the US EPA *unit risk factors*. A unit risk factor or slope factor, as it is sometimes referred to, expresses the likelihood (probability) of contracting cancer from a lifetime exposure (70 years) for a typical person (70 kg) breathing in 1 $\mu g/m^3$ of a pollutant. Monetary costs are discounted (3%) over the lifetime of the disease, including any latency period (delay time between exposure and manifestation of decease).

[5] 1 µm = 0.000001 m = 10^{-6} m.

Table 3.2: Summary of procedures for evaluating external costs.

Receptor	Range	Pollutant	Impact Evaluation
Crops, materials	regional	SO_2	Calculated by ECOSENSE using the built-in receptor density distributions for each European country. The ER functions are given in Appendices III and IV.
Global warming	regional	CO_2, N_2O, CH_4	Global warming impacts are based on the "representative" range of 18 ECU to 46 ECU per ton of $CO_{2,eq}$ (Appendix V). The global warming potential for N_2O is 310 and for CH_4 is 21.
Ozone	regional	VOC, NOx	Impact of 1500**,** 930 and 130 ECU per ton of NOx, NMVOC and CH_4, respectively [Rabl et al., 97]. Includes impacts on crops (21%) and public health (morbidity 47% and mortality 32%).
Public health *(Aerosols)*	regional	Nitrates and Sulfates	Calculated by ECOSENSE using regional concentration fields with the ER functions listed in Table 3.1 and population data for the 100 x 100 km Eurogrid cells.
Public health *(Particulates)*	local & regional	$PM_{2.5}$, PM_{10}	For the regional scale, concentrations are estimated by the WTM algorithm in ECOSENSE, whereas locally concentrations are calculated by the ISC model. Local impacts are calculated using the 10 x 10 km resolution data for population. The ER functions for morbidity and mortality endpoints are listed in Table 3.1.
Public health *(Sulfur-dioxide)*	local & regional	SO_2	For the local domain, the concentration values per ton of pollutant are numerically equal to those for particulates (i.e., no removal or transformation at local scale). The ER functions for "acute" mortality and the single morbidity endpoint associated with this pollutant are given in Table 3.1.
Public health *(Cancers)*	local & regional	Heavy metals and Dioxins	Pollutant dispersion is assumed to be similar to particulate transport. The damage costs given below are average values for Europe. Implicit in these values is the assumption that a cancer has a monetary unit value of 1 500 000 ECU per case [Rabl et al., 97]. • ***As 1.92 x 10^5 ECU per ton;*** • ***Cd 2.341 x 10^4 ECU per ton;*** • ***Cr 1.58 x 10^5 ECU per ton;*** • ***Ni 3.23 x 10^3 ECU per ton;*** • ***TCDD 2.08 x 10^{10} ECU per ton of TEQ.***
Public health *(Cancers)*	local & regional	Diesel particles	Assume the same concentration profiles as calculated for particulates. Impacts are estimated using the unit risk factor provided in Table 3.1.
Public health	local &	CO	Same procedures as already used for particulates and

(Morbidity)	regional	SO_2 pollutants. The ER function is listed in Table 3.1.

3.5. UNCERTAINTY ANALYSIS

The structure of the Impact Pathways Analysis is essentially a multiplicative process, involving the product of the following four random independent parameters: incremental concentration, ER function, receptor density and monetary cost. For such a function, the natural distribution is a *lognormal* distribution, which is characterized by a median value (*best guess or estimate*) μ_g and a geometric standard deviation σ_g. Together these factors define the 68 % and 95 % confidence intervals (CI) according to the equations given below:

$$\text{for 68\% CI,} \left(\frac{\mu_g}{\sigma_g}, \quad \mu_g \bullet \sigma_g\right) \qquad \text{for 95\% CI,} \left(\frac{\mu_g}{\sigma_g^2}, \quad \mu_g \bullet \sigma_g^2\right).$$

Therefore, to evaluate the 68 % uncertainty range, we simply divide and multiply the estimated damage cost by σ_g, whereas for the 95 % CI we divide and multiply our best guesses by σ_g^2.

There are three uncertainty categories, which are identified by the letters A, B and C. These are arranged in order of *confidence level* or degree of uncertainty, with A corresponding to the highest confidence level and C representing the lowest. Rather than picking a single value for the geometric standard deviation σ_g, a plausible range is given for each category. Category A, for example, has a σ_g range of 2.5 to 4, while category B has a range of 4 to 6 and, finally, category C has a range of 6 to 10. Clearly, the higher the value of σ_g , the more uncertain is the estimated damage cost. It is very important to note that the standard deviation values given here refer to a lognormal distribution, and, therefore, represent large intervals. This is especially evident when damage cost ranges are plotted on a linear scale.

Nitrates have a B? rating, which is the same as B, but indicates that the effect could be zero. We have chosen this ‘special’ rating because health impacts for nitrate aerosols are the least well understood of all pollutants due to the lack of convincing epidemiological studies.

The uncertainty ratings for all of the impacts considered in this study are summarized in Appendix II (*Analysis of Health Effects*), whereas a complete discussion of error analysis may be found in Appendix VIII (*Uncertainty and Sensitivity Analysis*). Both appendices are found at the end of this report.

3.6. REFERENCES

European Commission, DGXII, Science, Research and Development, JOULE Program, (1995b) "ExternE: Externalities of Energy," Report 2, Methodology.

Hurley, F., Donnan, P., (March 1997) "An Update of Exposure-Response (E-R) Functions for the Acute and Chronic Public Health Effects of Air Pollution," Institute of Occupational Medicine (IOM), Edinburgh, UK, Internal paper for ExternE Project.

Rabl, A., Eyre, N., (1997) "An Estimate of Regional and Global O_3 Damage from Precursor NOx and VOC Emissions," Ecole des Mines, 60, blvd St-Michel, F 75272 Paris, Cedex 06.

Rabl, A., Spadaro, J.V., McGavran, P.D., (1997) "Health Risks of Air Pollution from Incinerators: a Perspective," Ecole des Mines, 60, blvd St-Michel, F 75272 Paris, Cedex 06, (submitted for journal publication).

Vossiniotis, G., Arabatzis, G., Assimacopoulos, D., (1996) "Description of ROADPOL: A Gaussian Dispersion Model for Line Sources," program manual, National Technical University of Athens, Greece.

Wackter, D.J., Foster, J.A., (1992) *Industrial Source Complex (ISC) Dispersion Model User's Guide,* 2nd Ed., Vol 1., EPA 450/4-88-002a, US Environmental Protection Agency, Research Triangle Park, NC, USA.

Zannetti, P., (1990) *Air Pollution Modeling. Theories, Computational Methods and Available Software,* Van Nostrand-Reinhold.

4. IMPLEMENTATION RESULTS BY FUEL CYCLE

4.1. SUMMARY OF RESULTS

4.1.1. Introduction

The French national implementation cycles analyzed in the present report include the coal, natural gas, fuel oil, biomass and waste incineration. Of these, the coal, natural gas and fuel oil cycles were studied previously as part of the Joule II program, and a detailed discussion of the fuel cycle stages and prior results may be found in the report by Rabl et al. [1996]. Here, we have simply updated these results to be consistent with the latest ExternE methodology. On the other hand, the biomass-to-electricity and municipal solid waste (MSW) incineration cycles have been assessed for the first time, and complete details may be found in the latter sections of this chapter. The French nuclear and hydroelectric fuel cycles have already been covered in Rabl et al. [1996] and Lesgards [1995] and have not been modified in this work.

The main characteristics of the cycles presented in this study are summarized in Table 4.1. It should be pointed out that although emissions data for the waste incineration cycle are normalized by the annual electricity production, the incinerator's main objective is to provide thermal energy to the district heating system in Paris, and, of course, to dispose of waste. When presenting waste incineration results later on, we have decided to normalize the externalities by the annual electricity and heat production as well as per ton of waste burned, which incidentally we believe is the most appropriate parameter for reporting waste incineration damage costs.

4.1.2. Environmental burdens

As with all fuel cycles considered in this study, the primary impact pathways include damages to public health, crops and building surfaces (also referred to as material damages). Of these categories, public health costs, which include both morbidity and mortality endpoints, account for more than 98% of the total externality, excluding global warming effects. As already noted in the previous chapter, mortality costs are approximately six (6) times higher than those for morbidity.

Public health costs are always dominated by impacts from aerosols or secondary particulates (nitrates and sulfates) and ozone which together account for more than 80% of the estimated external costs, excluding global warming damages. For the fossil fuel cycles (coal, oil and gas) this fraction increases to 94% or more! At the local scale, that is within the first 50 kilometers from the emission source, aerosol impacts are negligible (certainly no more than a few percent of the total aerosol impact). Over this range, instead, damages arise only from particulate (TSP) and SO_2 emissions. Depending on the local receptor density, local impacts can account from 20% to

75% (or more in some instances) of the overall particulate and SO_2 damage costs (see, for example, Figure 5.4). It is also very important to note that the geographic range of the impact extends over hundreds or even thousands of kilometers from the emission source (see Figure 5.4).

Table 4.1: Characteristics of French fuel cycles.

	Coal	Fuel Oil	Natural Gas	Biomass	Waste *
Site	***Cordemais*** (Nantes)	***Cordemais*** (Nantes)	***Cordemais*** (Nantes)	***Albi*** (Toulouse)	***Paris*** (N-W suburbs)
Technology	*hypothetical new plant* Pulverized fuel, flue gas desulfurization steam turbine	*Existing plant* Low S oil, Low NOx burner, steam turbine	*hypothetical new plant* Gas turbine combined cycle	*hypothetical* Biomass (poplar wood) gasifier with intercooled steam injected gas turbine	*Existing plant* Municipal solid waste, electrostatic precipitator and wet scrubbing of flue gases
Conversion efficiency (%)	38	39	52	38	
Annual electricity production [6]	600 MW_{el} 2100 GWh_{el}	700 MW_{el} 1050 GWh_{el}	250 MW_{el} 1500 GWh_{el}	40 MW_{el} 245 GWh_{el}	21.9 GWh_{el}
Annual heat production					1240 GWh_{th}
Stack height	220 m	150 m	110 m	40 m	100 m
Emissions					
PM_{10}	0.17 g/kWh_{el}	0.13 g/kWh_{el}	negligible	0.04 g/kWh_{el}	4.6 g/kWh_{el}
SOx	1.36 g/kWh_{el}	5.26 g/kWh_{el}	negligible	0.04 g/kWh_{el}	18.3 g/kWh_{el}
NOx	2.22 g/kWh_{el}	1.20 g/kWh_{el}	0.71 g/kWh_{el}	0.35 g/kWh_{el}	52.6 g/kWh_{el}
$CO_{2,\,eq}$ [7]	1085 g/kWh_{el}	866 g/kWh_{el}	433 g/kWh_{el}	17.7 g/kWh_{el}	26100 g/kWh_{el}

* Since this project is concerned with fuel cycles for electricity, we have been asked to express all emissions and external costs per kWh_{el} ; however, this makes no sense for this waste incinerator since it is not intended to produce electricity but to supply heat to the district heating system.

[6] 1 MW = 10^6 Watts (W); 1 GWh = 10^9 Watt-hours (Wh)

[7] The '*eq*' subscript indicates that CO_2, N_2O and CH_4 emissions are combined through the use of the Global Warming Potential (GWP) factors, which are taken to be 310 and 21 for N_2O and CH_4, respectively.

In a few instances, we have also evaluated cancer costs from exposure to carcinogenic substances, including dioxins and furlans, diesel particulates and trace pollutants such as heavy metals (As, Cr, Ni and Cd). By comparison to other health impacts, cancer costs account for less than 0.1% of the total externality, and, therefore, represent an insignificant contribution to the total.

Damages to crops and building surfaces, due to SO_2 and ozone pollutants, are of equal magnitude and small by comparison to effects on health (about 2% of the overall externality). We have also evaluated impacts to forests and found that the numbers are negligible, as are damages to ecosystems.

It is important to keep in mind that the externalities quantified in our analyses are those associated *only* with airborne emissions, while impacts related to soil and liquid emissions have not been evaluated at this point. Although possibly significant, a reliable and simple accounting framework for estimating damages to soil and waterways has yet to be developed.

4.1.3. Results for French cycles

The external costs, expressed in mECU [8] per kWh electricity, for the various cycles assessed in this report are illustrated in Figure 4.1. In addition to the aggregated cost, the externality for each cycle is further broken-down by pollutant, including particulate matter (PM), NOx and SO_2 components. For the case of global warming impacts, a "*representative*" interval is given instead. The range is 18 ECU to 46 ECU per ton of CO_2 which reflects the various scenarios and different discount rates proposed in Appendix V. NOx damages include impacts from nitrate aerosols and ozone formation, whereas SO_2 estimates include direct impacts on health, that is mortality and morbidity effects, plus damages from sulfate aerosols, losses in crop yield and damages to building surfaces (materials).

As one can clearly see in Figure 4.1a, even if global warming effects were excluded from the total, damage costs for the coal and fuel oil cycles are comparable to or exceed the average retail price of electricity in France! The only notable exceptions are the natural gas and biomass fuel cycles, whose external costs are about an order of magnitude smaller than the electricity price. The biomass fuel cycle has the lowest external cost. Once again, we should emphasis that the damages for the waste incineration facility shown here are unfairly large given that the primary purpose for this incinerator is *not* to produce electricity, *but* rather to generate heat. Therefore, results for this incinerator should not be interpreted or viewed as representative or typical of external costs associated with waste-to-electricity generation. If global warming impacts are included in the total cost, externalities *could* exceed the price of electricity by as much as 100% or even more, clearly this depends on the assumed value chosen for the damage per ton of CO_2, which at the moment is

[8] 1 mECU = 0.001 ECU = \$ 0.00125 = 0.0065 Francs.

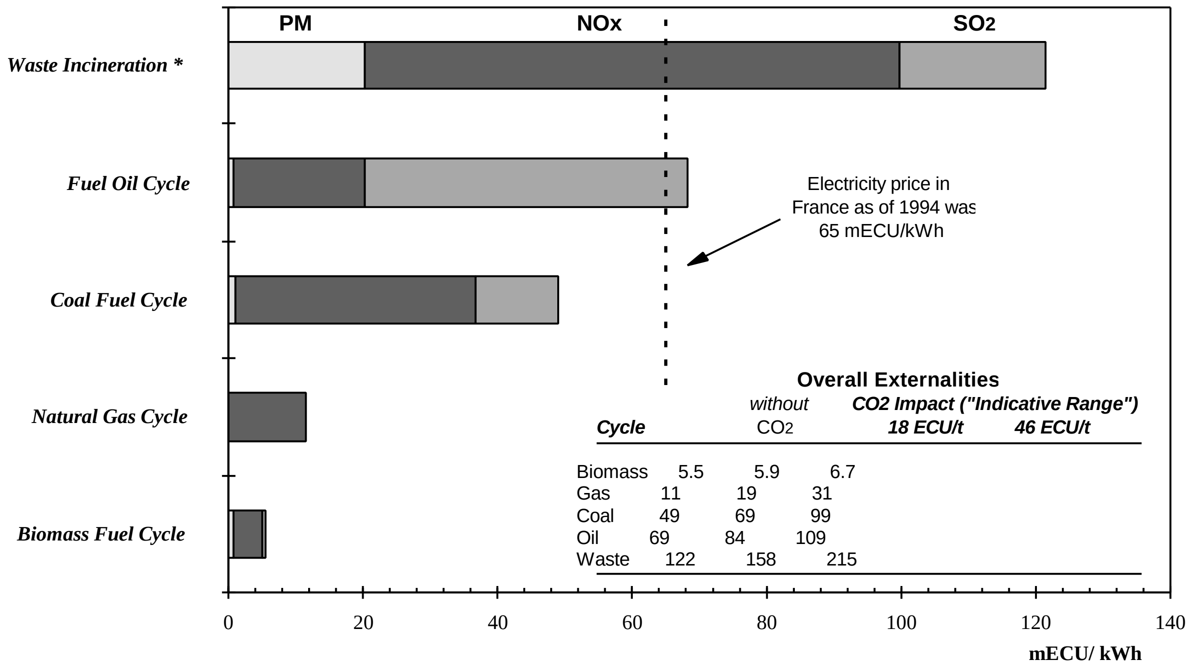
quite uncertain. As a matter of fact, global warming impacts may vary by two orders of magnitude (Appendix V)!

In Figure 4.1b, we show the external costs (without CO_2 impacts) and the 68% confidence intervals for these estimates, which are indicated by the horizontal error bars. The damage ranges are calculated assuming a "*total*" geometric standard deviation of $\mathbf{s_{g,\ total} = 5}$. It is abundantly clear that the uncertainty ranges are quite large, and the damage estimates (*best guesses*) do *not* lie in the middle of the damage range, as they would for a Gaussian or normal distribution, but rather are closer to the lower limit of the range. This is not so surprising if we realize that a lognormal distribution has a positive skew, that is, stretched in the direction of increasing values. Following the discussion on uncertainty presented in the previous chapter, the lower bound is one-fifth (1/5) of the externality, while the upper bound is five (5) times as large.

As already pointed out, most of the externality, and therefore the uncertainty, is due to damage costs on health imposed by aerosols, particularly from nitrates. Since the epidemiological evidence linking nitrates to health effects is the weakest step in the damage calculation (evidenced by the B? uncertainty rating given to nitrate impacts - see Appendices II and VIII at the end of this report for more details), it goes without saying that further research is needed in this area to confirm or disprove the implication of health impacts, which under present working knowledge are being attributed to aerosols. If the nitrate impact were zero, for example, the total external cost would then drop by 60% to 90% for all cycles, except for the Oil Fuel cycle, where the nitrate contribution to the total is about 25%.

Before concluding this section, we should point out that the assumed "*total sigma*" given above is only a preliminary estimate based on the observation that mortality costs always dominate the total impact (80% or more of the total externality, excluding global warming). Therefore, we anticipate that the aggregated damage over all pollutants should have a lognormal distribution with an approximate standard deviation equal to that for mortality (B rating). A more rigorous calculation is much too complicated and will not be attempted here.

(a)



(b)

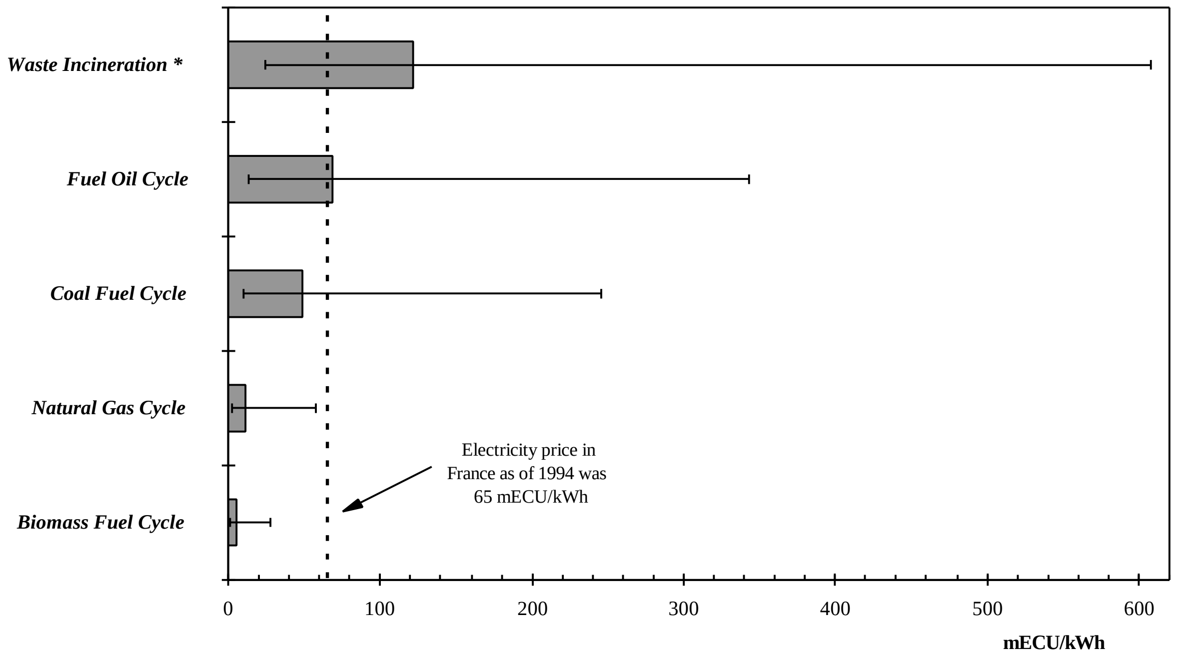


Figure 4.1: Damage costs for fuel cycles in French (a) and uncertainty ranges for externalities (b). The bars do not include the global warming impact. The effect of CO_2 is shown in the last two columns of the tabular insert in (a). ***** see note under Table 4.1.

4.2. REVIEW OF EXTERNALITY ESTIMATES BY CYCLE

4.2.1. Introduction

As pointed out earlier, the coal, natural gas and oil fuel cycles were assessed in the Joule II phase of the ExternE Program. For complete details of the French implementation, including a description of the various fuel cycle stages and externality costs, we refer the reader to the report by Rabl et al. [1996]. The executive summary for this study is reprinted in its entirety in Chapter 8.

Although the methodology used for estimating the impacts and damage costs (IPA procedure) has not changed between the two phases of the ExternE study, a number of refinements and modifications have been added to the analysis, according to the improved level of understanding gained over the last two years. Particularly important are revisions which affect the public health sector. Of these changes, the most notable ones are reported below.

1. Both acute and chronic effects are now included in the mortality impact estimate for particulates and aerosols.
2. An exposure-response (ER) function is now available for quantifying the acute mortality impact from direct exposure to SO_2 concentrations.
3. Rather than evaluating the number of deaths, we now count the number of Years Of Life Lost (YOLL) for the entire population at risk. For particulates and aerosols, 10 YOLLs is approximately equal to 1 death, whereas for acute mortality estimates involving SO_2, 0.75 YOLLs (i.e., 9 months) is equal to 1 death. The Value of a Life Year Lost (VLYL) is based on the valuation of a loss of life or "Value of Statistical Life" (VSL) and a discount rate of 3%. The VSL value in the present work is taken to be $3.1 \mathbf{x} 10^6$ ECU.
4. Damage costs for ozone (from NOx and VOC transformations) and greenhouse gases have been improved. Previously, global warming damages were valued at 13.8 ECU per ton of $CO_{2,eq}$ [Cline, 92]. The "representative" range proposed here is 18 ECU to 46 ECU per ton of $CO_{2,eq}$ (see Appendix V). The external costs for ozone are as follows: 1500 ECU per ton of NOx and 930 ECU per ton of VOC. 32% of these costs are attributable to acute mortality impacts and 47% to various morbidity effects. The remaining 21% are damage costs to crops [Rabl and Eyre, 1997].

4.2.2. Fossil Fuel Cycles (Coal, Natural gas and Oil)

The upstream, downstream and power generation fuel cycle stages for the coal, natural gas and fuel oil power plants are identified in Figures 4.2, 4.4 and 4.6, respectively. In addition to a brief description of each fuel cycle stage (additional details may be found in the report by Rabl et al., 1996), we also include at each step the predicted airborne emissions for the *classical* pollutants (PM_{10}, CO_2, CH_4, SO_2, NOx and VOC). It is important to note that most of upstream emissions take place *outside* of Europe, namely, in the countries from which the fuel is imported and over the sea during fuel transport. Therefore, in the present analysis, we only consider the impacts from greenhouse gas emissions (CO_2 and CH_4) because these are independent of the location of the emission source.

All three installations are assumed to be located in Cordemais, an industrial area along the north Atlantic coast of France near the city of Nantes (see map of France in Figure 5.3). The choice of the Cordemais site is a logical one for placing fossil fuel power plants because it is located close to the St-Nazaire port facility and can, therefore, benefit from low transport costs of imported coal and oil. In 1992, France imported 66%, 91% and 97% of the coal, natural gas and oil needed to meet its energy demands, including electricity generation [Statistiques Energétiques du Ministère de l'Industrie, France, August 1993]. As already mentioned in Section 1.4.2 (*Overview of the French energy sector*), fossil fuels are used only to meet peak electricity demand, particularly in winter months.

The estimated environmental burdens of the fossil fuel cycles are summarized in the table and graph provided below. Full details are given in Tables 4.2-4.4 and Figure 4.3 for the coal cycle, Tables 4.5-4.7 and Figure 4.5 for the natural gas cycle and Tables 4.8-4.10 and Figure 4.7 for the oil cycle. As seen, the anticipated annual damages are normalized by the electricity production. CO_2 impacts are valued at 18 ECU or 46 ECU per ton, according to the *representative* range proposed in Appendix V. In the third column of the table, we also show the predicted annual mortality rate (YOLL/yr) for each installation. Assuming that 1 death is equivalent to 10 YOLLs, the annual *death rate* would be one-tenth (1/10) as large. For the coal power plant, for example, we expect around 100 deaths each year due to air pollution.

As shown in the figure, damages are disaggregated according to pollutant. NOx impacts include effects on public health and crops due to nitrate and ozone formation. Meanwhile, SO_2 damages include impacts to crops, building surfaces (materials) and public health effects due to sulfate formation and *direct* exposure to SO_2 itself (primarily acute mortality). External costs are expressed as a percentage (fraction) of the total (overall) impact, assuming a global warming cost of 18 ECU per ton of CO_2.

Our analysis of the fossil fuel cycles has identified four main conclusions.

1. The environmental burdens are clearly dominated by health effects. In fact, the public health sector accounts for more than 98% of the total external cost! Excluding global warming impacts, nitrate and sulfate aerosols are responsible for more than 91% of the total burden, followed by ozone with 3-7%, crops with 1-2% and particulates with 0-2% of the total cost. With greenhouse effects included, aerosols contribute between 40% and 80% of the total,

depending, of course, on the assumed damage cost per ton of CO_2 and fuel cycle. If global warming impacts are valued at 18 ECU/t_{CO2}, the CO_2 impact ranges between 20% and 40% of the total externality, with aerosols making up most of the remaining difference (ozone accounts for 3-5%).

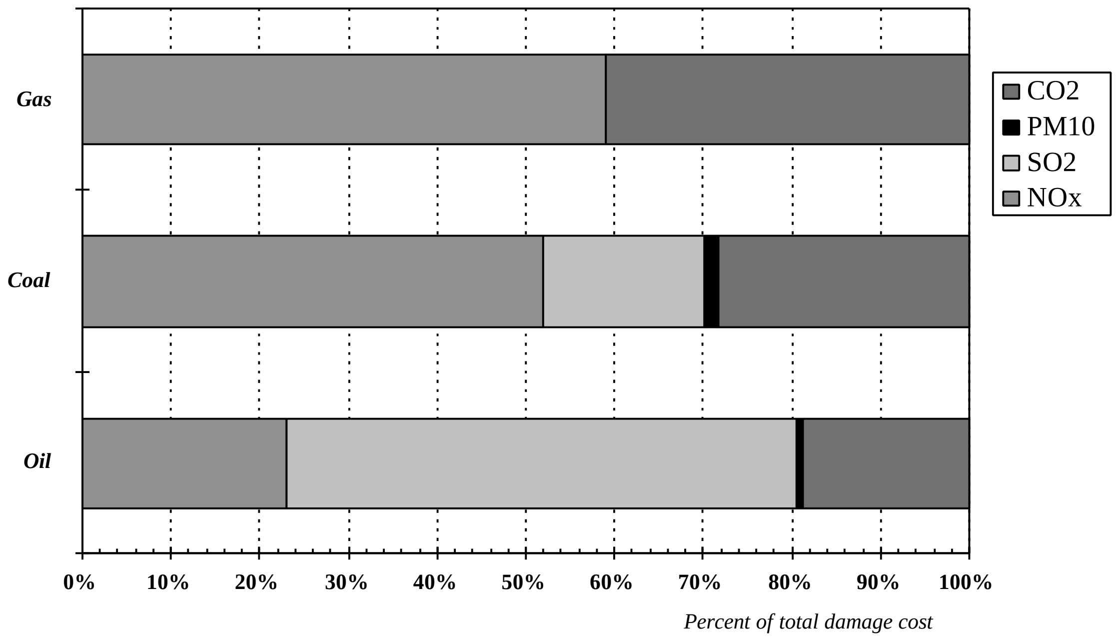
2. Normalized per ton of precursor pollutant [9], NOx at 14600 ECU per ton has the highest damage cost of all pollutants, followed by SO_2 with 8900 ECU per ton and particulates with an external cost between 6100 and 6500 ECU per ton of PM_{10}. NOx impacts include only nitrate aerosol effects; ozone impacts are kept separately. Meanwhile, SO_2 costs include impacts to crops, materials and public health via sulfates and direct SO_2 exposure (about 110-120 ECU per ton of SO_2). For particulates, we report a damage range (6% variation) because of stack height differences between the coal and oil power plants. Roughly, 85% of these costs are due to mortality impacts and 15% to morbidity effects.
3. Impacts to forests and ecosystems are negligible.
4. The natural gas fuel cycle has the lowest environmental burdens of all fossil fuel cycles assessed in this study. In fact, the external costs are about one-quarter (1/4) of those for either the coal or oil fuel cycles.

Summary of fossil fuel results

			Damage (ECU/kWh)		
Fuel Cycle	**GWh/yr**	**YOLLs/yr**	**Excluding CO_2**	**18 ECU per ton of CO_2**	**46 ECU per ton of CO_2**
Coal	2100	980	49.2	68.7	99.1
Gas	1500	160	11.4	19.3	31.4
Oil	1050	690	68.7	84.3	108.5

External costs as a percentage of overall impact (CO_2 valued at 18 ECU per ton)

[9] For nitrates, the precursor pollutant is NOx, whereas for sulfate aerosols it is SO_2.


Gas
Coal
Oil
CO2
PM10
SO2
NOx
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent of total damage cost

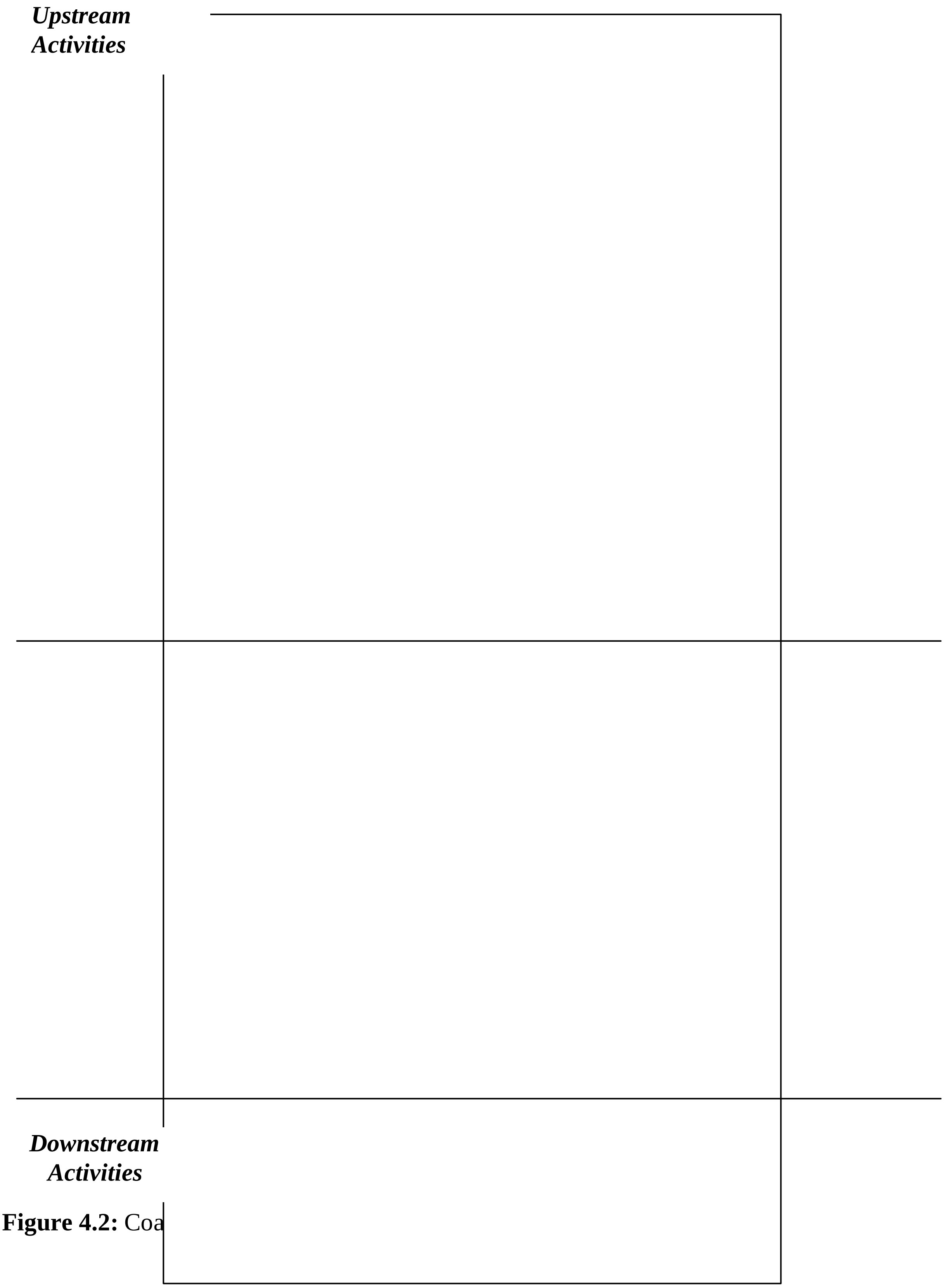


Figure 4.2: Coa

Table 4.2: Damages for the coal fuel cycle.

	mECU/kWh	s_g
POWER GENERATION		
Public health		
Mortality*- YOLL *(VSL)*	**40.2 (151.6)**	
of which TSP	*0.9 (3.3)*	B
SO_2	*10.5 (45.4)*	B
NO_x	*27.7 (101.8)*	B
NO_x *(via ozone)*	*1.1*	B
NMVOC (via ozone)	*0.01*	B
Morbidity	**8.2**	
of which TSP, SO_2*,* NO_x*, CO*	*6.6*	A
NO_x *(via ozone)*	*1.6*	B
NMVOC (via ozone)	*0.02*	B
Accidents	nq	
Occupational health	nq	
Major accidents	nq	
Crops	**0.72**	
of which SO_2	*0.006*	A
NO_x *(via ozone)*	*0.70*	B
NMVOC (via ozone)	*0.01*	B
Ecosystems	ng	
Materials	**0.12**	B
Noise	nq	
Visual impacts	nq	
Global warming (indicative range)		
low (valued at 18 ECU/t)	16.2	C
upper (valued at 46 ECU/t)	41.4	C
OTHER FUEL CYCLE STAGES		
Public health	nq	
Occupational health	nq	
Ecological effects	nq	
Road damages	nq	
Global warming (indicative range)		
from extraction/transport emissions		
low (valued at 18 ECU/t)	3.3	C
upper (valued at 46 ECU/t)	8.5	C

*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.

Table 4.3: Sub-total damages for the coal fuel cycle.

		mECU/kWh
YOLL *(VSL)*	low	68.7 (180.1)
	upper	99.1 (210.5)

Table 4.4: Damages by pollutant.

	ECU / t of pollutant
SO_2 *- YOLL *(VSL)*	8900 (34700)
NO_x *- YOLL *(VSL)*	14600 (48000)
PM_{10} *- YOLL *(VSL)*	6100 (20300)
NO_x (via ozone)	1500
VOC (via ozone)	930
CO_2	18 - 46

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

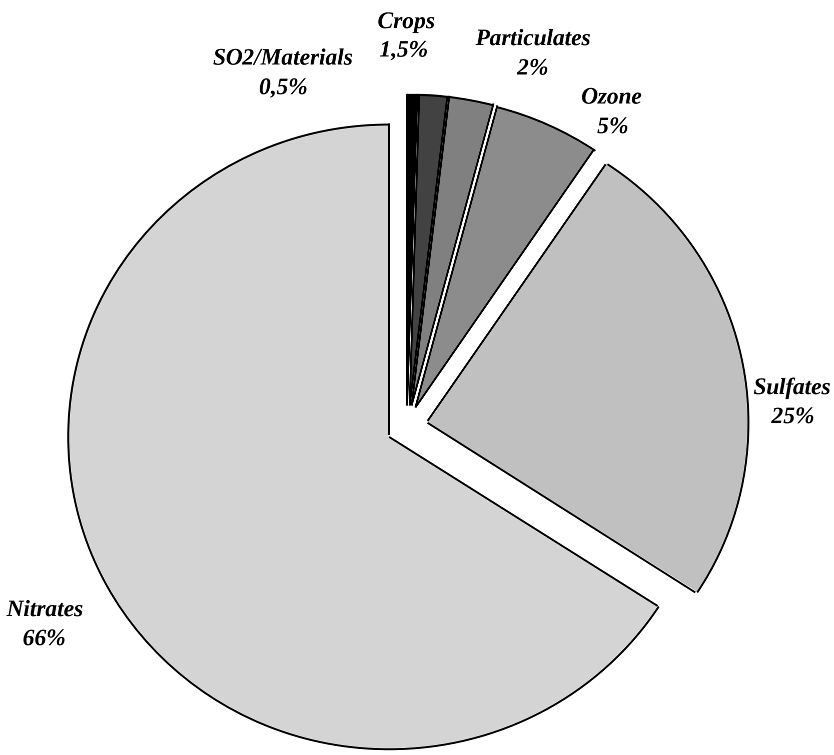


Figure 4.3: Breakdown of damage costs, excluding global warming, by pollutant for the coal power plant in Cordemais near Nantes, France. Total = 49.2 mECU/kWh_{el}.

Upstream Activities

Gas extraction:
Gas supply - Arzew, Algeria
Air emissions - NO_x (0.02 g/kWh)
CO_2 (13.00 g/kWh)
CH_4 (3.60 g/kWh)
Gas is usually desulfurized just after extraction (original sulfur content is 4%).

Liquefaction losses:
Gas losses - < 1% of transported volume
Air emissions - NO_x (0.10 g/kWh)
CO_2 (70.00 g/kWh)

Fuel transport:
Gas is transported from the extraction site to the harbor of Montoir, near Cordemais in France, by land via pipeline (500 km) and by waterway via ship (4500 km).
Air emissions - SO_2 (0.06 g/kWh)
NO_x (0.03 g/kWh)
CO_2 (12.00 g/kWh)

Electricity production:
Location of plant - Cordemais (near Nantes)
Technology - Gas turbine combined cycle
Efficiency - 52%
Hours of operation - 6000 hr/ yr
Annual production - 1500 GWh (250 MW)

Stack parameters - height = 110 m
diameter = 10 m
exit temperature = 500 K
exit gas speed = 9.8 m/s

Air emissions - PM_{10} (negligible)
SO_2 (negligible)
NO_x (0.71 g/kWh)
CO_2 (401.00 g/kWh)
VOC (0.024 g/kWh)

Figure 4.4: Fuel cycle stages for Natural gas.

Table 4.5: Damages for the natural gas fuel cycle.

	mECU/kWh	s_g
POWER GENERATION		
Public health		
Mortality*- YOLL *(VSL)*	**9.15 (32.7)**	
of which TSP	*ng*	
SO_2	*ng*	
NO_x	*8.8 (32.4)*	B
NO_x (via ozone)	*0.3*	B
NMVOC (via ozone)	*0.007*	B
Morbidity	**2.1**	
of which TSP, SO_2, NO_x, CO	*1.6*	A
NO_x (via ozone)	*0.5*	B
NMVOC (via ozone)	*0.01*	B
Accidents	nq	
Occupational health	nq	
Major accidents	nq	
Crops	**0.22**	
of which SO_2	*ng*	A
NO_x (via ozone)	*0.22*	B
NMVOC (via ozone)	*0.005*	B
Ecosystems	ng	
Materials	***ng***	
Noise	nq	
Visual impacts	nq	
Global warming (indicative range)		
low (valued at 18 ECU/t)	7.2	C
upper (valued at 46 ECU/t)	18.4	C
OTHER FUEL CYCLE STAGES		
Public health	nq	
Occupational health	nq	
Ecological effects	nq	
Road damages	nq	
Global warming (indicative range)		
from extraction/transport/liquefaction emissions		
low (valued at 18 ECU/t)	0.6	C
upper (valued at 46 ECU/t)	1.5	C

*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.

Table 4.6: Sub-total damages for the natural gas fuel cycle.

		mECU/kWh
YOLL *(VSL)*	low	19.3 (42.8)
	upper	31.4 (54.9)

Table 4.7: Damages by pollutant.

	ECU / t of pollutant
SO_2 *- YOLL *(VSL)*	–
NO_x *- YOLL *(VSL)*	14600 (48000)
PM_{10} *- YOLL *(VSL)*	–
NO_x (via ozone)	1500
VOC (via ozone)	930
CO_2	18 - 46

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

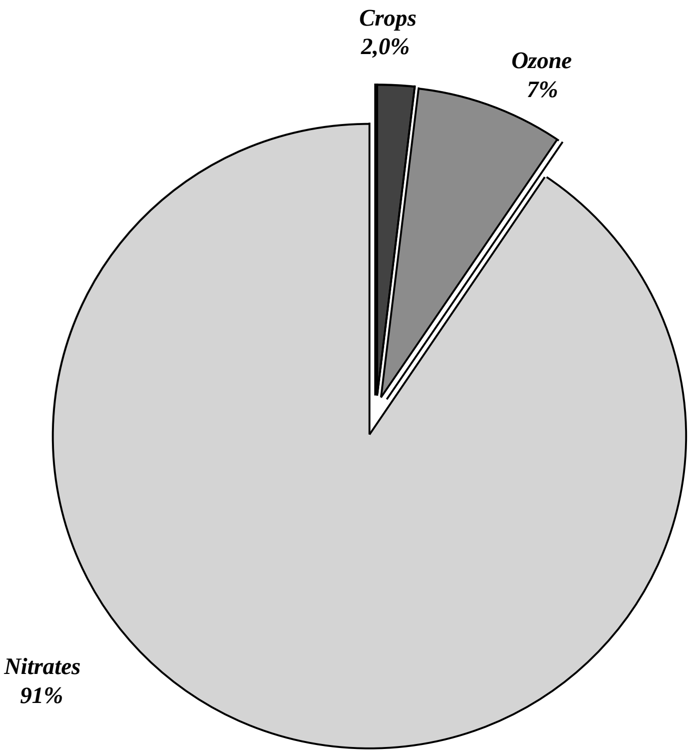


Figure 4.5: Breakdown of damage costs, excluding global warming, by pollutant for the natural gas power plant in Cordemais near Nantes, France. Total = 11.4 mECU/kWh$_{el}$.

Upstream Activities

Oil extraction:
Oil supply - Imported from overseas
Air emissions - SO_2 (1.100 g/kWh)
NO_x (0.033 g/kWh)
CO_2 (22.000 g/kWh)
CH_4 (2.000 g/kWh)
VOC (0.270 g/kWh)

Fuel transport:
Oil is transported from the extraction site to the harbor of Montoir, near Cordemais in France, by land via pipeline (500 km) and by waterway via tanker (12500 km).
Air emissions - SO_2 (0.355 g/kWh)
NO_x (0.027 g/kWh)
CO_2 (13.900 g/kWh)

Fuel preparation (Refining):
The Cordemais power plant is designed to use low sulfur content oil (< 1% S).
Air emissions - SO_2 (0.11 g/kWh)
NO_x (0.02 g/kWh)
CO_2 (11.00 g/kWh)

Storage losses:
It is estimated that in France 40,000 tons of hydrocarbons are released to the air each year via evaporation at either the refinery or user site.
Air emissions - CH_4 (0.01 g/kWh)

```
Electricity production:
Location of plant   - Cordemais (near  Nantes)
Technology          - low S oil, low  NOx burners,
                       steam turbine
Efficiency          - 39%
Hours of operation - 1500 hr/ yr
Annual production   - 1050 GWh (700 MW)

Stack parameters    - height           = 150 m
                      diameter         =  10 m
                      exit temperature = 500 K
                      exit gas speed   = 9.8 m/s

Air emissions       - PM10 (  0.13 g/kWh)
                      SO2  (  5.26 g/kWh)
                      NOx  (  1.20 g/kWh)
                      CO2  (740.00 g/kWh)
                      VOC (  0.48 g/kWh)
```

Figure 4.6: Stages for oil-to electricity conversion.

Table 4.8: Damages for the oil fuel cycle.

	mECU/kWh		σ_g
POWER GENERATION			
Public health			
Mortality*- YOLL *(VSL)*	**57.1**	**(234.0)**	
of which TSP	*0.7*	*(2.6)*	B
SO_2	*40.7*	*(175.7)*	B
NO_x	*15.0*	*(55.0)*	B
NO_x (via ozone)	*0.6*		B
NMVOC (via ozone)	*0.1*		B
Morbidity	**10.6**		
of which TSP, SO_2, NO_x, CO	*9.5*		A
NO_x (via ozone)	*0.9*		B
NMVOC (via ozone)	*0.2*		B
Accidents	nq		

Occupational health	nq	
Major accidents	nq	
Crops	**0.50**	
of which SO_2	*0.023*	A
NO_x (via ozone)	*0.378*	B
NMVOC (via ozone)	*0.094*	B
Ecosystems	ng	
Materials	**0.46**	B
Noise	nq	
Visual impacts	nq	
Global warming (indicative range)		
low (valued at 18 ECU/t)	13.3	C
upper (valued at 46 ECU/t)	34.0	C
OTHER FUEL CYCLE STAGES		
Public health	nq	
Occupational health	nq	
Ecological effects	nq	
Road damages	nq	
Global warming (indicative range)		
extraction/transport/refining/storage emissions		
low (valued at 18 ECU/t)	2.3	C
upper (valued at 46 ECU/t)	5.8	C

*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.

Table 4.9: Sub-total damages for the oil fuel cycle.

		mECU/kWh
YOLL *(VSL)*	low	84.3 (261.2)
	upper	108.5 (285.4)

Table 4.10: Damages by pollutant.

	ECU / t of pollutant
SO_2 *- YOLL *(VSL)*	8900 (34700)
NO_x *- YOLL *(VSL)*	14600 (48000)
PM_{10} *- YOLL *(VSL)*	6500 (21000)
NO_x (via ozone)	1500
VOC (via ozone)	930
CO_2	18 - 46

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

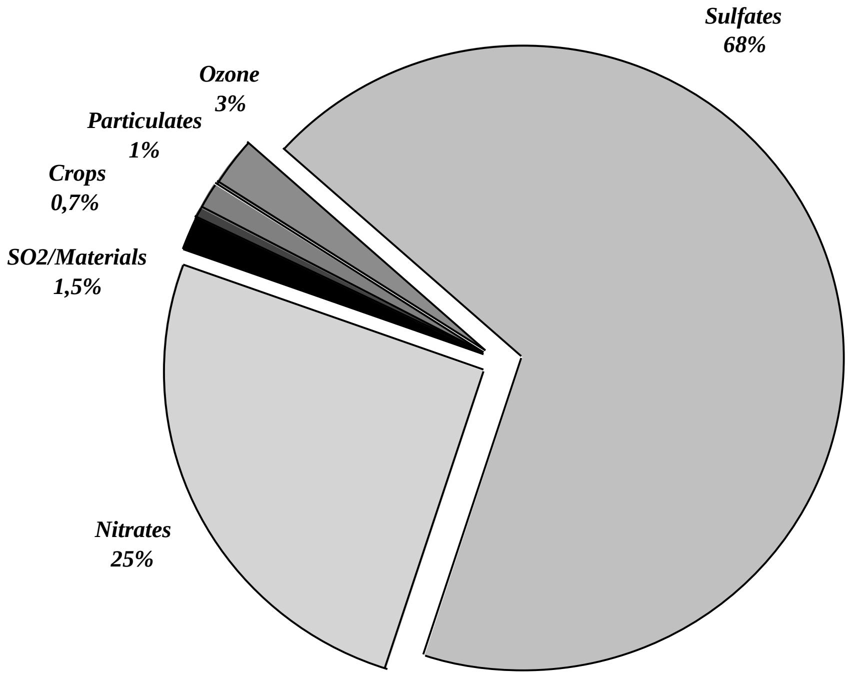


Figure 4.7: Breakdown of damage costs, excluding global warming, by pollutant for the oil fuel power plant in Cordemais near Nantes, France. Total = 68.7 $mECU/kWh_{el}$.

4.2.3. Biomass Fuel Cycle

4.2.3.1. Introduction

The biomass-to-electricity reference facility considered in this study is a hypothetical power plant assumed to be located near Albi, a small town not far from the city of Toulouse, in the southern region of France. At the present time, no biomass installations are either operating in France or are being planned for the immediate future, although some interest in using biomass for producing electricity does exist (renewable fuel cycle). In Table 4.11, the external costs for the wood-to-electricity fuel cycle are compared against those for the fossil fuel cycles, including coal, natural gas and fuel oil. The emission factors are the same as those given in Table 4.1, whereas the damages per ton of pollutant are the "*average*" estimates shown in Table 5.2. As one can clearly observe, the externalities from wood-to-electricity conversion (based on the BIG/ISTIG configuration discussed below) are much lower than those associated with the fossil fuel cycles, about 40% of the damage cost for natural gas and an order of magnitude smaller than that for coal and fuel oil. Therefore, the potential advantages of the biomass fuel cycle in reducing the overall externalities due to electricity production, as well as taking advantage of renewable energy resources, can be quite significant and merit further investigation, with the intent of using this technology to meet future demands in the electricity sector (baseload or peak).

Table 4.11: External costs for the power generation stage only (mECU/kWh_{el}) for various fuel cycles, assuming the emission factors in Table 4.1 and damage costs per ton of pollutant given in Table 5.2.

Pollutant	Biomass	Coal	Natural Gas	Fuel Oil
Particulates	0.55	2.14	0.	1.64
NOx	4.50	41.29	13.21	22.32
SO_2	0.36	15.10	0.	58.39
sub-Total	**5.4**	**58.5**	**13.2**	**83.3**

4.2.3.2. Definition of the biomass fuel cycle

The technology characterization and the projected emission factors from upstream, downstream and "direct" (i.e., from the power plant itself) processes are summarized in Figure 4.8 with additional details given in Table 4.12. The biomass facility has an electrical generation capacity of 40 MW, and assuming a 70% capacity factor, the annual electrical output is just over 245 GWh. The biomass fuel assumed for this analysis is poplar wood, which is grown according to the short-rotation intensive culture (SRIC) strategy [ORNL, 92]. To meet the projected electrical demand, nearly 25000 acres of land must be set aside to produce the required 130000 tons of wood feedstock. Finally, on a yearly basis, about 1300 tons of bottom ash and fly ash are anticipated as residual waste products. Since the ash is rich in nitrogen, carbon, sodium and potassium, it can be used as an effective fertilizer and soil conditioner. Therefore, wood ashes represent a "beneficial" impact of the biomass fuel cycle. The only downstream impact, therefore, comes from the emissions from transport of the ashes back to the plantation field.

The biomass to electricity conversion technology is based on the highly efficient Biomass-Gasifier Intercooled STeam-Injected Gas turbine technology, BIG/ISTIG for short, discussed by Larson *et al.* [1989]. In a biomass-gasifier turbine, the wood is converted into a gas inside a highly pressurized air-blown reactor before being combusted in a gas turbine. To prevent turbine blade damage and avoid efficiency losses, the "raw" gas stream is passed through an electrostatic precipitator before entering the turbine stage. For the particular biomass plant considered here, the overall electrical conversion efficiency is expected to be 38.4% [see Larson *et al.*, 1989].

Turning our attention to gas emissions, we readily note that wood-fired electricity production is dominated by NOx discharges, which are 5.5 times as large as particulate emissions and nearly 8 times as significant as SOx values. Regarding carbon dioxide emissions, we assume that the ***net*** contribution of CO_2 to the atmosphere is approximately zero, since the carbon dioxide emitted during wood combustion is merely CO_2 absorbed by the feedstock during growth.

Upstream emissions include releases from agricultural equipment used to grow and harvest the wood, and from transportation vehicles (trucks) used to haul the feedstock from the production field to the power plant. From an economic standpoint, the transportation distance between the field and the biomass plant is kept at a minimum, typically less than 50 kilometers. At the present time, “biogenic” emissions from the growth of wood (feedstock releases to the atmosphere via biological interactions), other than CO_2 sequestering, agricultural chemical releases (due to pesticides, fertilizers, etc.) and emissions due to crop storage have not been considered.

For atmospheric dispersion calculations, we have aggregated transport and agricultural emissions independently and then assigned these values to two separate point sources. One was located halfway along the road connecting the plantation field and the power plant, and the other was placed in the middle of the crop field. A stack height of 2.5 meters was used for near ground emissions. Other stack assumptions are listed in Table 4.12.

Upstream activities

Ground-level
Air emissions:

$PM_{2.5}$	2.6 t/yr
SOx	1.8 t/yr
NOx	26.9 t/yr
CO	26.9 t/yr
VOC	6.3 t/yr
CO_2	4270 t/yr.

Feedstock production:
Biomass fuel - Poplar wood (SRIC)
Biomass production - 152 000 dry t/yr
Plantation area - 25 000 acres (100 km^2)

Feedstock transport:
Average hauling distance - 55 km
Hauling tonnage - 133 461 dry t/yr

Electricity production:
Proposed location of biomass plant - Albi (near Toulouse)
Conversion technology - BIG/ISTIG (η=38.4%)
Annual electricity production - 245 GWh (40MW)
Annual capacity - 70%
Air emissions (43400 Nm^3/h) - PM_{10} (40.1 mg/Nm^3)
(stack height = 40 m) - SOx (29.5 mg/Nm^3)
- NOx (223.0 mg/Nm^3)
- CO (7.4 mg/Nm^3)
- VOC (11.1 mg/Nm^3)

Downstream activities

Ground-level
Air emissions:

$PM_{2.5}$	0.05 t/yr
SOx	0.02 t/yr
NOx	0.5 t/yr
CO	0.5 t/yr
VOC	0.1 t/yr
CO_2	74 t/yr.

Transport of waste:
Wood ash - 1 281 t/yr

Disposal of waste:
Ashes returned to biomass field and used as fertilizer.

Figure 4.8: Biomass fuel cycle stages.

Table 4.12: Technical assumptions and emissions to air for the biomass to electricity power plant. The geographical coordinates given here are for the Albi location (near Toulouse).

Plant location				
Geographical latitude	43.8	^{o}N		Biomass crop field located within 50 kilometers from the power plant.
Geographical longitude	2.2	^{o}E		
Elevation at site	200	m		Above sea level
Technical data				
Generator capacity	40	MW_{el}		
Full load operation	6132	hrs/yr		Capacity factor of 70%
Electricity production	245280	MWh_{el} /yr		
Conversion efficiency	38.4	%		Biomass-gasifier with gas turbine conversion technology [Larson *et al.*, 1989]
Feedstock requirements	128120	dry tons/yr		Poplar wood from short rotation plantation (24911 acres of land required).
Recoverable ashes	1281	t/yr		Returned to field as fertilizer
Stack parameters	***Upstream & downstream sources***	***Direct emissions***		
Height (in m)	2.5	40		For impacts due to transport and agricultural equipment, aggregate emissions separately and use two point sources.
Inside diameter (in m)	0.05	4		
Flue gas exit temperature (in K)	350	373		
Flue gas exit speed (in m/s)	0.001	1.31		For direct emissions, the *flue gas exhaust volume* is equal to 12 Nm^3/sec.
Pollutant emissions	***Upstream (kg/yr)***	***Direct (kg/yr)***	***Downstream (kg/yr)***	
Particulates (1)	2579	10792	53	Upstream emissions include farming equipment and feedstock transport.
SO_2	1836	7849	23	
NOx	26873	59358	526	Downstream emissions include transport and spread of ashes.
CO	26873	1980	526	
VOC (2)	6265	2968	115	
CO_2	4270396	0	74331	CO_2 combustion emissions cancel CO_2 uptake during plant growth.

Notes:

[1] Particulate classification: diesel particles ($PM_{2.5}$) for upstream and downstream sources and PM_{10} for electricity production releases.

[2] Additional VOC sources from plant growth include: 989 tons/yr (4.03 gm/kWh) isoprene emissions and 124 tons/yr (0.51 gm/kWh) monoterpene releases. Nitrogen emissions to air from fertilizers ($N_2H_4O_3$ and urea) amount to 41 tons/yr (0.17 gm/kWh).

Definitions: t = ton; K = Kelvins; 1 kg = 1000 g; Nm^3 = normal-cubic-meter, i.e., the volume of a parcel of air at 273 K.

4.2.3.3. Summary and interpretation of results

The damage cost estimates for the biomass-to-electricity fuel cycle are summarized in Tables 4.13, 4.14 and 4.15. Furthermore, a breakdown by pollutant, as a percentage of total, is shown in Figure 4.9. The overall damage cost is 5.5 mECU/kWh_{el}, excluding CO_2 damages and between 5.9 and 6.7 mECU/kWh_{el} if global warming costs are included in the total. As already noted for the fossil fuel cycles, the total cost is clearly dominated by externalities to the public health sector, particularly from nitrate and sulfate aerosols. Together, these pollutants contribute between 60% and 70% of the total damage cost (CO_2 impacts included). It should be noted that health costs from diesel particulate emissions, namely cancers, account for less than 0.5% of the total externality or 0.003 mECU/kWh_{el}. Altogether, health impacts account for 96% of the external costs. The additional 4% is split between road damages and impacts to crops and materials (building surfaces).

In terms of Years Of Life Lost (YOLLs), the mortality rate from airborne pollution is 12.5 YOLL per year. If we value 1 death at 10 YOLLs, the death rate is 1.25 lives per year. Nearly all these deaths (about 95%) occur within the borders of France.

In our analysis, we assume that the CO_2 emitted to the air during wood combustion is approximately offset by the amount of CO_2 sequestered during plant growth. Hence, the *net* atmospheric CO_2 contribution from these two fuel-cycle stages is assumed to be zero. The use of agricultural machinery and transport vehicles are the only two sources of global warming gases which we have considered in this assessment.

The damage costs per ton of pollutant, including both primary and secondary species, are listed in Table 4.15. Compared to the aerosol costs for the Cordemais site, the nitrate damage per ton of NOx is approximately 25% lower, whereas for sulfates, the cost per ton of SO_2 has decreased by about 16%. The smaller damage costs for the Albi location reflect the lower population density in the region surrounding the biomass facility. The difference in cost estimates between these two sites is not as great as one might have anticipated only because aerosol impacts are not very sensitive to local receptor densities. For particulate emissions, on the other hand, the damage per ton is higher at Albi. This is because of the much lower stack height at which particulates are emitted to the air, 40 m at Albi versus 150 m or 220 m at Cordemais.

For particulate impacts, we provide two estimates for the damage cost per ton of pollutant, which are based on the type pollution source. Namely, we treat particulate emissions from wood combustion as PM_{10}, and those emitted from farming and transport vehicles as $PM_{2.5}$. As seen in Table 4.15, the damage per ton of $PM_{2.5}$ is about twice the cost for PM_{10}. Two reasons explain this difference. First, the $PM_{2.5}$ emissions occur at ground-level, instead of 40 m above ground, as for the case of PM_{10} releases. Second, because of the smaller size, $PM_{2.5}$ are more toxic to humans than PM_{10}. As a matter of fact, the exposure-response functions for quantifying health impacts for the $PM_{2.5}$ specie are about 1.6 times larger than the corresponding ones used for PM_{10}.

Whereas in Figure 4.9 we showed the damage costs for each pollutant as a fraction of the total impact, in Figure 4.10 we present the same data, but this time using an absolute scale, namely, in mECU per kWh_{el}. In particular, we have plotted the results using both a logarithmic and a linear scale. Since damage costs for different pollutants often vary by several orders of magnitude, the advantage of using a logarithmic axis is that it permits us to easily compare very small and very large numbers and also to quantify the differences on an order of magnitude. For instance, in Figure 4.10a, it is abundantly clear that cancer costs are three (3) orders of magnitude smaller than nitrate damages, and may, therefore, be neglected as an insignificant effect.

The advantage of using a linear scale, on the other hand, is that it permits us to put the damage costs into proper perspective. That is, identify which pollutants contribute the most to the overall impact. For example, in Figure 4.10b, it is immediately obvious that nitrate and sulfate aerosols, particulates and ozone are the relevant pollutants. As for the rest, they don't matter. In fact, their impacts are so small that they are "*invisible*".

In Figures 4.11 and 4.12, we show the regional and local scale marginal concentration increases and mortality impact distributions for NOx and particulate emissions from all fuel-cycle stages (i.e., from upstream, power generation and downstream steps). For the regional domain, we show contours for nitrate aerosols, and for the local scale, we present distributions for particulates (we include both particulate species, namely PM_{10} and $PM_{2.5}$). Concentrations [10] are given in units of ng/m^3, whereas mortality impacts are expressed in mYOLL/yr [11] per cell (where the cell size is 100 by 100 km^2 for the regional domain and 10 by 10 km^2 for the local scale). The biomass facility, located in Eurogrid cell (2,-7), is identified by the *white* circle, meanwhile, the plantation field is indicated by the ***black*** circle marked with a white X.

Regarding the concentration spreads, the regional distributions tend to have an oval-like shape, which appears to be centered about a point lying several hundred kilometers north-east of the emission site. This pattern is not so surprising, since it normally can take up to several hours for nitrate aerosols to form in the atmosphere. In the meantime, the primary pollutant (NOx in this case) is transported downstream of the emission site along the prevailing wind direction. Typically, peak aerosol concentrations occur within 50 kilometers from the pollution source. Local concentration fields are highly dependent on the meteorological conditions existing near the source. Generally, the peak concentration value occurs within the first few kilometers from the source.

---

[10] 1 ng = 10^{-9} g.

[11] 1 mYOLL = 10^{-3} YOLL.

At first glance, the damage profile for the regional scale (Figure 4.11b) may seem a bit random or even erratic, but, in fact, it is consistent with the population distribution across Europe, which, of course, is highly irregular over the impact region. Although the nitrate concentration level will eventually start to decrease as we move far enough from the emission source, the highest damages (indicated by the dark colored areas) typically occur at or near large cities, like Madrid, Paris and Rome, where the local population densities are up to two orders of magnitude higher than the European average (158 persons per km^2). This highly localized increase in receptor density more than offsets the drop in pollutant concentration level, and is, therefore, responsible for the observed "sporadic" peaks in damage values.

Table 4.13: Damages for the biomass fuel cycle.

	mECU/kWh	s_g
POWER GENERATION		
Public health		
Mortality*- YOLL *(VSL)*	**4.34 (15.64)**	
of which TSP	*0.66 (2.42)*	B
SO_2	*0.25 (1.08)*	B
NO_x	*3.25 (11.96)*	B
NO_x (via ozone)	*0.17*	B
NMVOC (via ozone)	*0.012*	B
Morbidity	**0.97**	
of which TSP, SO_2, NO_x, CO	*0.70*	A
NO_x (via ozone)	*0.25*	B
NMVOC (via ozone)	*0.018*	B
Accidents	nq	
Occupational health	nq	
Major accidents	nq	
Crops	**0.12**	
of which SO_2	*0.0002*	A
NO_x (via ozone)	*0.11*	B
NMVOC (via ozone)	*0.01*	B
Ecosystems	ng	
Materials	**0.004**	B
Noise	ng	
Visual impacts	ng	
Global warming (indicative range)	**0 ****	
low (valued at 18 ECU/t)		
upper (valued at 46 ECU/t)		
OTHER FUEL CYCLE STAGES		
Public health		
Cancers from farming and transport activities	**0.003**	B
Occupational health	nq	
Ecological effects	nq	
Road damages	**0.14 - 0.41**	A
Global warming (indicative range)		
from farming/transport emissions		
low (valued at 18 ECU/t)	0.32	C
upper (valued at 46 ECU/t)	0.81	C

*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.

** We assume that CO_2 sequestering during plant growth cancels out the emitted CO_2 during combustion of the biomass.

Table 4.14: Sub-total damages for the biomass fuel cycle.

		mECU/kWh
YOLL *(VSL)*	low	5.9 (17.1)
	upper	6.7 (18.0)

Table 4.15: Damages by pollutant.

	ECU / t of pollutant
SO_2 *- YOLL *(VSL)*	7500 (28300)
NO_x *- YOLL *(VSL)*	10800 (35400)
PM_{10} *- YOLL *(VSL)* - power generation	11500 (37700)
$PM_{2.5}$ *- YOLL *(VSL)* - transport/farming	21500 (70500)
NO_x (via ozone)	1500
VOC (via ozone)	930
CO_2	18 - 46

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

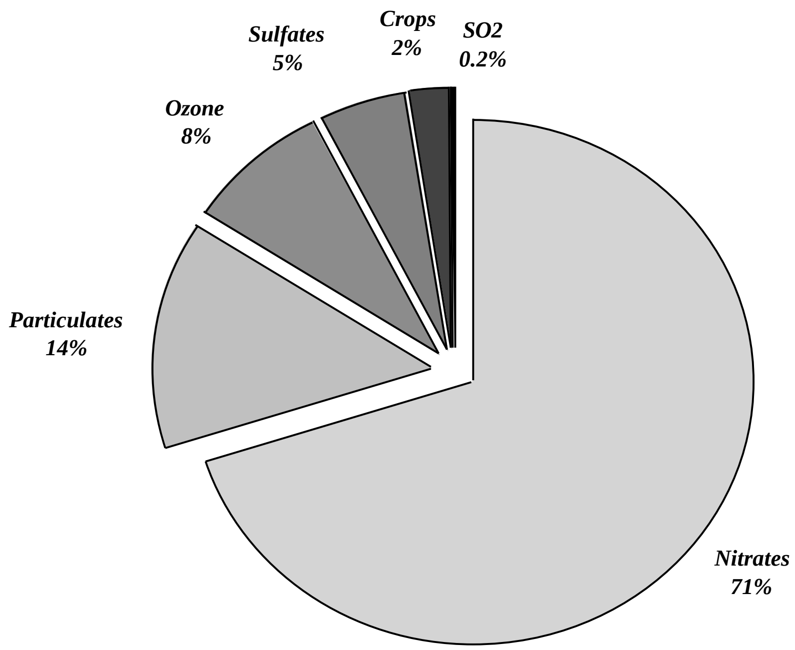
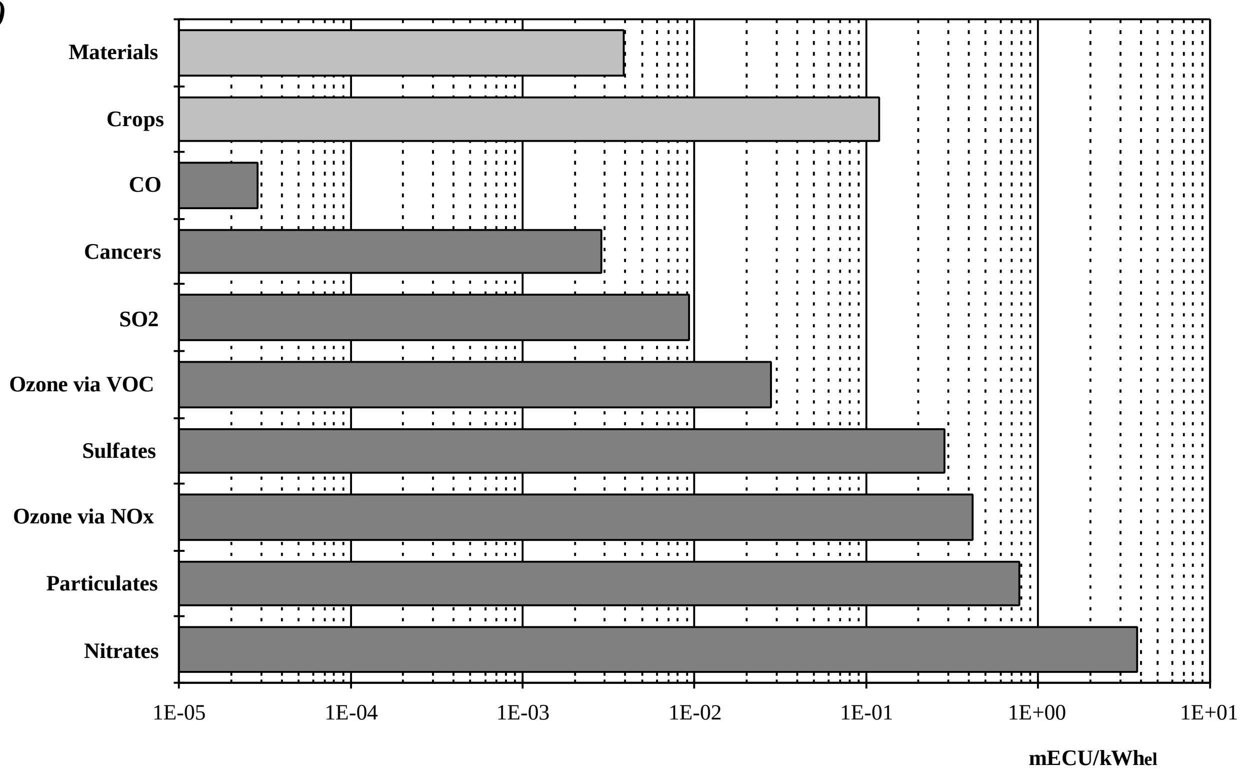


Figure 4.9: Breakdown of damage costs, excluding global warming, by pollutant for the biomass plant in Albi near Toulouse, France (upstream/downstream and power production stages included). Total = 5.5 mECU/kWh_{el}.

(A)



(B)

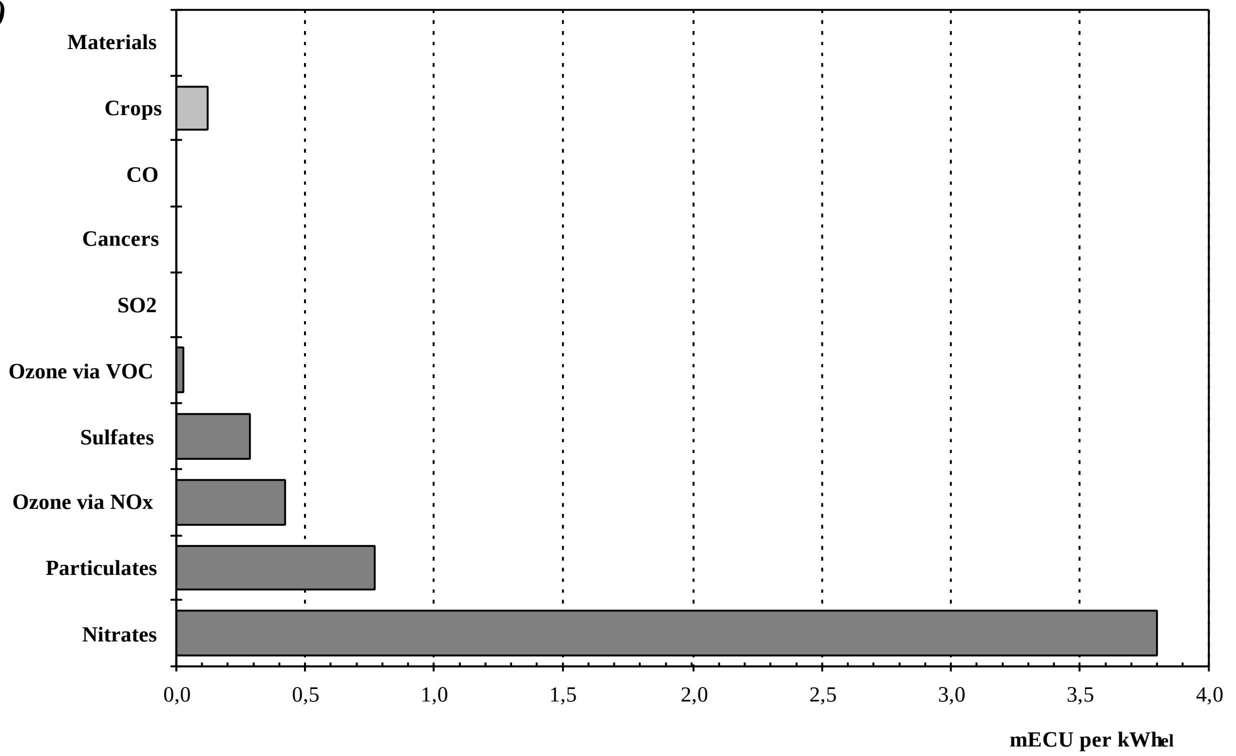


Figure 4.10: Damage costs for the French biomass plant in Albi, near Toulouse.

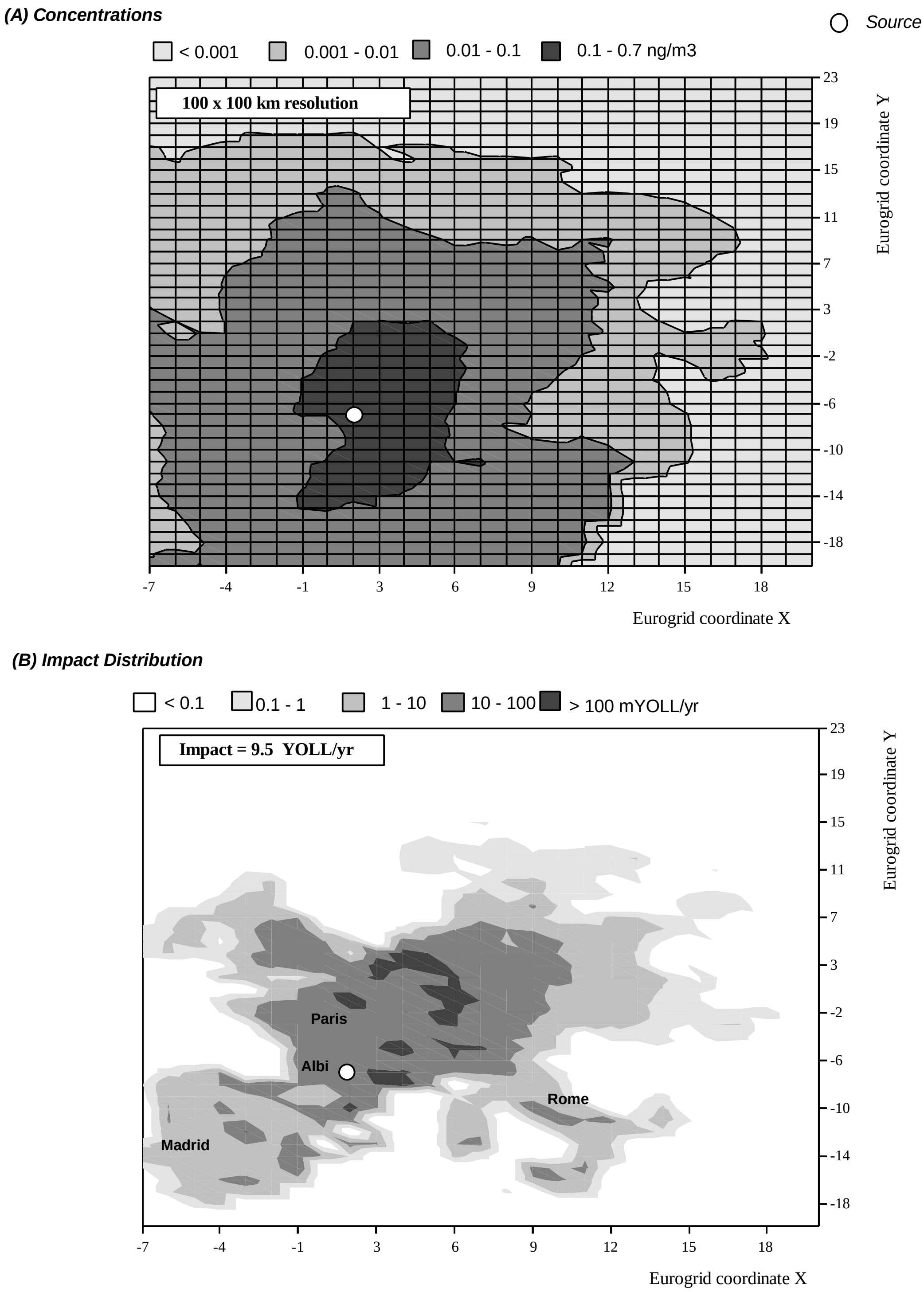


Figure 4.11: Nitrate aerosol concentrations (A) and mortality distributions (B) for the biomass plant located in Albi. Densities are per Eurogrid cell (100 x 100 km^2). The power plant is located in Eurogrid Cell (2, -7). Damages include emissions from upstream, generation and downstream processes.

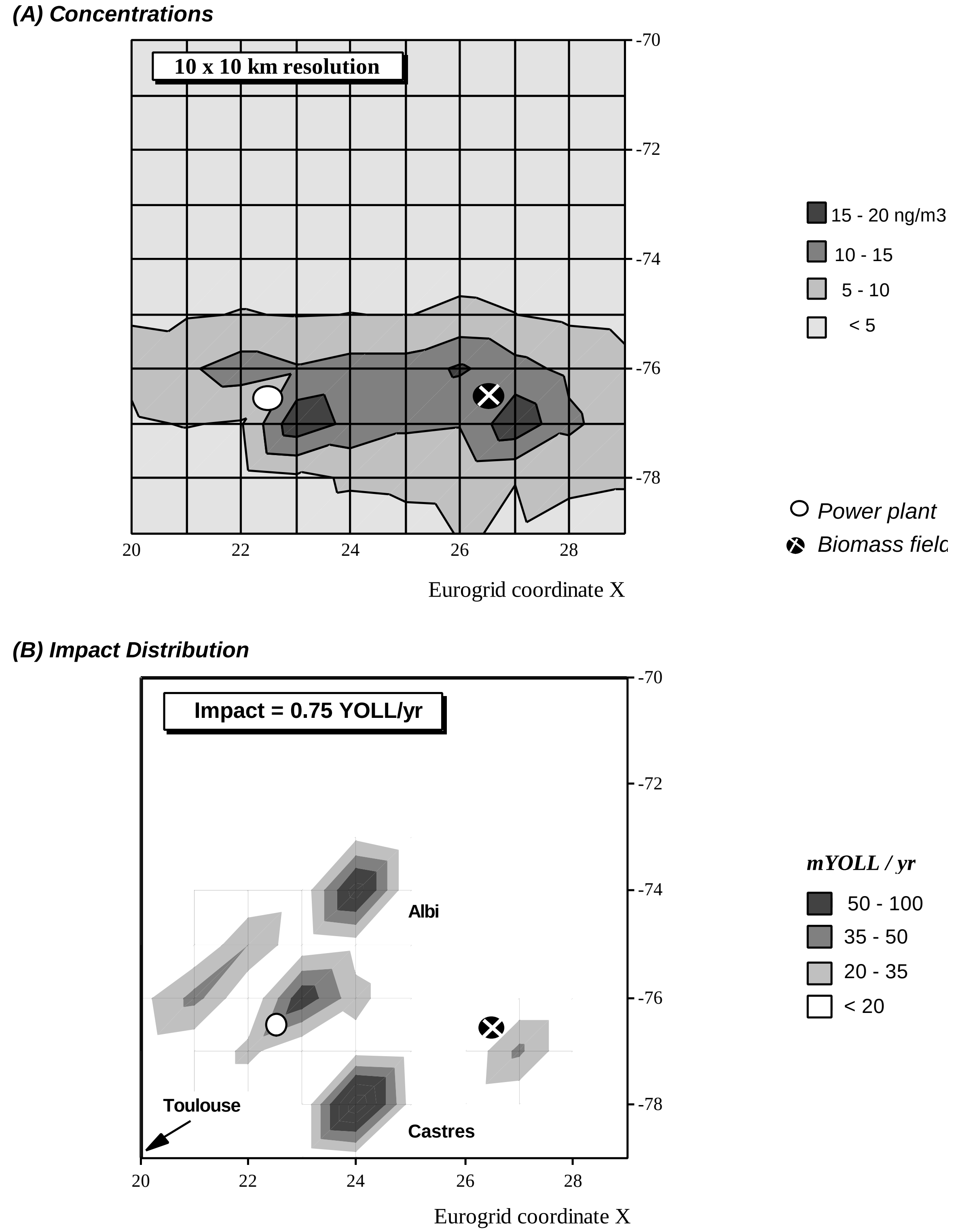


Figure 4.12: Particulate concentrations (A) and mortality distributions (B) for the biomass plant located near Albi. Densities are per *small* Eurogrid cell (10 x 10 km^2). Impacts include emissions from upstream, direct and downstream processes.

4.2.4. Nuclear Fuel Cycle

The French nuclear fuel cycle was studied in an earlier phase of the ExternE Project (Joule II). The full details may be found in the report by Rabl et al. [1996]. The executive summary for this report may be found in Chapter 8 (*Previous Results for the Nuclear and Hydro Fuel Cycles*).

4.2.5. Hydroelectric Fuel Cycle

For the present report, we have not assessed the external costs for the hydroelectric fuel cycle. However, the French implementation of the hydro fuel cycle was studied earlier by Lesgards [1995]. The executive summary for this report has been reproduced in Chapter 8.

4.2.6. Waste Incineration

4.2.6.1. Introduction

With regard to the municipal solid waste (MSW) incinerator facility considered in this report, it is located in the north-west suburbs of Paris, about 8 kilometers from the center of the city. The Paris MSW incinerator is one of the three largest facilities of its kind located within the Ile-de-France province (the remaining two facilities are also located not very far from the city of Paris). The processed waste comes from Paris and its nearest 81 communities. Other than treating waste, the primary purpose of this plant is to supply heat to the district heating system in Paris and, *less importantly*, some electricity to the grid. The amount of recovered electricity varies greatly from year to year, whereas heat recovery depends on the thermal load, which is more constant over time.

Presently, 42% of all municipal solid waste generated in France is incinerated, hence, it has become increasingly more important to consider the potential environmental implications and risks from waste incineration and management, including an analysis of waste disposal by burning the refuse versus storing the waste at a nearby landfill. This issue has become even more important because starting in the year 2004 all of the household waste produced in France must be first treated thermally (incinerated) and only then the remaining ashes placed in a landfill.

Another issue which has gained particular attention in recent times is the potential risk to public health due to emissions of heavy metals (As, Cd, Ni, ...), acidic gases (HCl, HF) and dioxins, which are highly toxic chemicals released to the environment during the combustion of plastic materials. Therefore, calculating impacts from these species represents a crucial step in evaluating the overall effectiveness and *cleanliness* of waste incineration. As will be shown latter on in this section, cancers from heavy metals and dioxin emissions contribute less than

0.1% of the external costs arising from thermal treatment of waste. This conclusion is contrary to public concern on the matter.

4.2.6.2. Definition of the waste incineration cycle

For the municipal solid waste facility selected for this study, the technical data and average pollutant emission levels are summarized in Table 4.16. The various stages in the waste incineration cycle are outlined in Figure 4.13. Nearly 660000 tons of waste are processed each year. This figure represents 2.1% of the total refuse currently generated in French households. For each ton of waste burned, approximately 29% of residual substances are generated, including 256 kg of slag, 17.6 kg of scrap iron and 15.1 kg of filter ash. These substances are later transported to nearby landfills or re-processed into building materials, such as cinder blocks. The heating value (net calorific value) of waste, for this particular plant, is around 7200 kJ per kg of waste burned. Prior to being released into the atmosphere, the combustion gases are passed through an electrostatic precipitator device and a wet scrubbing unit, thereby reducing particulate (including heavy metals) and SOx concentration levels in the exhaust gases. At the present time, no precautions are taken to reduce either NOx or dioxin emission levels. For the wet scrubbing stage, nearly one million cubic meters of water are retrieved from the Seine river each year, producing 1050 tons of sludge.

In addition to processing waste, the incinerator provides 21.9 GWh of electricity per year. Meanwhile, 1238 GWh per year of thermal energy is recovered in the form of steam and used for district heating and hot water uses. It is worthwhile noting that for this particular installation the ratio of recovered heat to electricity production is 57 to 1.

The emission rates given in Table 4.16 are only from waste combustion. Upstream and downstream releases due to hauling of waste and residual products to and from the incinerator plant have not been evaluated, under the assumption that the transport distances would be comparable for other waste treatment methods. For the local scale pollutant transport analysis, we use meteorological data obtained from the Mountsouris weather station in Paris.

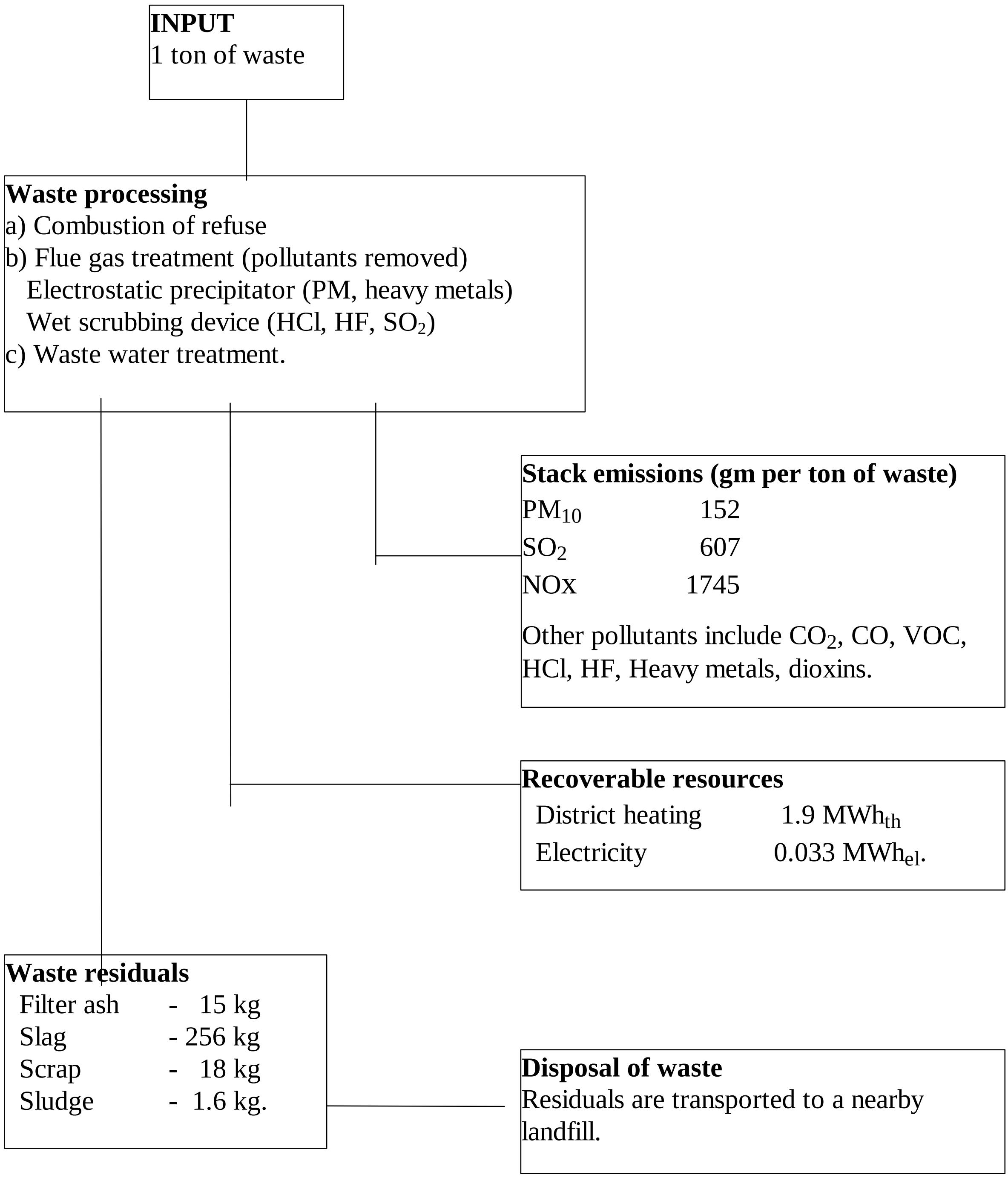


Figure 4.13: Stages for waste incineration.

Table 4.16: Technical specifications and emissions for the MSW incinerator in Paris.

Plant location			
Geographical latitude	48.91	°N	Incinerator facility located in the North-West suburbs of Paris.
Geographical longitude	2.30	°E	
Elevation at site	50	m	Above sea level
Technical data			
Waste capacity (1995)	658850	t	Refuse from Paris and nearby communities
Slag and Ashes	178853	t	11613 tons of scrap iron recovered
Full load operation	7963	hrs	
Heat recovered	1312.9	GWh_{th}	Heat content of waste = 7174 kJ/kg
Heat sold	1237.8	GWh_{th}	
Electricity bought	0.943	GWh_{el}	
Electricity sold	22.8	GWh_{el}	Net electricity = 21.9 GWh_{el}
Ratio of heat to electricity	57:1		
Stack parameters			
Height	100	m	single stack
Inside diameter	3.46	m	
Flue gas exit temperature	400	K	
Flue gas exit speed	20.5	m/s	Flue gas exit volume = 141 Nm^3/s
Pollutant emissions	***Measured (mg/Nm^3)***	***EC, 1989 regulation***	***Ratio of measured to EC regulation***
Particulates (100 tons/yr)	24.7	30	0.82
SOx (400 tons/yr)	99.0	300	0.33
NOx (1150 tons/yr)	284.5	--	--
CO (80 tons/yr)	19.8	100	0.20
VOC (46 tons/yr)	11.4	20	0.57
CO_2 (550000 tons/yr)	136071	--	--
N_20 (66 tons/yr)	16.3	--	--
HCl + HF (76.5 tons/yr)	18.9	52	0.36
Cd+Cr+As+Ni (0.6 tons/yr)	0.139	2.35	0.06
Dioxins	no data	0.1 ng/m^3 toxic waste	--

4.2.6.3. Summary and interpretation of results

The waste incineration damage costs per impact category and per ton of pollutant are summarized numerically in Tables 4.17 through 4.19 and graphically in Figures 4.14 and 4.15. Unlike the results for the previous fuel cycles, the present externalities are normalized per ton of waste, as well as per unit electricity (kWh_{el}) and unit thermal energy (MJ) for the reference year 1995. The assessed externalities are only for airborne emissions from thermal treatment of waste.

Although we have normalized the costs by the amount of electricity generated, we should not forget that the primary objectives of the Paris MSW installation are waste treatment and supply of thermal energy to the Paris district heating system. Any recovered electricity, in addition to the minimum demand needed to operate the incineration facility itself, should be viewed *only* as a bonus. In fact, the net amount of electricity generated by the incinerator (on average less than 3 MW in 1995) represents an insignificant contribution to the electricity use for the city of Paris. Therefore, reporting damage costs in units of electricity are irrelevant for this installation. Moreover, these results might suggest, and unfairly so, that waste incineration is a *dirty* technology for producing electricity. To put things into perspective, we should remember that the main purpose of an incinerator is to treat waste, and ***not*** to produce electricity or heat from waste materials. That is, waste incineration is not a fuel cycle. The recovered electric and thermal energy resources are merely *benefits* of the waste incineration cycle, and should only be valued as such.

The environmental burdens due to electricity and heat production are allocated according to the *exergy* procedure discussed by Krewitt, Lorenzoni and Pirilä [1996]. This method is the preferred approach in the ExternE Project for assessing the external impacts and associated damage costs from Combined Heat and Power production facilities. For the case of the Paris MSW incinerator, about 92% of the total cost is allocated to heat production, while 8% is attributed to electricity generation.

The annual overall external cost for waste incineration is 52 ECU per ton of waste, excluding CO_2 emissions, and between 67 and 92 ECU/t waste if global warming costs are included. It should be noted that these damage estimates are comparable to the average waste treatment cost in France, which is around 62 ECU/t waste (approximately 400 FF/t waste). As already pointed out for the other cycles, nitrate and sulfate aerosols account for the lion's share of the total externality, around 76% of the total if greenhouse impacts are excluded. Ozone and particulate damages account for most of the remaining cost (21%). It is important to note that cancer costs for dioxins and heavy metals represent only 0.07% of the total cost (without CO_2 impacts). Since dioxin levels are not measured for the Paris MSW installation, we have assumed an emission rate equal to the EC 1994 regulation limit of 0.1 ng/Nm^3 (10^{-7} mg/Nm^3). Even if the true emission rate for this pollutant was one-hundred (100) times higher, which we believe is an upper limit for current incinerators not yet complying with the EC 1994 regulation limit, the damage cost for cancers would still be less than 3% of the total (approximately 1.6 ECU/t waste). Therefore, contrary to public opinion, the health costs from dioxin and heavy metal emissions, released to the air during waste combustion, are **small**!

Depending on how we value global warming impacts (i.e., which cost per ton of CO_2 is used), public health costs contribute between 56% and 76% of the total externality, followed by CO_2 costs, which account for 23% to 43% of the total. Impacts to crops and materials are responsible for about 1% of the external cost. In terms of physical impacts, the mortality rate for this incinerator is about 330 YOLLs per year or 33 annual deaths (1 death = 10 YOLLs). If nitrate impacts are assumed to be zero, the annual mortality rate drops to 123 YOLLs or 12 deaths. Nearly three-quarters (3/4) of these impacts occur inside the Ile-de-France region and 95% within the borders of France.

Finally, two important issues arise when dealing with the waste incineration cycle.

1. Greenhouse gas emissions from waste incineration *should* be reduced by the amount of emissions that would have been released to the air anyway, particularly methane (CH_4) contributions, if the waste products would have biodegraded in a landfill in the first place. Hence, we are really interested in the "net" or marginal emission increases of greenhouse gases from thermal treatment of municipal solid waste, instead of the "raw" or absolute values given in Table 4.16. Consequently, the global warming damage costs assessed for the Paris MSW incinerator should be interpreted as upper limits only. The "true" impacts are lower, perhaps by a factor of two or even more.

2. If thermal and/or electrical energy is recuperated, the incinerator emissions *should* be lowered by the airborne releases that would take place if other heat and/or power producing installations were needed to generate these same quantities and forms of energy, i.e., *displaced technologies*. As an example, we present the three scenarios shown in Figure 4.16. In the first case, we assume that neither heat nor electricity resources are recovered during the waste combustion process. This is the baseline case, namely, the incinerator is used only to treat waste. In the remaining two cases, we explore by how much the incinerator emissions and the associated damage costs change on the basis of which technology is used for providing the actual recuperated heat and electricity loads. Ideally, these displaced technologies depend on local boilers and power generators. Negative numbers indicate that obtaining these resources as by-products from waste treatment is less polluting than using conventional boilers and generators. This is the case, for instance, for fuel oil boilers, which are especially high in SO_2 emissions.

Basically, both aspects focus on the need to reduce incinerator releases and, therefore, damage estimates for **avoided** emissions and externalities which would have otherwise occurred if the waste materials had been put in a landfill rather than having been incinerated.

Table 4.17: Damages for the waste incineration cycle.

	mECU/kWh**	ECU/t waste	mECU/MJ	s_g
POWER GENERATION				
Public health				
Mortality*- YOLL *(VSL)*	**100.6 (376.4)**	**42.8 (160.1)**	**5.86 (21.96)**	
of which TSP	*17.3 (63.6)*	*7.4 (27.0)*	*1.01 (3.72)*	B
SO_2	*18.4 (79.6)*	*7.8 (33.9)*	*1.08 (4.66)*	B
NO_x	*62.8 (231.1)*	*26.7 (98.3)*	*3.66 (13.47)*	B
NO_x (via ozone)	*2.0*	*0.85*	*0.11*	B
NMVOC (via ozone)	*0.05*	*0.02*	*0.004*	B
Morbidity	**19.4**	**8.25**	**1.13**	
of which TSP, SO_2, NO_x, CO	*16.4*	*6.98*	*0.95*	A
NO_x (via ozone)	*2.9*	*1.23*	*0.17*	B
NMVOC (via ozone)	*0.07*	*0.03*	*0.006*	B
Cancers				
(heavy metals and PCDD/F)	**0.08**	**0.034**	**0.005**	B
Accidents	nq	nq	nq	
Occupational health	nq	nq	nq	
Major accidents	nq	nq	nq	
Crops	**1.35**	**0.57**	**0.079**	
of which SO_2	*0.03*	*0.01*	*0.002*	A
NO_x (via ozone)	*1.29*	*0.55*	*0.075*	B
NMVOC (via ozone)	*0.03*	*0.01*	*0.002*	B
Ecosystems	ng	ng	ng	
Materials	**0.47**	**0.20**	**0.028**	A
Noise	nq	nq	nq	
Visual impacts	nq	nq	nq	
Global warming (indicative range)				
low (valued at 18 ECU/t)	36.6	15.6	2.13	C
upper (valued at 46 ECU/t)	93.6	39.8	5.43	C
OTHER FUEL CYCLE STAGES				
Public health	nq	nq	nq	
Occupational health	nq	nq	nq	
Ecological effects	nq	nq	nq	
Road damages	nq	nq	nq	
Global warming (indicative range)	nq	nq	nq	
low (valued at 18 ECU/t)				
upper (valued at 46 ECU/t)				

*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.

** see note under Table 4.18.

<u>*Notes*</u>

Electricity production: 22 GWh_{el}/yr (accounts for 7.8% of total impact),

Heat generation: 1238 GWh_{th}/yr (accounts for 92.2% of total impact),

Waste processed: 658850 tons/yr.

Table 4.18: Sub-total damages for the waste incineration cycle.

		mECU/kWh*	ECU/t waste	mECU/MJ
YOLL *(VSL)*	low	158.5 (434.3)	67.4 (184.7)	9.2 (25.3)
	upper	215.5 (491.3)	91.6 (208.9)	12.5 (28.6)

* Since this project is concerned with fuel cycles for electricity, we have been asked to express all emissions and external costs per kWh_{el} ; however, this makes no sense for this waste incinerator since it is not intended to produce electricity but to supply heat to the district heating system.

Table 4.19: Damages by pollutant.

	ECU / t of pollutant
SO_2 *- YOLL *(VSL)*	15300 (57700)
NO_x *- YOLL *(VSL)*	18000 (58900)
PM_{10} *- YOLL *(VSL)*	57000 (186000)
NO_x (via ozone)	1500
VOC (via ozone)	930
CO_2	18 - 46

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

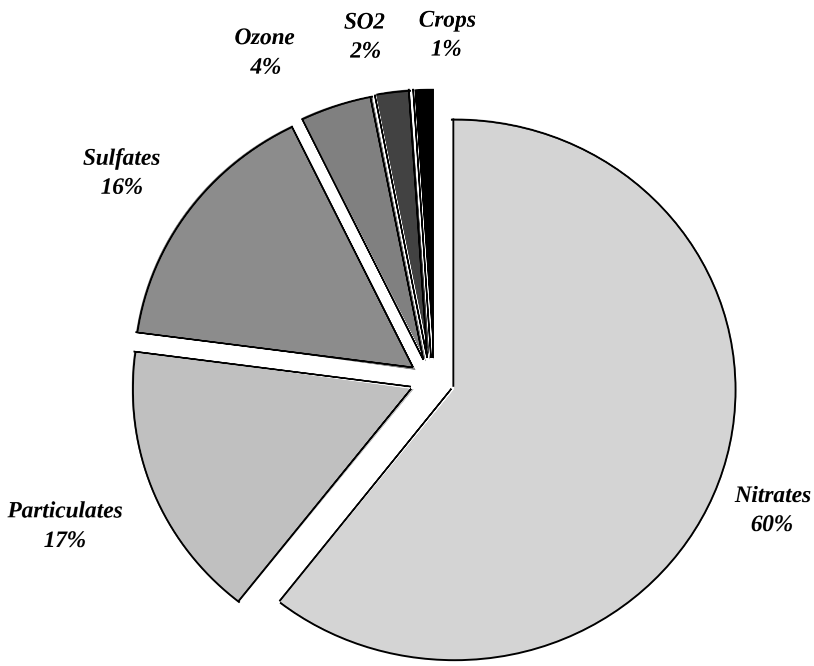


Figure 4.14: Breakdown of damage costs by pollutant for the MSW incinerator in Paris (excluding global warming). Total = 51.9 ECU per ton of waste.

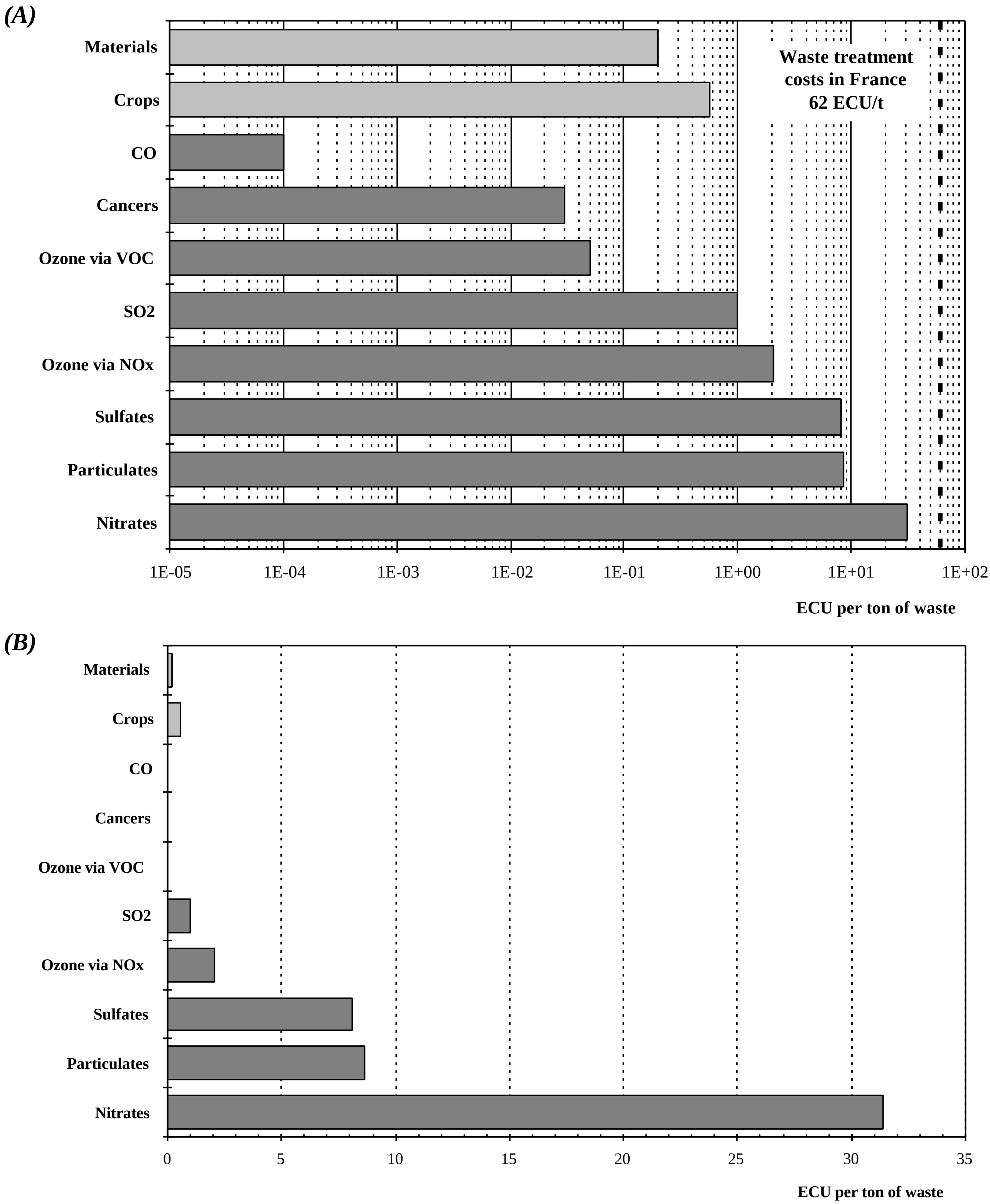


Figure 4.15: Damage costs (incineration stage only) for the MSW incinerator in Paris, France.

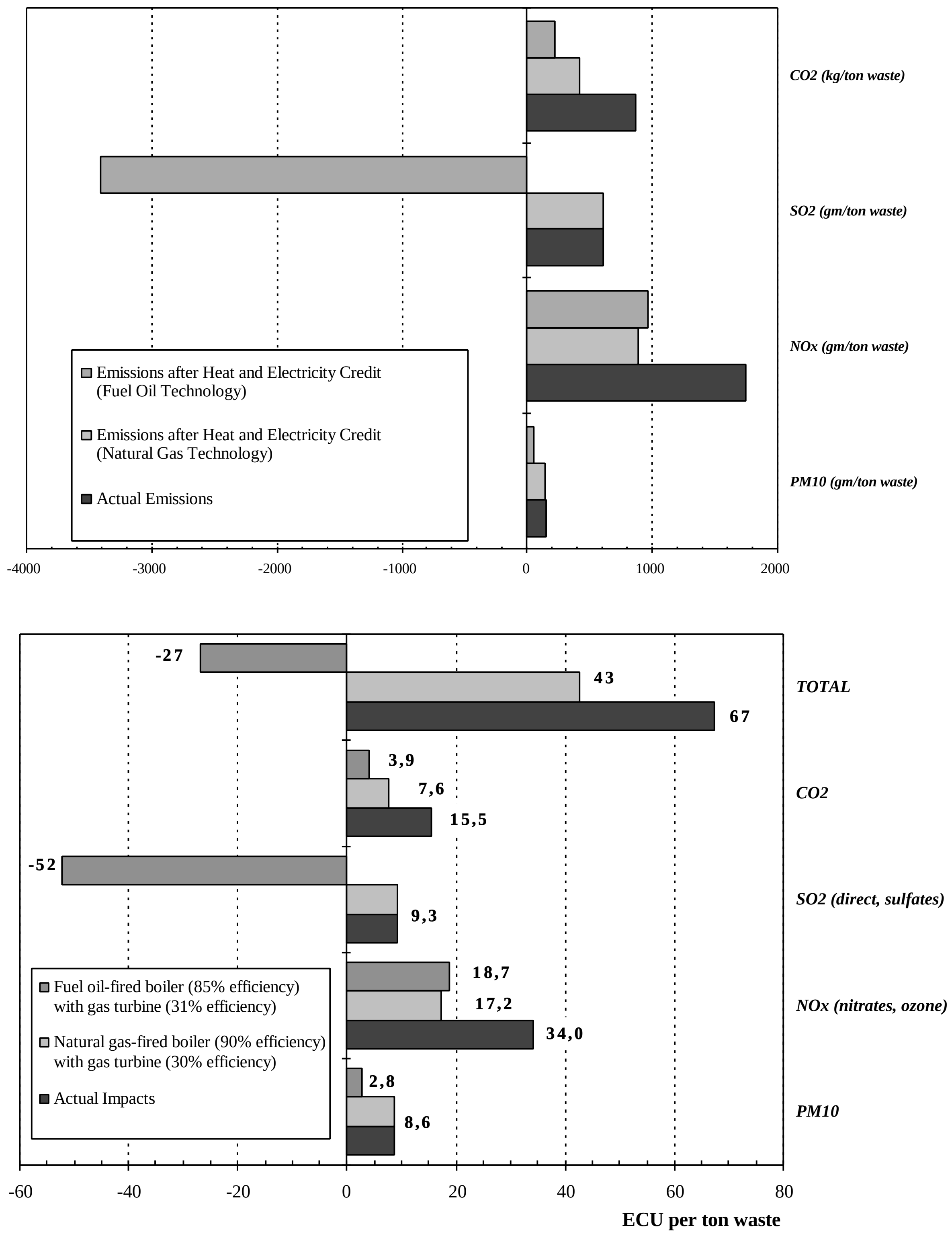


Figure 4.16: Avoided emissions and damage costs for recovered heat and electricity production using two different displaced technologies (Paris MSW incinerator). Global warming impacts are valued at 18 ECU per ton CO_2.

4.3. REFERENCES

Cline, W.R., (1992) "The Economics of Global Warming," Institute for International Economics, Washington, D.C., USA.

European Commission, DGXII, Science, Research and Development, JOULE (1995b). Externalities of Fuel Cycles 'ExternE' Project. Report 2, Methodology.

Krewitt, W., Lorenzoni, A., Pirilä, P., (1996) "Allocation of Environmental Damage from Combined Heat and Power Production between Electricity and Heat," Internal paper for ExternE Project.

Larson, E.D. Svenningsson, P., Bjerle, I., (1989) "Biomass Gasification for Gas Turbine Power Generation," Electricity: Efficient End-Use and New Generation Technologies, edited by Johansson, T.B., Bodland, B., Williams, R., Lund University Press, Lund, Sweden.

Lesgards, V. (1995) "Assessment of the Externalities of the Hydro Fuel Cycle - Implementation in France," European Commission, DGXII, JOULE Program and US Energy Department, Final Report for contract JOU2-CT92-0080, External Costs of Fuel Cycles.

ORNL/RFF, (1992) "Damages and Benefits of the Biomass-to-Electricity Fuel Cycle: Estimation Methods, Impacts and Values," Oak Ridge National Laboratory, Oak Ridge, TN, USA, November 1992.

Rabl, A., Eyre, N., (1997) "An Estimate of Regional and Global O_3 Damage from Precursor NOx and VOC Emissions," Ecole des Mines, 60, blvd St-Michel, F 75272 Paris, Cedex 06.

Rabl, A., Curtiss, P.S., Spadaro, J.V., Hernandez, B., Pons, A., (1996) "Environmental Impacts and Costs: The Nuclear and the Fossil Fuel Cycles," Version 3, European Commission, DGXII, JOULE Program, Final Report for contract JOU2-CT92-0236, External Costs of Fuel Cycles: Implementation of the Accounting Framework in France.

5. FRENCH ELECTRICITY SECTOR: AGGREGATE IMPACT

5.1. INTRODUCTION

We turn our attention now to the aggregated damage costs for the entire electricity sector in France. It should be noted that the results reported in this chapter represent **only** a rough and preliminary estimate of external costs of electricity generation. As indicated below, there are various sources of uncertainty, including the lack of a complete inventory of emissions data, which have made a detailed analysis impossible. Nevertheless, what really matters is the order of magnitude of the results, rather than the numbers themselves. With this caveat in mind, we begin our analysis and presentation of the results.

5.2. VARIABILITY OF DAMAGE COSTS

The aggregation procedure followed here for quantifying the externalities of electricity production is based on a ***bottom-up*** approach. Namely, we have estimated the damage costs for each of the power plants currently operating in France and summed the costs to obtain an aggregate value. This approach is preferred over the traditional *top-down* analysis since the damage costs per ton of pollutant emitted to the air have been found to be highly dependent on the geographical location of the source of air pollution, not to mention the physical characteristics of the stack from which the various pollutants are being expelled into the air.

5.2.1. Dependence of damage on stack parameters and weather data

As an example of the influence of stack parameters (emissions source characteristics) and meteorological data on the quantification of damages, we present the sensitivity results shown in Figure 5.1. In this case, the emission source is located in the suburbs of Paris.

Impacts have been normalized by the damage value assessed for the referenced state identified in the top right-hand corner of the figure. The reference value may be either a physical impact, such as YOLLs per year, or a damage cost, for example ECU per ton of pollutant emitted. Along the abscissa, we plot the variable which is being changed in dimensionless form, i.e., normalized by its reference state value. The advantage of presenting the results this way is that once the reference impact or damage cost is determined, the effect of varying any of the stack parameters is easily ascertained by simple scaling the damage value of the reference state by the factors provided in Figure 5.1.

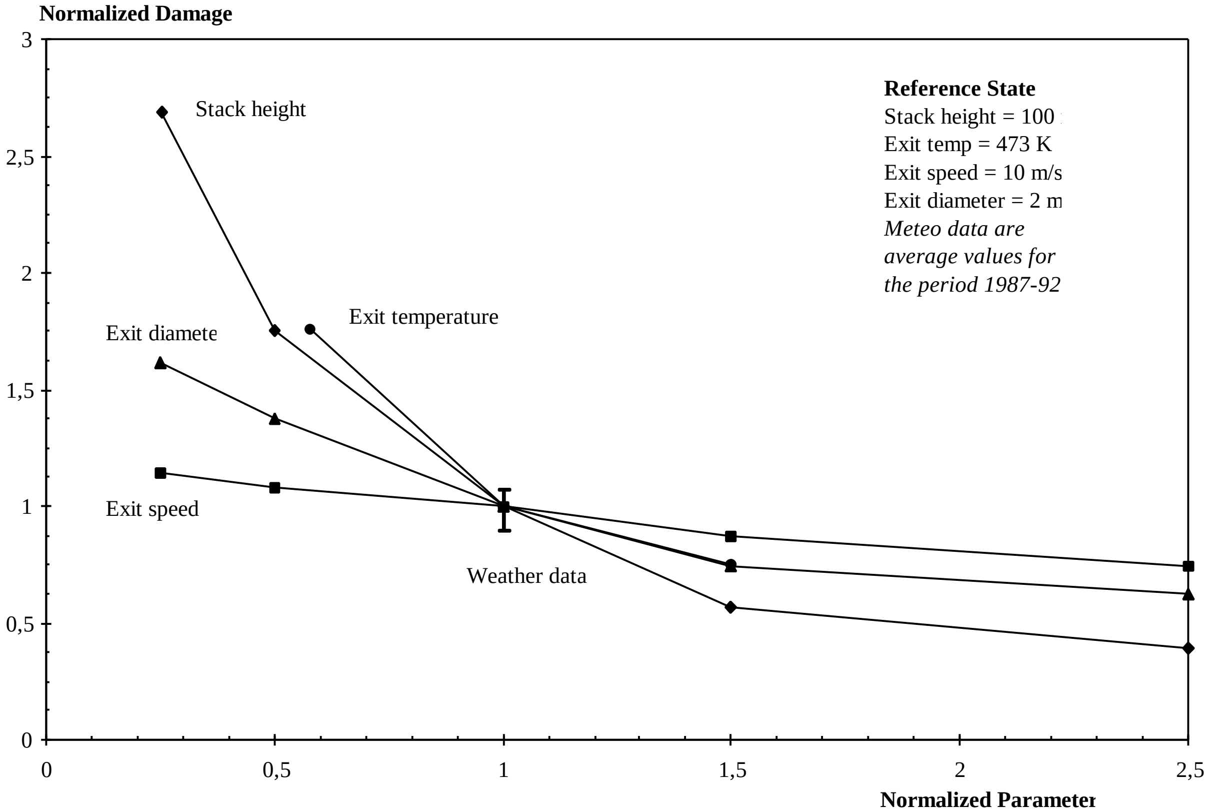


Figure 5.1: Influence of emission source parameters and meteorological data on damage estimates. The source is located in a suburb of Paris.

As one can easily see, of all the parameters varied, the damage seems to be most sensitive to changes in the stack height, followed by variations in flue gas exit temperature, exit diameter and exit speed. In fact, an increase in stack height by ten-fold (10 times), lowers the impact estimate by a factor of seven (7). Clearly such a strong dependence on emission source characteristics is due to the very high *local* receptor density near the emission source. For a more rural site, as in the case of Albi where the hypothetical biomass power plant was located in the previous chapter, stack height will still be the most influential parameter, but the impact over the same range shown here will vary at most by a factor of two (2). Finally, we note that changes in annual meteorological data have only a small effect, around 10% above or below the reference state damage.

5.2.2. Dependence of damage on geographical location of source

In Figure 5.2, we illustrate the dependence of damage on the geographic location of the emission source for several sites throughout France (emission sites are identified on the map of France shown in Figure 5.3). For this analysis, both rural and urban reference locations have been selected. The nearest city to the hypothetical pollution source is indicated in parentheses; these centers are between 25 and 50 kilometers away. Impacts include public health, crop and building surface damage costs, which are expressed in ECU per ton of precursor pollutant emitted to the air. In the case of nitrate aerosols, NOx is the precursor pollutant, whereas for sulfate aerosols, SO_2 in the precursor specie. For the *primary* particulates (i.e., PM_{10} and SO_2), we also show the effect of stack height dependence, which is identified here by the horizontal bars. The reference stack height for damage calculations is 100 m, while the range extends from 1 m (corresponding to a ground-level emission source) up to 250 m. Note that SO_2 damages have been scaled upwards by a factor of ten (10). This was done for the sole purpose of plotting all the data using a linear scale, rather than introducing a logarithmic axis.

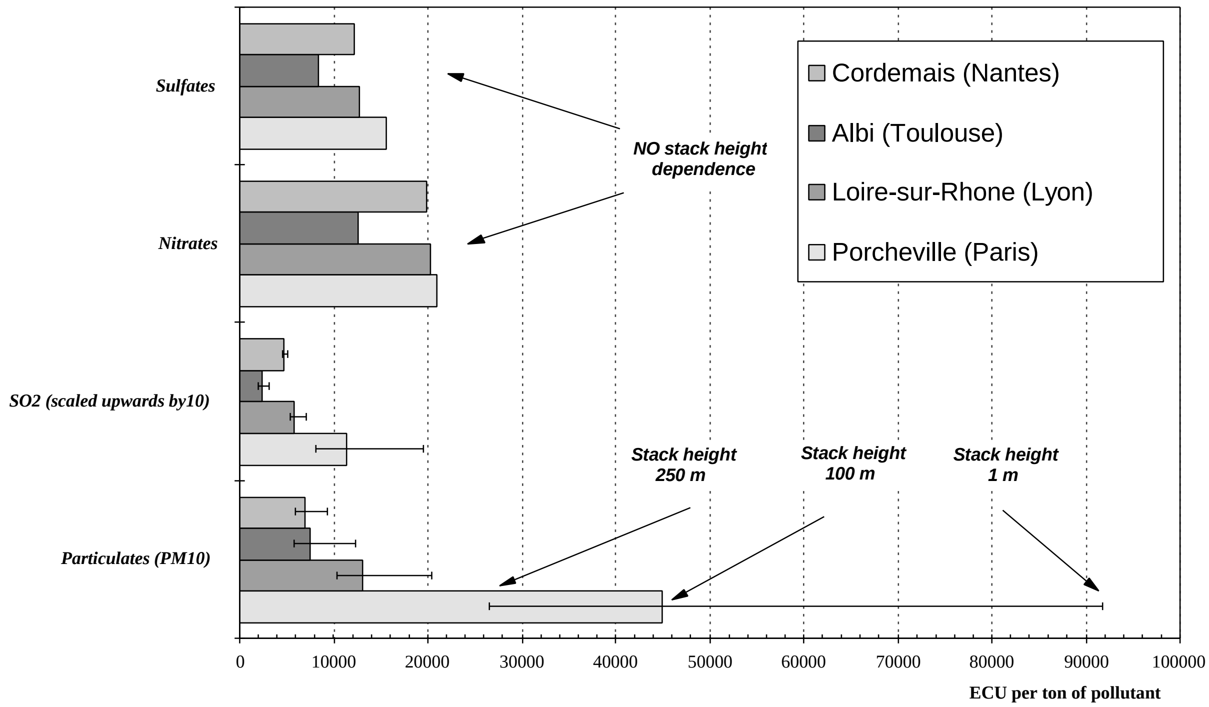


Figure 5.2: Damage costs per ton of pollutant for different sites across France. The reference emission stack height is 100 m. Impacts include costs for health, crops and building surfaces.

Damages for nitrate and sulfate aerosols are independent of stack height, as well as any of the other emission source characteristics, with the exception, of course, of the pollutant emission rate. As already pointed out in Chapter 3 (*Quantification of Externalities*), we assume that aerosols or *secondary* particulates are distributed uniformly across the vertical direction of the atmosphere, and, therefore, concentration distributions vary only with downwind distance from the source. It should be noted that aerosol impacts and damage costs are **only** relevant for the regional domain; that is, for the 100 by 100 km resolution scale. Local externalities - within the first 50 km from the source - are quite negligible, at best a few percent of the total damage [Spadaro, 1997].

As one can easily see, nitrate impacts always exceed sulfate damage costs. As a matter of fact, the ratio of nitrate-to-sulfate damages lies between 1.2 and 1.6. This same conclusion has also been found to be true for many other source locations across Europe. What this result indicates is that the NOx chemical reactivity in the atmosphere is higher than the transformation rate for the SO_2 pollutant, which in turn leads to higher concentrations and damage costs. In addition, with the exception of the Albi site, we observe that aerosol damages amongst the different sites do not vary substantially. Even in the case of Albi, however, impacts are within a factor of two (2) of the costs estimated for the other sites. This reasonably small variability of aerosol damage costs also holds for other emission sites studied across Europe; namely, impacts for different locations vary by no more than a factor of two. This results is not so surprising, since aerosol damages occur on a regional scale, and are, therefore, not sensitive to local conditions, particularly to receptor distributions.

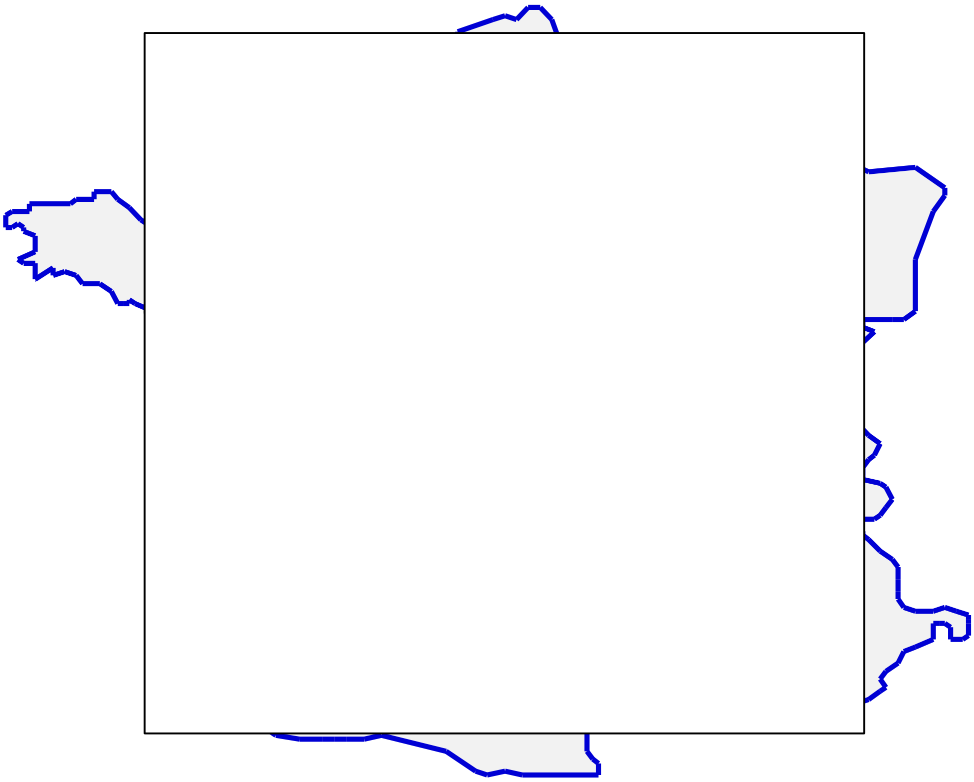


Figure 5.3: Map of France identifying the five regions used in the evaluation of the aggregated external costs of electricity.

With the exception of the Porcheville site, aerosol impacts are quite often larger than those assessed for the primary pollutants. The Porcheville case is an exception since the local receptor density is quite high, the source being located near Paris. Hence, PM_{10} impacts dominate in this case.

By comparison to aerosols, PM_{10} and SO_2 damages ***do*** vary significantly between the different locations. In fact, for a stack height of 100 m, the PM_{10} estimated damage per ton for the Porcheville site is about seven (7) times higher than that calculated for the Cordemais location. As shown in Figure 5.2, stack height always plays a major role in determining damage costs, much more so for a emission source in Porcheville than one located in Cordemais (this is due to differences in local receptor densities). Finally, we note that PM_{10} damages are much higher than SO_2 costs, by about a factor of 50. This difference is quite reasonable if we recall that SO_2 costs include *only* the acute mortality estimate, whereas PM_{10} damages include both the acute and chronic mortality effects. Since chronic mortality is valued at a much higher rate than acute impacts (in fact in monetized terms, 1 *chronic* YOLL is approximately equal to 70 *acute* YOLLs, see Appendix II for details), it follows that the damage cost per ton of PM_{10} should be much higher than that assessed per ton of SO_2.

5.2.3. Geographic range of impact

Before concluding this section, a few words should be said about the geographic impact range of the analysis. How far from the source, in other words, must the pollutant dispersion analysis and impact evaluation be carried out to account for *most* of the externality? As an example, in Figure 5.4, we show the "*primary*" particulate impact distributions for two emission sources: one is located near Paris, and the other close to the city of Nantes. Impacts or damage costs are expressed as a fraction of the total, thereby eliminating the absolute value of the estimates, which in this case, differ by a factor of five (5). The downwind distance from the source is expressed in km. At each distance value, we have summed the damage contributions along the azimuthal direction, assuming a coordinate system centered about the source. For this exercise, a reference stack height of 100 meters was chosen.

Two observations are worth commenting on. First, for the Paris case (urban surroundings) 75% of the total damage occurs in the local domain (i.e., within a radius of 50 km), whereas for Nantes (primarily rural surroundings) this figure is less than 20%. Second, the geographic impact range extends several *thousand* kilometers from the pollution source! Realistically, if we were interested in capturing 95% of the total impact or damage cost, the analysis would need to be carried out up to 500 km in the case that the source was located near Paris, and twice as far or 1000 km for a source located near Nantes.

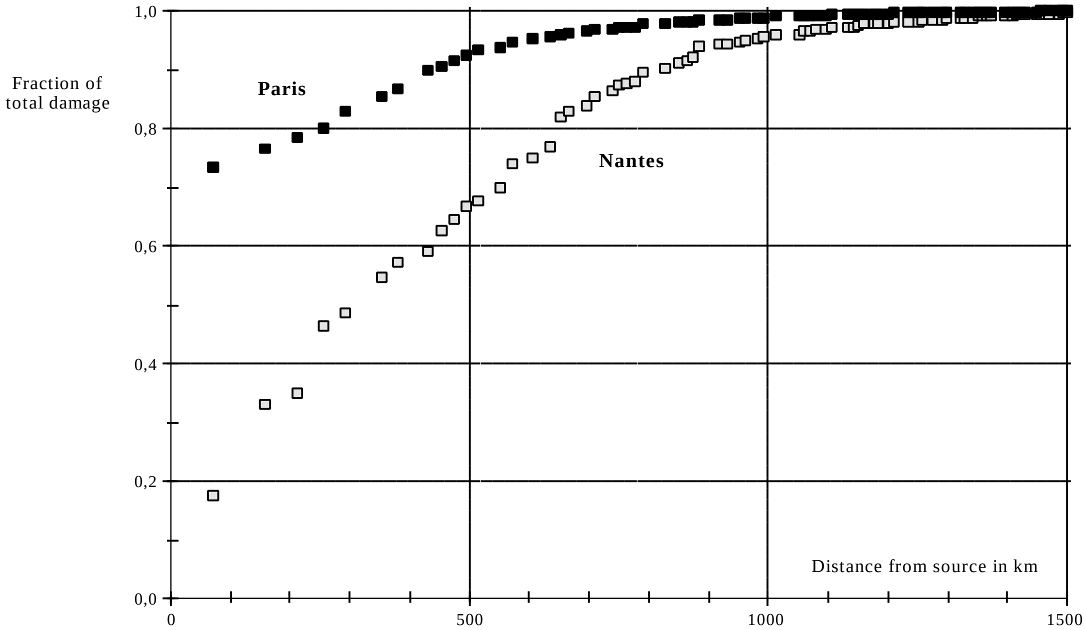


Figure 5.4: Variation of "primary" particulate damage with distance from source and geographic impact range for two French sites (reference stack height is 100 m).

5.3. AGGREGATION METHOD

In this section, we present the externality results from the production of electricity in France from all sources of energy, including fossil fuels (coal, fuel oil, coke and natural gas), renewable resources (hydro) and nuclear fuel. In the beginning of this chapter, we mentioned that the aggregation results reported here are *preliminary* estimates, which should be used as an indication of the order of magnitude of the damage costs, and not to be taken at full-face value. We, therefore, highly *recommend* that implementation or exploitation of these data for whatever purposes should only be pursued upon careful consideration of the uncertainties involved.

There are several major sources of incertitude. First, there are *inherent* uncertainties associated with the impact evaluation analysis method, these are discussed in full detail in the Methodology Chapter and in Appendix VIII on Uncertainty Analysis. Second, there are uncertainties in the emissions inventories, or more specifically *lack* of detailed emissions data by pollutant for all the different power plants, particularly for the Independent Power Producer (IPP) facilities. In addition, detailed information on other stack parameters, such as data on exhaust flow volume, including exit speed and exit stack diameter, is quite often missing or incomplete. As shown in Figure 5.1, this could very well change the damage costs by a factor of two (2) or even more.

A third source of uncertainty arises because of the unavailability of a *multi-source* version of the ECOSENSE program. Within the same geographic area, quite often pollutant emissions from different power plants compete for the same atmospheric species during chemical transformations, in particular for NH_3 (see Appendix I, Figure 2). Because of this increased demand, it is certainly possible that the amount of ammonium present in the atmosphere could become locally *saturated*. That is, the ammonium concentration could become nil in some areas of France or Europe! If this situation should happen, an additional ton of SO_2 or NOx emitted to the atmosphere would have **no** additional impact. To rule out this scenario, we would need a multi-source ECOSENSE version, which, unfortunately, was not available for the aggregation calculations carried out in the present work [12]. The unavailability of such a model introduces, therefore, a certain amount of uncertainty, which is impossible to value at this time.

A fourth source of uncertainty comes from extrapolation or *transferability* of damage results from a reference power plant to all facilities using that same type of fuel. We refer here, for example, to the hydroelectric sector, which accounts for 16% of the total electricity production in 1995. Damage costs for these installations are *highly site dependent*; that is, based on local economies and local environmental issues. Fortunately, the external costs from hydro-to-electricity conversion are small compared to damage costs from fossil fuel cycles.

Finally, for nuclear externalities, there is the important issue of discounting of inter-generational damage costs. In other words, should we use a 0%, 3%, 10% or some other discount rate? And, how long into the future should costs be discounted? In addition, the issue of transferability of reference damage results amongst the many nuclear facilities in France is uncertain, since not all plants are equal.

The aggregation procedure followed here consists in estimating the external costs for all the power plants currently operating in France and adding the damage costs together to get an aggregate impact for the entire electricity system (*bottom-up* approach). We have attempted, whenever possible, to use **real** plant and site specific characteristics. The externalities are quantified according to the procedures outlined in Chapter 3.

The aggregation method has been simplified in a number of ways. Below, we identify the main *assumptions* used in the present analysis.

[12] A multi-source ECOSENSE model is currently available only to the German team of the ExternE National Implementation Project, who developed the ECOSENSE program in the first place.

1. We have only quantified external costs for airborne emissions. These include, for example, particulate (PM_{10}), SO_2, NOx and CO_2 pollutants. SO_2 impacts include direct effects on public health (mostly mortality), as well as indirect costs from sulfate aerosols. NOx damages, on the other hand, include only indirect effects on public health (mortality + morbidity impacts) and losses in crop yields due to chemical transformations of this pollutant into nitrate aerosols and ozone species. A *representative* impact range is provided for global warming estimates, rather than a single value.

2. Damage costs are assessed only for the power generation stages for each fuel type. Pollutant emission levels from upstream and downstream fuel cycle stages, as already pointed out in Chapter 2 (*Methodology*), are typically small by comparison to airborne releases which take place at the power plant site itself.

3. EdF has provided us with detailed emissions data and other relevant stack parameters, including stack heights, for each of the fossil fuel power plants they operated in 1995. Unfortunately, these data are *confidential*, and we have not been given permission to reproduce them explicitly in this report. Hence, cumulative emissions, annual electricity production and aggregate damage costs by fuel type and by pollutant are the only results reported here.

4. For the individual IPP facilities, a database for the various pollutant emission rates and stack conditions is at best incomplete or altogether missing! Most of the statistics that are currently reported include only the annual electricity production by fuel type, which is further broken-down by French administrative region. To estimate the externalities for both the coal and fuel oil installations, we have simply used the "*average*" damage costs per unit electricity, namely $mECU/kWh_{el}$, (**unit damage cost factor**) which have been calculated using the *real* emissions data for the EdF owned and operated fossil fuel installations. For the natural gas facilities, on the other hand, we have used a damage cost of 11.4 mECU/kWh (excludes global warming effects), which is the externality assessed for the reference natural gas power plant in Section 4.2.2. It should be noted that IPP installations in France, currently, contribute more than one-half (52%) of the electricity load developed from fossil fuels. Therefore, ignoring these externalities, on the basis that fossil fuels contribute only 7% of the load, is a serious mistake, in light of the fact that more than 92% of the total cost from the French electricity system comes from the fossil fuels sector! See Table 5.3 below. However, we should emphasize again that the unit damage costs attributed to the IPP power plants are only rough approximations, since we have no emissions data to do a real analysis. Therefore, the damage estimates for these installations are highly uncertain.

5. Regarding the French hydroelectric facilities, we have assumed a single unit damage cost factor for this entire energy sector. An *average* value of 3 $mECU/kWh_{el}$ was chosen. This value is based on the French hydro fuel cycle report prepared by Lesgards [1995], and is similar in magnitude to the damage costs assessed for the Sauda Hydroelectric Development Project in

Norway [EC, 1995f]. As already noted above, the external costs for hydroelectric power plants are **highly** site specific. Hence, transferring a single case value to the entire hydroelectric sector in France is at the very best a rough estimate of the externalities involved with this type of fuel-to-electricity conversion technology. The confidence level for the hydroelectric damage estimates reported here should be regarded as being low.

6. Damage costs for the nuclear energy sector are based on the reference case study for the French nuclear fuel cycle assessed by Rabl et al. in 1995 and revised in 1996. The previous results were based on a VSL valuation of cancer deaths. An exact YOLL valuation would necessitate a completely new analysis. As a simple shortcut, therefore, we have divided the cancer costs by two (2), since the cost of a cancer death is now estimated to be approximately 1.5 MECU compared to the VSL value of 3.1 MECU. As we have done for the hydroelectric facilities, a *single* unit cost factor is applied to the entire nuclear energy sector. This *average* cost value is 0.05 mECU/kWh_{el}, which reflects a discount rate of 3%.

5.4. AGGREGATION RESULTS

The external costs from electricity production in France are summarized in Tables 5.1, 5.2 and 5.3. In Figure 5.5, we show the current energy mix in France and the damage costs by electricity sector or fuel type, excluding global warming impacts. As previously noted, the overall damage cost calculated here is based on 1995 emissions data. For EdF fossil fuel installations, the total airborne emissions for PM_{10}, SO_2, NOx and CO_2 pollutants were, respectively, 2.6 kt, 86 kt, 43 kt and 16400 kt (1 kt = 1000 t). The gross electricity production for 1995 was 502 TWh_{el}, of which 95% was produced by EdF and 5% by several Independent Power Producers. By far, the largest share of electricity was produced by nuclear, about 385 TWh_{el} or 77% of the total. Hydroelectric plants contributed 81 TWh_{el} or 16%, and the so called classical thermo-electric power plants (fossil fuels) produced just over 7% of the total or 36 TWh_{el}.

In keeping with EdF's request to maintain complete anonymity of its individual installations, including plant site, production capacity and stack emissions, we have first assessed the externalities for each installation separately and, thereafter, combined the damage costs over five regions or *zones*, covering the entire geographical area of France. A map showing these zones explicitly is provided in Figure 5.3.

As seen in Table 5.1, for each zone, we aggregate damage costs in MECU per year or in mECU per kWh_{el} generated within that zone. Damage costs per ton of pollutant are also calculated. In the last column, labeled *ALL*, the emissions and impacts are summed over all zones.

The external costs per ton of pollutant averaged over all zones are given in Table 5.2. At over 17000 ECU per ton of NOx ($21300 or 110000 FF), nitrate aerosols have the highest damage cost of all pollutants. Particulates are next with 12600 ECU ($15800 or 82000 FF), followed by sulfates with 11000 ECU per ton of SO_2 ($13800 or 72000 FF). By comparison to primary particulates and aerosols, direct impacts from SO_2 emissions are quite small, valued at only 200 ECU per ton of SO_2. Most of the these damage costs, as already pointed out in the table, are attributed to mortality impacts.

If damages are normalized by the electricity production, on the other hand, sulfates are at the top of the list, with 53.5 $mECU/kWh_{el}$, followed by nitrates with 41.8 $mECU/kWh_{el}$. Particulates are a distant third with an impact just under 2 $mECU/kWh_{el}$, which, incidentally, is not very different to the cost estimated for SO_2 from direct impacts.

Finally, in Table 5.3, we show the damage costs for the entire electricity system broken-down by energy sector. The *aggregate* cost over all sectors, excluding the CO_2 impact contribution, is around 3360 million ECU (21840 million FF) or 6.7 $mECU/kWh_{el}$. It should be noted that *this figure is rather large*. In fact, to put this value into proper perspective, we note that it represents 0.3% of the Gross Domestic Product (GDP) of France in 1996! Furthermore, even if nitrate impacts were assumed to be zero, on the basis that nitrate damages on public health are the least credible of all assessed externalities, the damage cost would certainly be lower, but only by one-third (1/3). Namely, the new aggregate cost would drop to 2130 million ECU (13800 million FF) or 4.2 $mECU/kWh_{el}$. Clearly, this last figure is still large (about 0.2% of GDP).

Another useful insight of the importance of the aggregate result just calculated may be gained by comparing the increase in mortality rate against the baseline rate, which in Europe is about 99 deaths per 10,000 persons per year. Based on the 1995 emission inventories, the mortality rate from air pollution attributable to electricity production is 36030 Years Of Life Lost (YOLLs). If we assume 1 death is equivalent to 10 YOLLs, and, furthermore, that only two-thirds (2/3) of these deaths occur within the geographical borders of France (this is really a conservative estimate), the annual death toll in France is approximately 2400 lives or 0.41 deaths per 10,000 persons [13]. Compared to the baseline mortality rate, this value represents an increase of 0.4%! Although this result is significant, we should not loose sight of the assumptions inherent in this analysis.

To estimate the confidence intervals (CI) for the aggregate cost, we have assumed a lognormal distribution with a geometric standard deviation (σ_g) equal to 5. We have picked this value since

[13] (36030 YOLLs ∗ deaths/10 YOLL ∗ 2/3 ∗ 1/5870) per 10,000 persons = 0.409 deaths per 10,000 persons. The population of France is 58.7 million inhabitants, and we assume that 2/3 of the deaths occur in France.

damages are dominated by mortality impacts, which in this case account for approximately 80% of the total cost. The uncertainty ranges for our aggregate cost are as follows:

672 to 16800 MECU/yr (1.3 - 33 mECU/kWh_{el}) for the **68% CI**,

134 to 84000 MECU/yr (0.3 - 167 mECU/kWh_{el}) for the **95% CI**.

Although thermo-electric plants contribute only 7% of the total electricity, combined, these installations account for a whooping 92% of the overall externality! By contrast, the nuclear sector contributes more than three-quarters (3/4) of the electricity, but the estimated damage cost is now less than 1% of the total. The remaining 7% of the aggregate cost comes from hydroelectric generation.

Up to now, we have ignored the impacts from CO_2 emissions. In Table 5.4, we have attempted to quantify the global warming effects, based on the representative range of 18 ECU to 46 ECU per ton of $CO_{2,eq}$. As can be seen, the aggregate cost increases by 500 MECU to 1300 MECU per year or by 1 mECU to 2.6 mECU per kWh_{el}. Therefore, global warming costs increase our earlier estimates between 15% and 39%. The break-down by fuel type is practically unchanged whether or not global warming effects are included in the aggregate damage cost.

Table 5.1: External costs for the French electricity system (EdF power plants *only*). Combined electricity production for coal, oil and coke power plants was 17.5 TWh_{el} in 1995.

Pollutant	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	ALL
Particulates (PM_{10})						
Emissions (tons/yr) from						**2558**
Coal power plants						*2341*
Fuel oil power plants						*217*
Coke gas power plants						*0*
Damage per ton (ECU/t)	**35400**	**12500**	**7200**	**6900**	**6200**	**12600**
Annual Impact (MECU/yr)	**11.96**	**12.34**	**1.62**	**0.74**	**5.57**	**32.23**
Annual Impact (mECU/kWh)	**4.54**	**2.17**	**3.91**	**1.25**	**0.80**	**1.97**
Sulphur-dioxide (SO_2) *						
Emissions (tons/yr) from						**85917**
Coal power plants						*76092*
Fuel oil power plants						*9045*
Coke gas power plants						*780*
Damage per ton (ECU/t)	**13900**	**11100**	**7200**	**10700**	**10500**	**11200**
Annual Impact (MECU/yr)	**184.2**	**315.2**	**16.3**	**51.5**	**392.2**	**959.3**
Annual Impact (mECU/kWh)	**69.9**	**55.2**	**39.2**	**29.3**	**55.8**	**54.7**
Nitrogen (NOx) **						
Emissions (tons/yr) from						**42935**
Coal power plants						*40344*
Fuel oil power plants						*1841*
Coke gas power plants						*750*
Damage per ton (ECU/t)	**19600**	**18800**	**12000**	**18700**	**18500**	**18600**
Annual Impact (MECU/yr)	**107.2**	**268.4**	**14.9**	**35.3**	**371.5**	**797.3**
Annual Impact (mECU/kWh)	**40.7**	**47.0**	**35.8**	**20.1**	**52.9**	**45.5**
Carbon-dioxide ($CO_{2,eq}$)						
Emissions (kt/yr)	**2388**	**4965**	**347**	**2841**	**5832**	**16373**

* SO_2 damage costs include ‘direct’ impacts from SO_2 and sulfate aerosols.
** NOx damage costs include impacts from nitrate aerosols and ozone.

Table 5.2: “*Aggregate*” damage costs by pollutant (EdF fossil fuel plants only, 17.5 TWh_{el}/yr).

Pollutant	ECU per ton of pollutant	$mECU/kWh_{el}$	Breakdown of impacts by endpoint
Particulates (PM_{10})	12600	2.0	*85% mortality*; 15% morbidity
SO_2 (*direct*)	200	1.1	mostly mortality costs
SO_2 (*via Sulfates*)	11000	53.5	same as particulate
NOx (*via Nitrates*)	17100	41.8	same as particulates
NOx (*via Ozone*)	1500	3.7	*32% mortality*; 47% morbidity and 21% loss in crop yields

CO_2	18 to 46	16.8 to 43.0	see Appendix V

Table 5.3: Aggregated externalities for the French electricity sector without CO_2 impacts (1995 emissions data).

Fuel Cycle [1]	Annual Electricity GWh/yr	Fraction of Electricity System	**Damage (excluding CO_2)** MECU/yr	mECU/kWh	Fraction of Total
Coal EdF	15281	3.0%	1622	106	48%
Coal IPP	6719	1.3%	*? 713 ?*	*? 106 ?*	*21%*
Oil EdF	1093	0.2%	145	132	4%
Oil IPP	3807	0.8%	*? 503 ?*	*? 132 ?*	*15%*
Coke Gas (EdF)	1165	0.2%	22	19	< 1%
Natural Gas (IPP)	8145	1.6%	*? 93 ?*	*? 11 ?*	3%
Hydro EdF [2]	73270	14.6%	220	3	7%
Hydro IPP	7690	1.5%	*? 23 ?*	*? 3 ?*	*< 1%*
Nuclear [3]	385000	76.7%	19	0.05	1%
TOTAL	***502210***	***100%***	***3360***	***6.70***	***100%***
TOTAL 68% confidence interval ($\sigma g = 5$)			***672 - 16800***	***1.3 - 33***	

[1] Includes power plants operated by the French national utility Electricité de France (EdF) and Independent Power Producers (IPP). Since no emissions data are available for the IPP power plants, we have assumed here that the external cost per kWh for the IPP plants is numerically the same as the value estimated for the EdF facilities. **Note,** to highlight the uncertainties the corresponding numbers are in *italics* and marked by **?**. For the IPP natural gas facilities we have assumed a damage cost of 11.4 mECU/kWh (based on the results presented in Section 4.2.2).

[2] Except for minor modifications, the hydroelectric damage estimates are based on the French hydro fuel cycle results prepared by Lesgards [1995]. It is important to note that these data are very uncertain, given that hydroelectric externalities are **highly** site specific, and cannot be easily transferred to other hydroelectric sites across France. Includes hydro plants operated by EdF and the Compagnie National du Rhone (CNR).

[3] Damage estimates for the French nuclear fuel cycle are based on the results by Rabl et al., 1996, which have been modified to be consistent with the current methodology. For the aggregated externality, we have assumed a 3% discount rate.

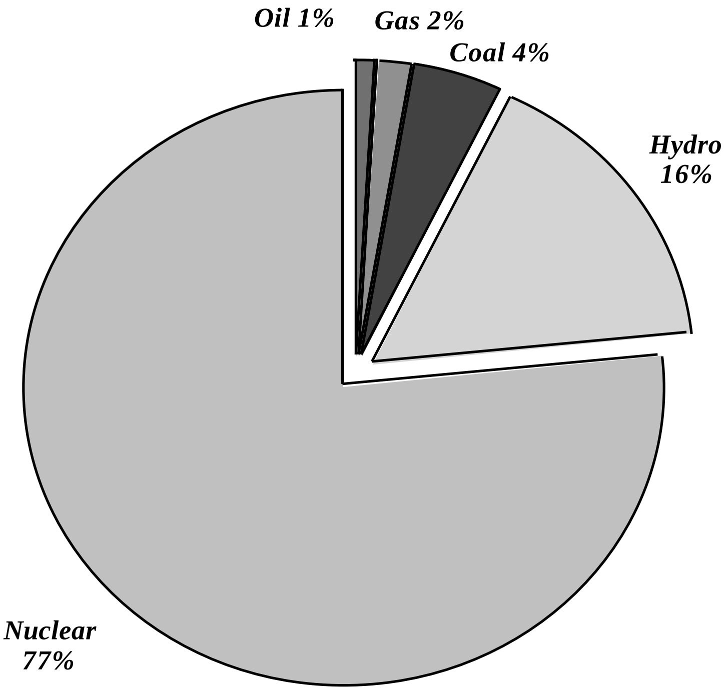
Units: 1 GWh = 10^6 kWh; 1 MECU = 10^6 ECU = 10^9 mECU.

Table 5.4: Aggregated damage costs for the French electricity sector, with low and high CO_2 cost (1995 emissions data).

Fuel Cycle [1]	**Annual**		**Damage (@ 18 ECU/t$_{CO2}$)**			**Damage (@ 46 ECU/t$_{CO2}$)**		
	Electricity GWh/yr	**% of total electricity**	**MECU/yr**	**mECU/kWh**	**% of total damage**	**MECU/yr**	**mECU/kWh**	**% of total damage**
Coal EdF	15281	3.0%	1859	122	48%	2227	146	48%
Coal IPP	6719	1.3%	*? 817 ?*	*? 122 ?*	*21%*	*? 979 ?*	*? 146 ?*	*21%*
Oil EdF	1093	0.2%	160	146	4%	183	168	4%
Oil IPP	3807	0.8%	*? 556 ?*	*? 146 ?*	*14%*	*? 638 ?*	*? 168 ?*	*14%*
Coke Gas EdF	1165	0.2%	65	56	2%	132	113	3%
Natural Gas IPP	8145	1.6%	*? 155 ?*	*? 19 ?*	*4%*	*? 244 ?*	*? 30 ?*	*5%*
Hydro EdF [1]	73270	14.6%	220	3	6%	220	3	5%
Hydro IPP	7690	1.5%	*? 23 ?*	*? 3 ?*	*0.6%*	*? 23 ?*	*? 3 ?*	*0.5%*
Nuclear [1]	385000	76.7%	19	0.05	0.5%	19	0.05	0.4%
TOTAL	***502210***	*100%*	***3874***	***7.7***	*100%*	***4665***	***9.3***	*100%*

[1] See notes under Table 5.3.

Energy mix in 1995 (502 TWh/yr)



Externality (3400 MECU/yr)

Figure 5.5: French energy mix and breakdown of damages (excluding CO_2 impact) by electricity sector. Gas includes coke gas and natural gas contributions.

5.5. References

CPDP (1996) *1995 Pétrole et Énergies, Comite Professionnel Du Petrol*, Tour Corosa, B.P. 282, 92505 Rueil Malmaison Cedex, France.

DGEMP (1995) *Production-Distribution de l'énergie électrique en France, Statistiques 94*, Ministère de l'Industrie, de la Poste et des Télécommunications.

European Commission, DGXII, Science, Research and Development, JOULE Program, (1995f) "ExternE: Externalities of Energy," Report 6, Wind & Hydro Fuel Cycles.

Lesgards, V. (1995) "Assessment of the Externalities of the Hydro Fuel Cycle - Implementation in France," European Commission, DGXII, JOULE Program and US Energy Department, Final Report for contract JOU2-CT92-0080, External Costs of Fuel Cycles.

Rabl, A., Curtiss, P.S., Spadaro, J.V., Hernandez, B., Pons, A., (1996) "Environmental Impacts and Costs: The Nuclear and the Fossil Fuel Cycles," Version 3, European Commission, DGXII, JOULE Program, Final Report for contract JOU2-CT92-0236, External Costs of Fuel Cycles: Implementation of the Accounting Framework in France.

Sibieude, C., Sibieude, T., *Les Rouages Economiques de l'Environnement*, Les Editions de l'Atelier / Les Editions Ouvrières, 12 Avenue Soeur Rosalie, 75013 Paris, France.

Spadaro, J.V. (1997) "A Simple Method for Estimating Aerosol Concentrations and Health Impacts," Internal paper for ExternE Transport Project.

6. POLICY CASE STUDY - INCINERATORS AND CARS: A COMPARISON OF EMISSIONS AND DAMAGES

6.1. INTRODUCTION AND DISCUSSION

Thermal treatment (incineration, pyrolysis, or gasification) is a major option for the disposal of waste, full of promise because it greatly reduces the space requirement of landfills yet highly controversial because of perceived health risks from air pollution, especially dioxins. Whereas such fears are natural after the bad practices of the past, the decisions to be considered now concern new clean technologies, subject to the stringent new regulations proposed by the EC [1994].

It is interesting to put the health risks of MSW incinerators into perspective by means of several comparisons. We consider incineration of MSW (municipal solid waste), under the extreme scenario that **all** MSW is incinerated; to facilitate the interpretation we assume a round number of 500 kg/person for annual production of MSW per capita, close to the current average in Europe. For emissions data we consider the EC regulations of 1989 which are currently applicable, as well as the new EC regulations proposed in 1994. Since NOx emissions were not regulated by EC [1989], we assume 300 mg/m^3 as typical value for existing installations.

In addition, to consider the benefits achievable be energy recovery, we evaluate the net emissions and impacts attributable to MSW incineration if 50% of the heat from the incinerator is used in a district heating system and displaces pollution that would otherwise be emitted by conventional boilers or furnaces fired by natural gas or oil (half of each).

For the comparison with cars we assume data representative of France: an average mileage of 5850 km/yr per person, with current emission factors for three types of private car (gasoline without catalyst, gasoline with catalyst, and diesel). We consider only air pollution.

We begin by showing the damage costs for incinerators, per tonne of pollutant in Figure 6.1 (note that scale is logarithmic) and per tonne of waste in Figure 6.2. Despite their high toxicity, the micropollutants do not dominate the total damage. This is especially striking for dioxins whose toxicity is extreme but whose emission rate is so low that the damage per tonne of waste is very small compared to the classical air pollutants. Damage of NO_X via nitrates appears to dominate, but we note the great uncertainty of the nitrate impacts.

The sum of the costs per tonne waste is 12.3 ECU/t with and 3.8 ECU/t without the nitrate contribution. It is interesting to note that the market cost of MSW incineration in France is approximately 60 ECU/t with current (pre EC 1994) regulations. Therefore any remaining external costs after imposition of the EC 1994 Directive are small compared to the market cost of MSW incineration.

In Figure 6.3 we compare the emissions of MSW incineration with emissions from private cars, both per capita. A comparison of emissions has the advantage of being unaffected by uncertainties in dispersion modeling and epidemiology. However, for particulates one should note that it does not take into account the fact that particulates from cars have higher damage per tonne, being smaller (and more toxic) and emitted at street level rather than from tall stacks.

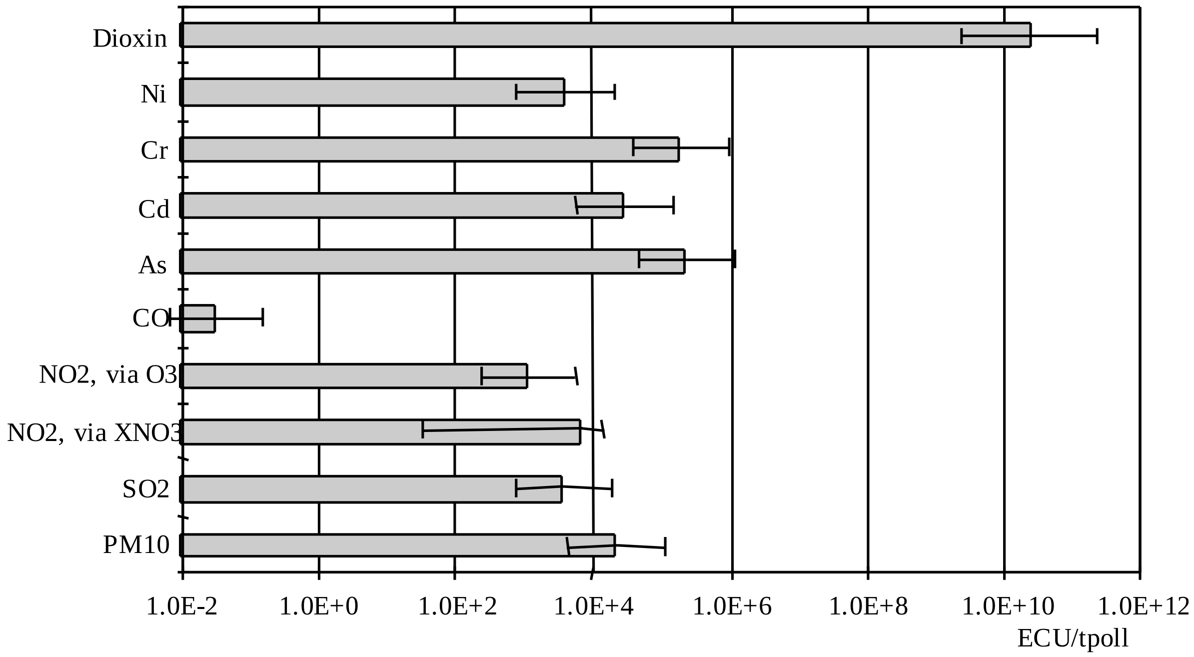
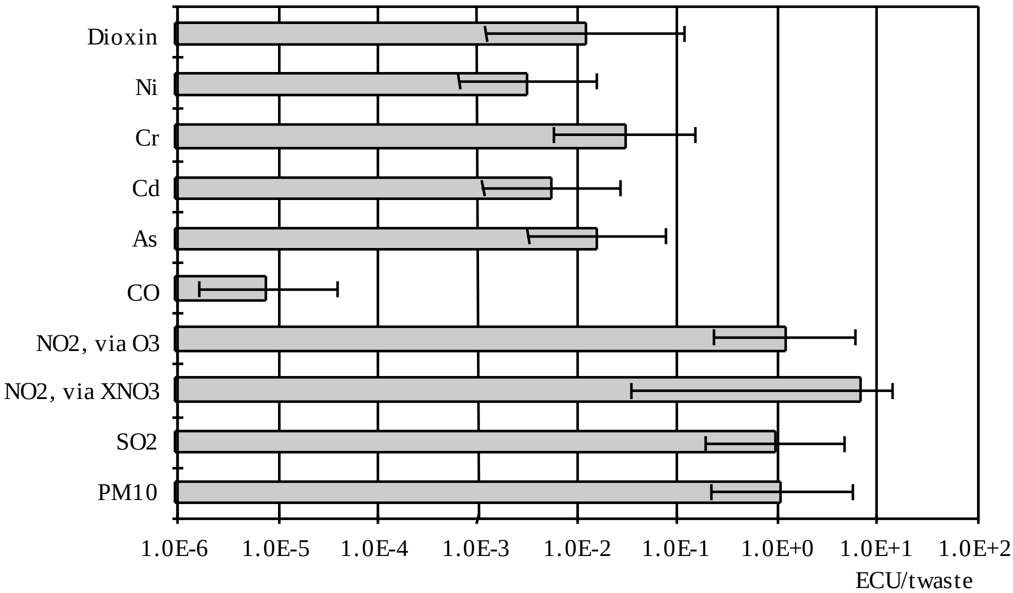


Figure 6.1: Mean damages per ton of pollutant emitted in Europe. Error bars indicate uncertainties.


Dioxin
Ni
Cr
Cd
As
CO
NO2, via O3
NO2, via XNO3
SO2
PM10
1.0E-6
1.0E-5
1.0E-4
1.0E-3
1.0E-2
1.0E-1
1.0E+0
1.0E+1
1.0E+2
ECU/twaste

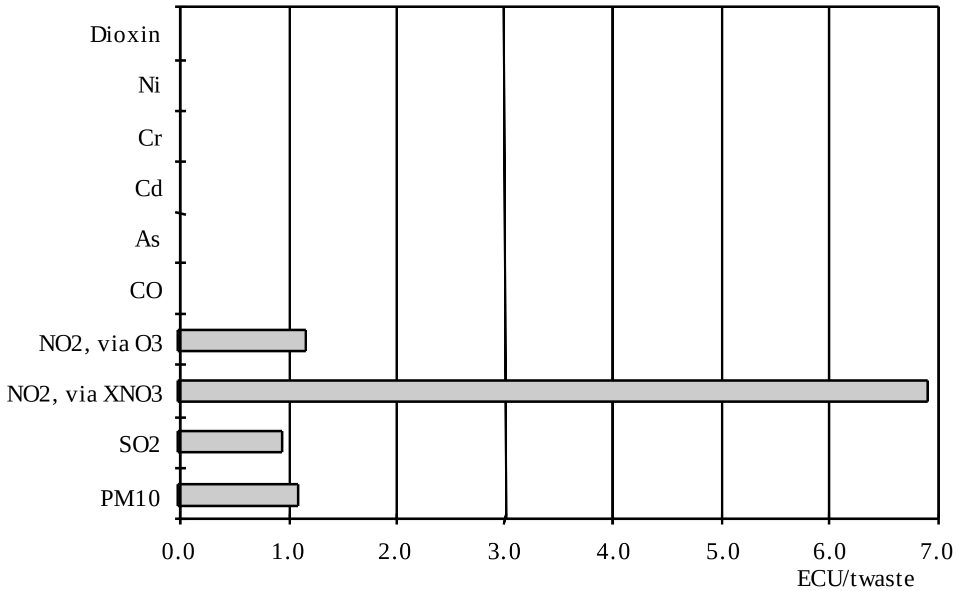


Fig a)

b) **ure 6.3:** Damage per ton of waste, for the damage per ton of pollutant values in Figure 6.x and emission rates of EC regulation proposed in 1994. a) logarithmic scale, b) linear scale.

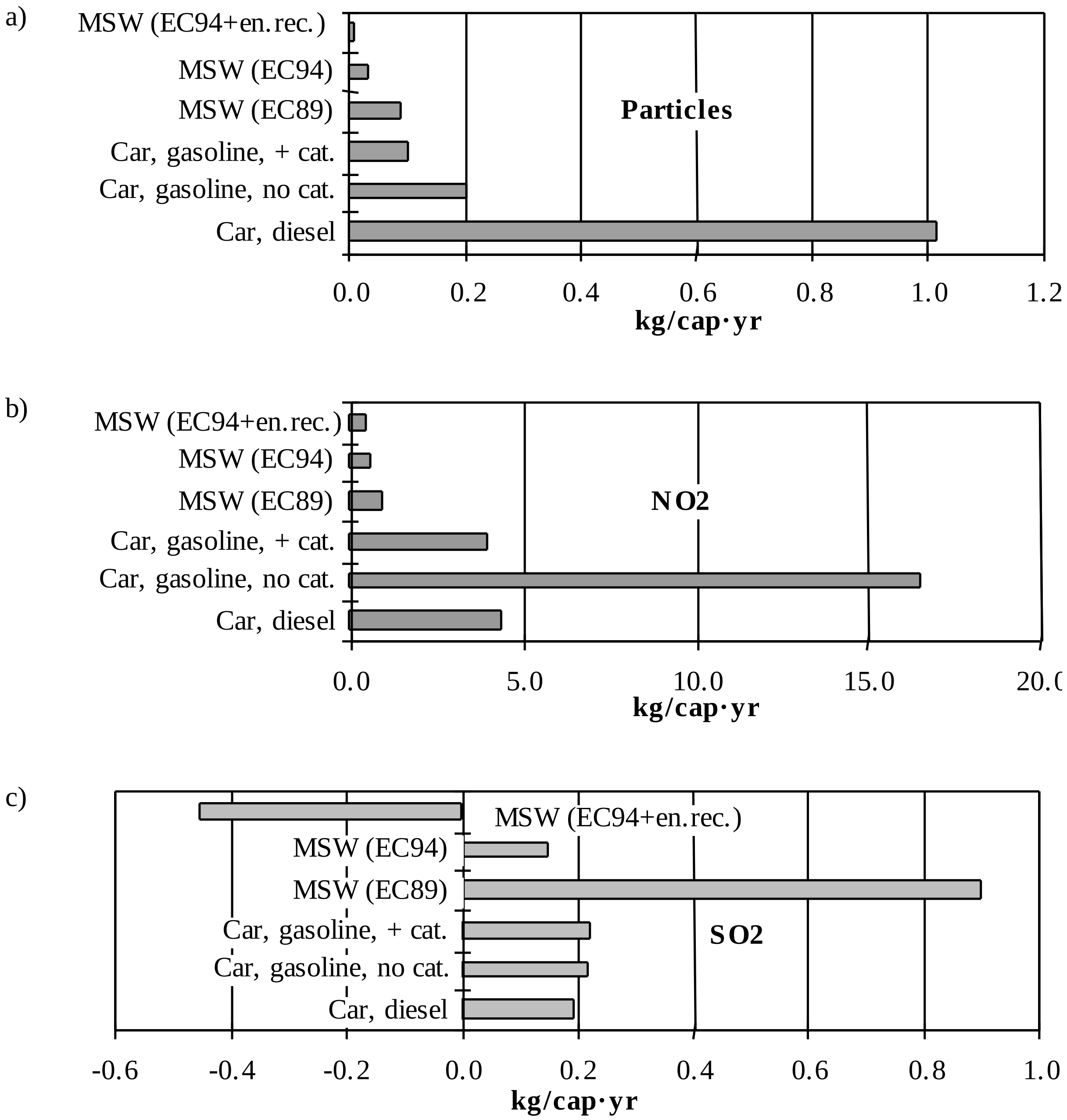


Figure 6.3: Emissions of MSW incineration compared with private cars, both per capita.

Finally in Figure 6.4 we compare the damage costs due to NO_X, SO_X and particulates of MSW incineration with those of private cars, both per capita. All these comparisons suggest that much of the current debate about health impacts of MSW incineration may not be focused on the most important impacts.

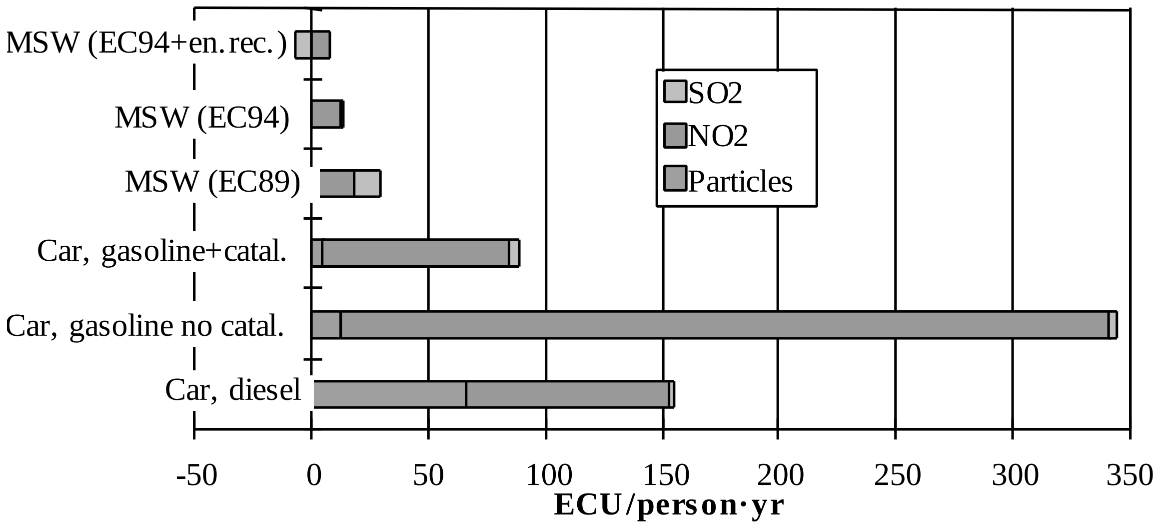


Figure 6.4: Damage costs due to NO_X, SO_X and particulates of MSW incineration compared with private cars, both per capita.

6.2. REFERENCES

Rabl, A., Spadaro, J.V., Desaigues, B., (1997) "Amelioration de l'Efficacite des Etudes d'Impact par la Valorisation Economique des Dommage (Installations Classees, Infrastructures)," Report for the Ministry of the Environment, Ecole des Mines, 60, blvd St-Michel, F 75272 Paris, Cedex 06, France.

Rabl, A., Spadaro, J.V., McGavran, P.D., (1997) "Health Risks of Air Pollution from Incinerators: a Perspective," Ecole des Mines, 60, blvd St-Michel, F 75272 Paris, Cedex 06, (submitted for journal publication).

Spadaro J.V., Rabl, A. (1997) "Environmental Costs due to Transportation: The French Implementation Cases," European Commission, DGXII, JOULE Program, Final Report for contract JOS3-CT95-0004, ExternE Transport Study.

7. CONCLUSIONS

We have applied the methodology of the ExternE Program to estimate the external costs of the major technologies for the production of electricity in France. In addition to technologies as currently used by Electricité de France (nuclear, coal, oil, and hydro), we have examined some that could be interesting in the future:

- combined cycle gas turbines fired by natural gas,
- potential new oil or coal fired power plants that satisfy new regulations,
- incineration of waste,
- gasification of biomass.

The dominant damage costs are due to health impacts and global warming; damage costs due to degradation of buildings and losses of crops almost negligible. The uncertainties large but at least the order of magnitude of most major damages and costs from normal operation of power plants can be estimated now. Major uncertainty lies in the health effects of nitrate and sulfate aerosols for which there is little or no direct epidemiological evidence; here the hypothesis has been made that the exposure-response functions for these aerosols are equal to those for particulates.

Among the health impacts, the largest term is due chronic mortality and the key parameter for the valuation is the value of statistical life (VSL, taken as 3.1 MECU in the ExternE Program). To value mortality impacts of air pollution, a fundamental choice has to be made whether one simply multiplies the number of premature deaths by the value of statistical life (VSL valuation) or whether one takes the reduction of life expectancy into account by multiplying the years of life lost (YOLL) by a value per YOLL (YOLL valuation). The latter approach is more rational and implies much smaller damage costs than the VSL valuation because the reduction of life expectancy for air pollution deaths is much smaller than the large reduction of life expectancy implicit in the value of life studies used to determine VSL. The ratio VSL/YOLL depends on the discount rate, and it is roughly in the range of 15 to 30.

Several general remarks should be kept in mind before using the numbers in this report. The externalities quantified in our analyses are those associated *only* with airborne emissions, while impacts related to soil and liquid emissions have not been evaluated at this point. Although possibly significant, a reliable and simple accounting framework for estimating damages to soil and waterways has yet to be developed.

The term fuel cycle is misleading, suggesting a monolithic well defined concept. In reality there is a set of activities and processes, possibly at many different sites and with a wide spectrum of different technologies. The choice of technologies is particularly striking in the results for the French nuclear fuel cycle where the C-14 doses from recycling dominate: other technologies capture much of the C-14 (Sellafield, UK) or do not recycle (USA, with entirely different impacts). Since most damages are proportional to the rates at which pollutants are emitted, one can account for technology dependence by rescaling the respective damages.

Apart from globally dispersing pollutants such as greenhouse gases, most impacts are site dependent. Roughly speaking their impacts are proportional to the receptor density (e.g. population) in the vicinity of the pollution source, but precise numbers depend on detailed conditions. For primary air pollutants such as particles the impacts can easily vary by an order of magnitude depending on the proximity of a large city. For secondary air pollutants (ozone, nitrates, sulfates) the sensitivity to local conditions is less pronounced because they are formed at some distance from the source. Site dependence is particularly strong for the hydro fuel cycle, and generally for water pollution, solid wastes, and mining (including accidents).

For nuclear the dominant impacts from normal operation are cancers and hereditary effects. For the public the individual risks are extremely small, but summed over the world population and over very long times, they appear significant - if the dose-response function is linear without threshold (all studies of the nuclear fuel cycle have assumed this as precautionary principle).

Compared to the natural background of radiation, the public dose from the normal operation of the nuclear fuel cycle is extremely small. Even if the entire world consumption of electricity were supplied by current French technology for 100 years, the incremental dose would be three orders of magnitude less than the typical background of dose of radiation.

The main controversies concern global warming for fossil fuels, and accidents, high level wastes, and proliferation for nuclear - issues that involve complex social and political questions in addition to science.

8. PREVIOUS RESULTS FOR THE FOSSIL FUEL, NUCLEAR AND HYDRO FUEL CYCLES

In the following chapter, we have reproduced the *Executive Summaries* for the French Implementation of the coal, natural gas, oil, nuclear and hydroelectric fuel cycles, which were assessed in the Joule II phase of the ExternE Program.

8.1. IMPLEMENTATION OF THE FOSSIL FUEL CYCLES FOR FRANCE

The summary below is taken from the report:

Rabl, A., Curtiss, P.S., Spadaro, J.V., Hernandez, B., Pons, A., (1996) "Environmental Impacts and Costs: The Nuclear and the Fossil Fuel Cycles," Version 3, European Commission, DGXII, JOULE Program, Final Report for contract JOU2-CT92-0236, External Costs of Fuel Cycles: Implementation of the Accounting Framework in France.

8.1.1. Objectives and Methodology

In recent years several estimates for the environmental costs of power generation have been published [e.g. Hohmeyer 1989; Ottinger et al 1991; Ontario Hydro 1993] with widely diverging results, often differing by orders of magnitude. The reason lies not only in the uncertainties, but in the lack of uniformity of the underlying hypotheses and methodologies.

To give a firmer and more consistent basis to such studies, the Commission of the European Communities, in a cooperative program with the US Department of Energy, has developed an accounting framework for quantifying the external costs of fuel cycles [EC 1995, ORNL/RFF 1994]. It is based on the analysis of impact pathways, with a common set of clearly stated assumptions. As shown in Fig.ES.1, one traces the impact pathway for each pollutant or other burden, from the source to the receptor, and evaluates the damage both in physical and in monetary units. The entire fuel cycle is analyzed, from the production of the fuel to the disposal of the waste and the decommissioning of the power plant.

The present project concerns the implementation of this methodology in France for the major cycles used in the production of electricity. This project yields many results that can be useful for a wide range of applications, from the choice of technologies (e.g. nuclear vs. coal) to the determination of socially optimal investments in pollution control. One should keep in mind the following points:

1. The term fuel cycle may be misleading, suggesting a monolithic well defined concept. In reality there is a set of activities and processes, possibly at many different sites and with a wide spectrum of different technologies.

2. Since most damages are proportional to the emissions, one can account for technology dependence by rescaling the respective damages.

3. Site dependence of pollutants such as particulates, NO_X and SO_X, requires local or regional analysis of the type reported in Fig.ES.3; dependence on emission site can be neglected only for the (long lived) greenhouse gases.

4. The damage per ton of a particular pollutant emitted from a particular site is well defined and can be internalized, for instance by an emission tax or tradable permit. By contrast, the total damage per kWh confounds different technologies and different actors with different responsibilities. For instance, a tax on total damage per kWh could penalize a power plant owner for spills from oil tankers or accidents in coal mines.

8.1.2. Key Assumptions for Fossil Fuel Cycles

8.1.2.1. Sites and Technologies

For the fossil cycles the site of Cordemais, near Nantes on the Atlantic coast, has been chosen because that is where EdF (Electricité de France) has its largest concentration of fossil power plants. To assess the site dependence, we have also examined how the impacts change if the power plant is moved to four other sites (see Fig.ES.3 and Appendix E).

The impacts per kWh have been calculated for emissions corresponding to current regulations for new power plants ("best available technology"), see TableES.1. Since incremental damage from each pollutant is proportional to the emission, it is easy to rescale the results for other technologies (See Chapters 9 and Part III).

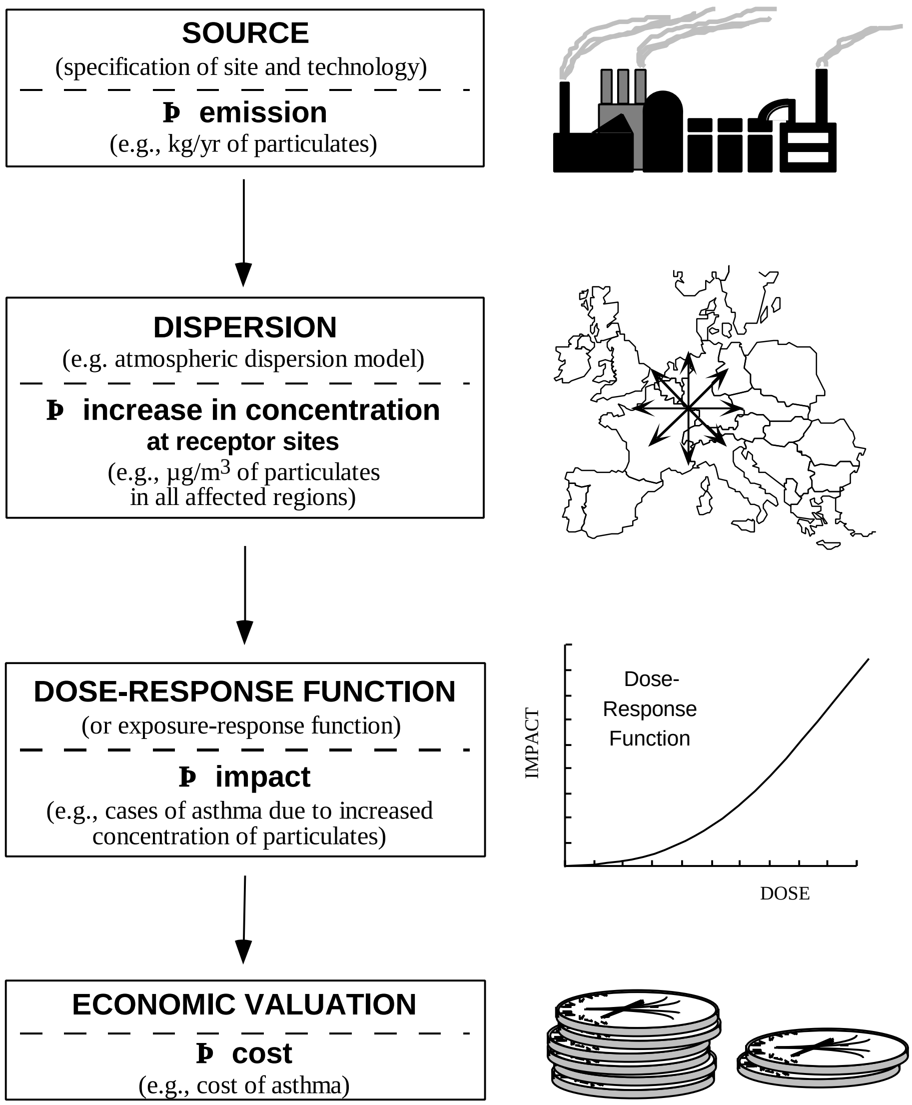


Fig.ES.1. The main steps of the impact pathways methodology.
Impacts and costs are summed over the receptors of concern (e.g., total population).

8.1.2.2. Software and Data

To carry out the numerous calculations, we have developed a software package, called PATHWAYS [Curtiss and Rabl 1996b]. It includes the data of the EUROGRID [1990] and

NUTS [EUROSTAT 1992] databases which provide information on human population, agricultural activities, and types and surface areas of various land use.
(See Chapters 3 and 4)

Table ES.1. Characteristics of fuel cycles for this study.
The site is Cordemais, near Nantes (-1.8° longitude, 47.3° latitude).
Greenhouse gases include upstream emissions.

	Coal	**Oil**	**Gas**
Technology	pulverized fuel, flue gas desulfurization, steam turbine	low S oil, low NO_x burner, steam turbine	gas turbine combined cycle
Peak capacity	600 MW_e	700 MW_e	
Hours of operation	3500 hr/yr	1500 hr/yr	base load
Annual production	2100 GWh_e/yr	1150 GWh_e/yr	
Stack height	220 m	150 m	
		Emissions, in g/kWh$_e$	
Particulates [a]	0.17 [a]	0.13 [a]	negligible [b]
NO_x (NO_2 equivalent) [a]	2.22 [a]	1.20 [a]	0.71 [b]
SO_x (SO_2 equivalent) [a]	1.36 [a]	5.26 [a]	negligible [b]
CO_2	900	740	401 [b]
Total greenhouse gases (CO_2 equiv)	1085 [c]	866 [c]	433 [b,c, d]

[a] communicated by EdF [Vacher 1993],

[b] EC [1995d]; greenhouse gases could be much higher if natural gas from Russia with large leaks.

[c] see Appendix D

[d] for gas from Norway, as communicated by GdF [Staropoli 1996]

8.1.2.3. Dispersion

The calculations for the fossil fuels are based on the ISC gaussian plume model [Wackter and Foster 1987] for local impacts, supplemented by long distance transport data that have been calculated for us with the EMEP atmospheric model [Barrett 1992].
(See Chapter 5)

8.1.2.4. Dose-response Functions

We have applied the dose-response functions recommended by the experts of the ExternE Program [EC 1995b]. Especially important are the ones for health effects of air pollution; they are assumed linear, in view of the lack of evidence for thresholds at current ambient concentrations. There is much uncertainty about the causative agents behind the observed health effects. The working hypothesis of the ExternE Program has been to use the health dose-response functions for PM_{10} and for O_3 as basis; effects of NO_2 and SO_2 are estimated as arising indirectly from nitrate and sulfate aerosols via the PM_{10} functions. Since, by contrast to sulfates, the literature shows no correlations with nitrate aerosols we indicate the corresponding impact as a range from 0 to the calculated number.

Most dose-response functions for health effects from air pollution are determined by short term correlations (time lags a few days at most); thus they measure only acute effects. The full impact also includes chronic effects which can be much larger, but are notoriously difficult to measure. In the present report we have used chronic dose-response functions only for mortality from particulates.
(See Chapter 6)

8.1.2.5. Economic Valuation

The ground rule is to account for individual preferences rather than just direct costs. The single most important parameter, for nuclear and fossil cycles, is the valuation of a loss of life ("value of statistical life"). We have used the official value 2.6 MECU (17 MFF or 3.4 M$) of the ExternE Program. Within the present project we have cofinanced the first French contingent valuation study for the value of life [Le Net et al. 1994], and we include an econometric analysis of the results in Appendix A.

Since the dominant costs (global warming for fossil and cancer risks for nuclear) are imposed on future generations, the discount rate is crucial. The guidelines of the EC/US fuel cycle study are to do the evaluation for three discount rates 0%, 3% and 10%, and the results for the nuclear fuel cycle are reported that way. However, using as criterion the perspective of future generations, we show that the appropriate discount rate for intergenerational effects is significantly lower than the conventional social discount rate, because it should include only economic growth, not pure time preference. Equally important is the rate at which future costs will evolve; only the difference between this rate and the discount rate matters. This difference ("effective discount rate") is likely to be close to zero.
(See Appendix B)

8.1.2.6. Global Warming

We have not performed a new analysis, adapting instead the results of EC [1995]. The value we cite, 14 ECU/t of CO_2, correspond to a reduction of 1 to 2% of world GNP for doubled CO_2, for effective discount rates close to zero.

8.1.2.7. Buildings and Historical Monuments

A direct evaluation of corrosion damage to materials requires an inventory of exposed surfaces, something for which we have found no data in France. Instead we analyze actual expenditures for cleaning and repainting of buildings. The resulting damage estimates are very small compared to the cost of electricity. Furthermore we find that the contribution of historical buildings and monuments is small compared to that of utilitarian buildings. We also show that the amenity loss is comparable to the cleaning cost; thus the total damage cost is approximately twice the cleaning cost.
(See Appendix C)

8.1.2.8. Upstream Impacts

In France most of the coal, oil and natural gas is imported, from a wide variety of sources, many of them overseas. Since a detailed analysis of the impacts of each fuel source was not feasible, we have only carried out a global assessment of emissions during the upstream activities. We find that the upstream emissions are small compared to those of the power generation phase, but not negligible, in particular the greenhouse gases CO_2 and CH_4. Another type of upstream impact frequently mentioned is air pollution from the production of the materials for constructing a power plant. However, using LCA data [SIMAPRO 1993; TEMIS 1994] we have found that these emissions are several orders of magnitude smaller than the emissions from the operation of fossil fuel power plants, consistent with the findings of ORNL/RFF [1994].
(See Appendix D)

8.1.2.9. Impacts on Workers

Many previous studies of fuel cycles tended to focus on impacts on workers rather than the public. In terms of internalization, workers and public are clearly different and the impacts should not be lumped together. In the present report impacts on workers have been quantified for the nuclear fuel cycle, but not for fossil fuels because of the difficulties of evaluating such impacts abroad.

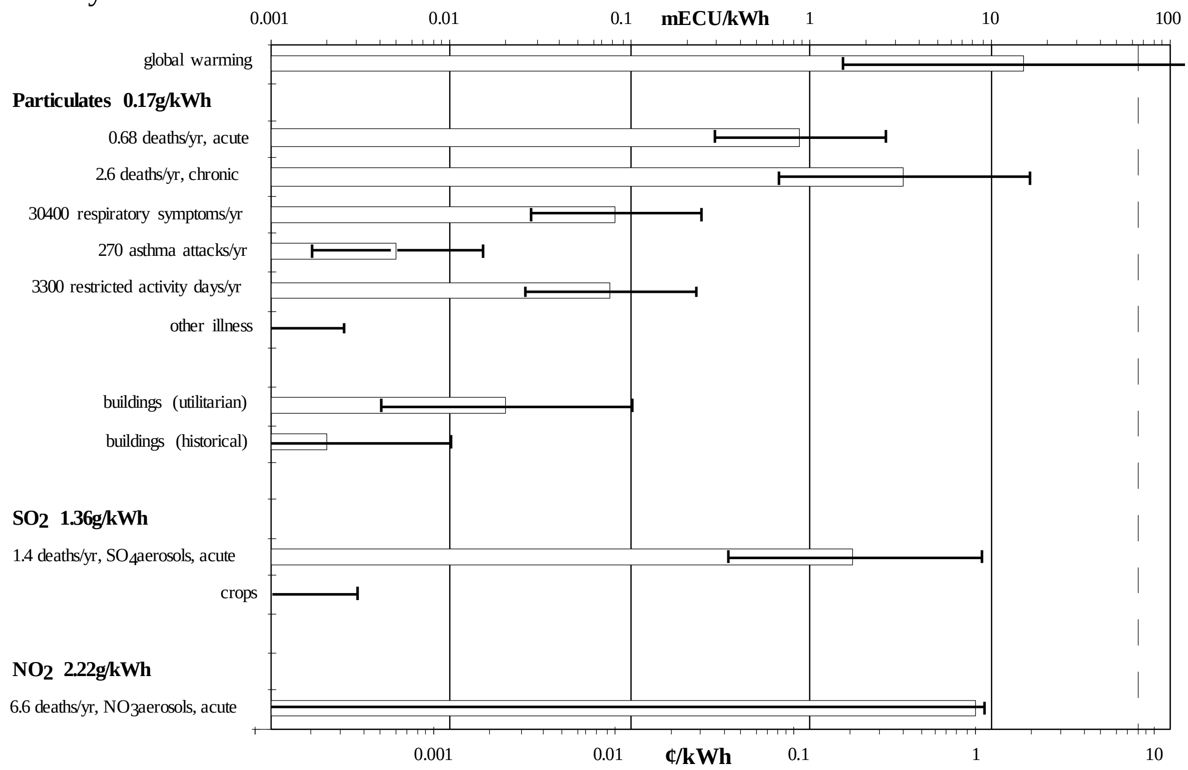
Instead we refer to recent studies by other teams, for the UK [Ball, Roberts and Simpson 1994] and for Germany [EC 1995c].

8.1.3. Results for the Fossil Fuel Cycles

8.1.3.1. The Numbers

Results are summarized in Tables ES.2 to 3. The costs are also plotted in Fig.ES.2, together with approximate confidence intervals as estimated in Chapter 8. The multiplicative confidence intervals appear to be around 3 to 5, corresponding to one geometric standard deviation or 68% probability.

a)



b
)

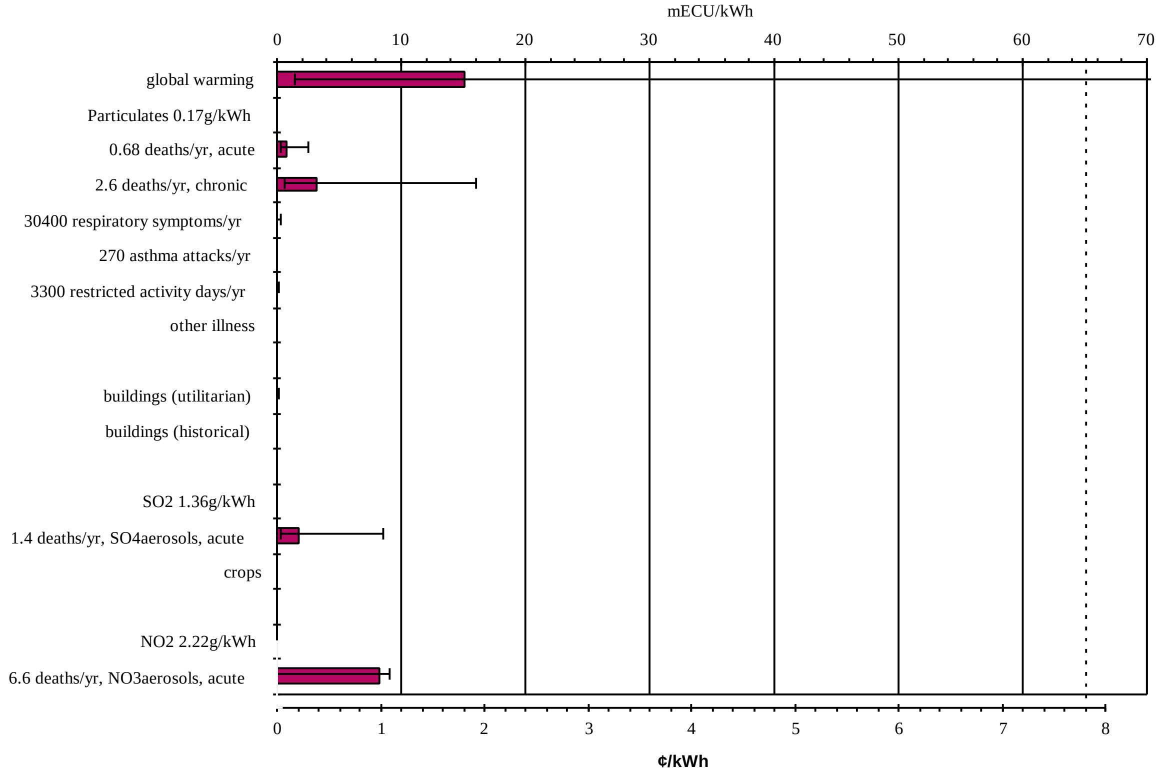


Fig.ES.2. Quantified impacts/year and costs (with uncertainties) for **coal** fuel cycle: intermediate load power plant at Cordemais, output 2.1×10^9 kWh/yr. Dashed line = average retail price 65 mECU/kWh. a) logarithmic scale b) linear scale

Table ES.2. Overview of results for **coal** fuel cycle: intermediate load power plant at Cordemais, output 2.1×10^9 kWh/yr winter only.

Burdens	Impact category	Physical impact	mECU/kWh	Confi-dence	Extent	Notes
Greenhouse gases 1085 g.CO_2 equiv/kWh, includ. upstream emiss.	global warming (sea level rise, crop failures, etc.)	5.9×10^{-16} °K/kWh after 10yr 3.4×10^{-16} °K/kWh after 100yr	**15** [EC 1995b]	low	G; P,F	X
Particulates 0.17 g/kWh	acute mortality	3.2×10^{-10} deaths/kWh	**0.84**	high	R; P	A
	chronic mortality Pope et al. [1995]	2.6×10^{-9} deaths/kWh	**3.1**	low	R; P	A
	morbidity	respiratory diseases	**0.17**	high	R; P	
	buildings	maintenance	**0.02**	medium	R; P	
	historical monuments	cost increase by 10^{-13}%/kWh	**0.002**	low	R; P,F	
SO_2 1.36 g/kWh	crops, direct	fertilizer or damage	**-0.002 to +0.002**	high	R; P	
	acute mortality via SO_4 aerosols		**1.7**	medium	R; P	
NO_2 2.22 g/kWh	crops, direct	fertilizer	mostly benefit	high	R; P	
	acute mortality via NO_3 aerosols		**0 to 8.2**	medium	R; P	
	O_3	impacts small for health,		medium	R; P	nq
	(from NO_X+VOC)	negligible for crops (winter only)		medium	R; P	nq
Subtotal			**20 to 29**	low		
Acid rain from SO_X and NO_X	agriculture and ecosystems		*(0.004 for liming) [EC 1995b]*		R; P,F	X, NQ
Thermal	ecosystems		*(0 to 0.02) [Rowe at al 1994]*		L; P	X, S
Land use	ecosystems				L; P,F	NQ, S
Occupational health	diseases		*(0.1 to 0.3) [EC 1995a]*		L; P	X, S, i
	accidents		*(0.8 to 2.0) [EC 1995a]*		L; P	X, S, i
Other	**?**		**?**			NQ
Total			**?**			

Confidence: high: s_g <˜ 3, medium: 3 < s_g < 10, low: s_g > 10, where s_g = geometric standard deviation (multiplicative confidence interval for 68% probability).

Notes: A: acute mortality only; chronic mortality might be almost ten times larger
i: a significant fraction of this cost may already be internalized
NQ: not quantified in this study, but probably important
nq: not quantified in this study, possibly significant
S: highly dependent on site or on technology
X: quantified in other studies and cited here *(not transferable if site dependent).*
Extent of Impacts: L: local, R: regional, G: global;
P: present generation, F: future generations (valuation depends on discount rate).
1 ECU = US$ 1.24 = 6.60 FF. Average retail price of electricity in France = 65 mECU/kWh [EdF 1994].

Table ES.2. Overview of results for **oil** and **natural gas**.

		oil steam turbine, peak load		**natural gas** combined cycle, base load	
Burdens	**Impact category**	**g/kWh**	**mECU/kWh**	**g/kWh**	**mECU/kWh**
Greenhouse gases	Global warming	866 g.CO_2 equiv/kWh, includ. upstream emiss.	**12**	433 g.CO_2 equiv/kWh, includ. upstream emiss.	**5.9**
Particulates	acute mortality	0.13 g/kWh	**0.64**	negligible	
	Morbidity		**0.13**		
	Buildings		**0.015**		
	Historical monuments		**0.0015**		
SO_2 via SO_4 aerosols	Health	5.26 g/kWh	**6.6**	negligible	
NO_2 via NO_3 aerosols	Health	1.20 g/kWh	**0 to 4.5**	0.71 g/kWh	**0 to 2.6**
NO_2 via O_3	health and crops	1.20 g/kWh	negligible in winter	0.71 g/kWh	**0.7**
Subtotal			**19.4 to 23.9**		**6.6 to 9.2**

Coal contains a variety of toxic metals some of which are emitted to the air during combustion (see Tables 9.1.1 and 9.1.2). Many of these, in particular Hg and Pb, do not appear to be carcinogenic and their thresholds for noncancer toxicity [EPA 1995] are much higher than the peak concentrations caused by the power plant. For the carcinogens with known dose-response function we have evaluated the damage costs for the inhalation pathway, as shown in Table ES.3. They are several orders of magnitude less than the health damage from ordinary particulates. Even if there were significant noninhalation pathways, they are unlikely to change to conclusion that heavy metal air pollution from coal is negligible compared to ordinary particulates.

Table ES.3. Comparison of particulates and heavy metals for Cordemais site. Damage for particulates is sum of health costs from Table ES.2 (counting acute but not chronic mortality), and for As and Cd it is upper limit obtained by using linear dose-response function of HEAST [EPA 1995] for inhalation, assuming that all resulting cancers are fatal. For other emission sites or population densities see Eq.1 and Fig.ES.3.

	Damage cost ECU/t	**Emission t/TWh**	**Damage cost mECU/kWh**
Particulates	6000	170	1.01
As	<140000	0.024 [a]	<3.43E-03
Cd	<12000	0.001 [a]	<1.17E-05

[a] from Table 9.1.1

8.1.3.2. Site Dependence

A systematic analysis of the site dependence of air pollution damage has been carried out (see Appendix E), by taking the same power plant and moving it to five sites that arguably span the full range of conditions, from Cordemais, a rural site on the Atlantic Coast, to Paris, a metropolitan area with twenty percent of the population of France. The corresponding variation of regional impacts is about a factor of ten, comparable to the variation of regional impacts that has been found for nuclear power plants, Fig.ES.6. This is illustrated in Fig.ES.3 for the impacts of SO_2. This graph also shows the variation with stack height.

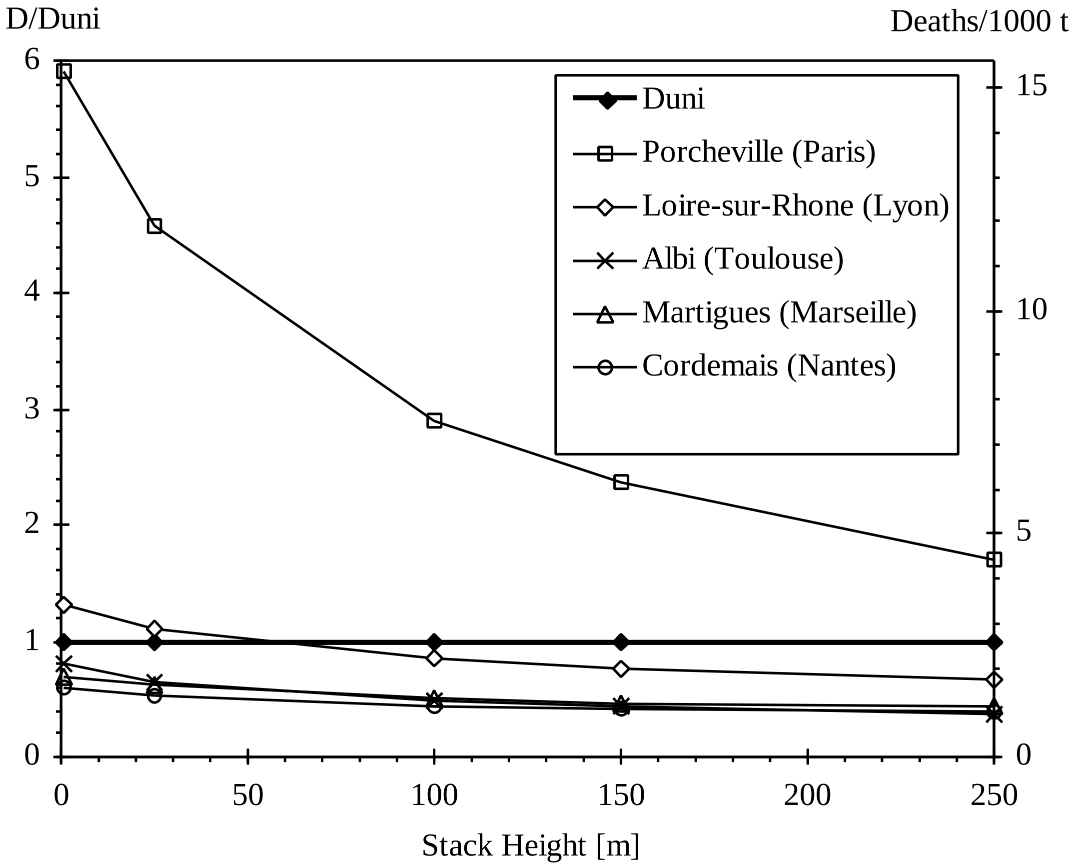


Fig.ES3. An example of dependence on site and on height of source for a primary pollutant: damage D from SO_2 emissions with **linear dose-response function**, for five sites in France, in units of D_{uni} for uniform world model Eq.1 (the nearest big city, 25 to 50 km away, is indicated in parentheses). The scale on the right indicates deaths/yr (acute mortality) from a plant with emission 1000 ton/yr.

NOTE: stack height dependence is stronger than in Version 2.1 and in Curtiss and Rabl [1994] because we now use an improved gaussian plume, the ISC model.

We have also shown that, in a uniform world (in the sense specified at the end of this paragraph) the equation for the total damage can be integrated in closed form to yield a very simple "uniform world model" for the total damage D_{uni} [in impact units of exposure-response function]

$$D_{uni} = d\ r\ Q/k \qquad (1)$$

where r = receptor density [receptors/m^2],

Q = emission rate of pollutant [g/s],
d = exposure-response function slope [impacts/(receptor·(g/m^3))], and
k = removal velocity [m/s]. The latter is defined as ratio k(**x**) = F(**x**)/c(**x**) of surface concentration c and total removal flux F (due to dry deposition, wet deposition or decay) at a point **x**. This formula is exact in a uniform world (linear dose-response function, uniform receptor density and uniform atmospheric removal rate k independent of **x**). The generalization to secondary pollutants is straightforward, but we have not yet tested its relevance. Eq.1, with the average population density of France, is shown by the horizontal line in Fig.ES.3; it is a remarkably good approximation for the average damage in France.

8.1.4. Conclusions for the Fossil Fuel Cycles

1. If one accepts the economic valuation, the dominant impact appears to be global warming, followed by health impacts from particulates. Crop losses are less important, and cleaning costs of buildings are small.
2. Impacts from the production of the materials for constructing a power plant are several orders of magnitude smaller than the emissions from the operation of fossil fuel power plants.
3. We have not yet analyzed the impacts of mining; among upstream impacts we have counted only global warming.
4. We have not yet analyzed the impacts of liquid or solid wastes for fossil fuels; they are difficult to predict to the extent that they depend on future waste management decisions.
5. The total damage is proportional to the density of receptors in the region of concern; the range can extend up to thousands of km for the important case of particulates, NO_X and SO_X with a linear dose-response function. Site dependent variations can easily cause the total damage to be three times larger or smaller than the "uniform world".
6. In view of the weight of the epidemiological evidence, the numbers for acute mortality due to particulates are quite firm; they can be considered lower bounds. The true mortality is probably higher because of aerosols and because of chronic effects. We have calculated aerosol impacts with the dose-response functions for acute mortality, and we show chronic effects only for mortality from particulates, based on Pope et al [1995].

8.2. IMPLEMENTATION OF THE NUCLEAR FUEL CYCLE FOR FRANCE

The summary below is taken from the report:

Rabl, A., Curtiss, P.S., Spadaro, J.V., Hernandez, B., Pons, A., (1996) "Environmental Impacts and Costs: The Nuclear and the Fossil Fuel Cycles," Version 3, European Commission, DGXII, JOULE Program, Final Report for contract JOU2-CT92-0236, External Costs of Fuel Cycles: Implementation of the Accounting Framework in France.

8.2.1. Work Accomplished on the Nuclear Fuel Cycle

The French nuclear fuel cycle was broken down into 8 separate stages. Reference sites and 1990's technology were chosen to represent the total nuclear fuel cycle, as it exists today. In addition, the transportation of material between the sites was considered. The facilities are assessed for routine operation, except in the cases of electricity generation and transportation, where accidental situations are evaluated. The impacts of construction and decommissioning of a facility are included in the electricity generation stage. It is important to stress that this methodology does not employ a worst case scenario analysis, as is usually done for safety or regulatory compliance assessments, but intends to evaluate the impacts expected from the operations. In a few cases, however, when no reasonable alternative seemed possible, conservative values were used.

The impact pathway approach requires an inventory and assessment of all potential impacts, however, within the context of the ExternE project it has not been possible to consider all of these. Therefore, only the most important impacts, called priority impacts, have been included. Releases of radioactive material to the environment, which potentially impact public health, were given the highest priority. Occupational health impacts, from both radiological and non-radiological causes, were the next priority, even though the extent to which occupational health impacts can be considered as externalities has not been addressed in this study.

8.2.2. Impact Assessment

Assessment of the impacts was organized by the type of routine emissions: atmospheric releases, liquid releases and solid wastes. The analysis of impacts of releases from severe accidents involves additional complex issues, therefore, it was treated as a distinct category. Health impacts to the workers - radiological and non-radiological - were also accounted for separately.

The most important choices for the assessment of the nuclear fuel cycle concern the definition of temporal and spatial boundaries. Due to the long half-life of some of the radionuclides, low-level doses will exist very far into the future. These low-level doses can add up to larger values when the total population dose is considered for thousands of years. The validity of the use of this type of modeling has been widely discussed. On one hand, there is a need to evaluate all the possible impacts if a complete assessment of the fuel cycle is to be made. On the other hand, the uncertainty of the models increases and the level of doses, that are estimated, fall into the range where there is no clear evidence of resulting radiological health effects.

If large distances and long time frames are included in the assessment of some fuel cycles and not in the assessment of others (due to lack of methodologies or lack of data) the direct comparison of the results becomes a problem. It is for this reason that the impacts estimated for the nuclear fuel cycle are presented in this report within time and space matrices. The short-term category includes immediate impacts, such as occupational injuries and accidents, medium-term includes the time period from 1 to 100 years, and long-term accounts for between 100 to 100,000 years into the future. The selection of a 100,000 year limit to the assessment was arbitrary, however the most significant part of the impacts are included.

The environmental (i.e. other than human health) impact from increased levels of radiation due to the routine releases of radionuclides has not been considered as a priority impact pathway. The most important of these types of impacts could be expected to occur as a result of a major accidental release. These have been included in the economic damage estimates as the loss of land-use and agricultural products after a potential severe reactor accident. Possible long-term ecological impacts have not been considered at this time.

The final stage of the impact pathway methodology is the economic valuation of the impacts. The economists involved in the ExternE project set a common value of a statistical life, based on a literature review of contingent valuation studies, adopted for all the fuel cycle assessments in the project. Being that for almost all cases in the nuclear fuel cycle, low-levels of exposure are under consideration, a methodology has been developed for the valuation of radiological impacts. The stochastic nature of the effects and the expected delay time between exposures and manifestation of the health effects must be taken into account. Due to the lack of contingent valuation studies directly applicable for the monetary valuation of the morbidity impact indicators (radiologically-induced non-fatal cancers and occupational injuries), the best available information was used.

8.2.3. Severe Accidents

Accidents are one of the most controversial features of environmental assessment of the nuclear fuel cycle. Within the scope of this project, this type of assessment has been confined to the electricity generation stage and the transportation of radioactive materials between sites. Although facilities at other stages of the nuclear fuel cycle handle very large inventories of radioactive material, their activities are generally believed to be of a lower risk. The probabilistic assessment of the transportation of materials between all the fuel cycle facilities includes risks from both conventional traffic accidents and releases of radioactive material. These have been found to be relatively small.

At this time, there is no general consensus on a methodology to assess the external costs of severe nuclear reactor accidents. In this project, a risk-based approach has been adopted. Due to the complexity of the assessment and the difficulty in finding facility-specific or generally-accepted input data, the evaluation that was completed provides indicative results for this type of methodology. An accident consequence assessment code has been used to estimate the doses, costs of countermeasures and economic losses that would be expected after an accident.

The source term considered in this study corresponds to a release of about 1% of the core (ST21). This source term is in the same order of magnitude as the reference accident scenario used by the French national safety authorities. To illustrate the sensitivity of the results the impacts of three other source terms are presented. The largest can be considered as release that would occur after a core melt accident with a total containment breach. The fraction of the core released, based on a source term used in an international inter-comparison study, is about 10% of the core inventory. The smallest release can be considered to represent the situation after a core melt accident where all the safety measures have operated as planned and there is only leakage from the intact containment (0.01% of the core inventory).

The probability of a core melt accident, based on a French assessment of a major core melt accident at a 1300 MW PWR reactor, is taken to be 1.0E-5 per reactor.year. This is broadly consistent with other similar assessments based on engineering fault tree analysis, although a wide range of estimates have been proposed. The conditional probabilities of the large and small releases that would occur after a core melt accident are taken from a US Nuclear Regulatory Commission report, and are 0.19 for the three largest source terms and 0.81 for the lowest.

8.2.4. Results for the Nuclear Fuel Cycle

8.2.4.1. Doses

The total collective dose for all the stages of the fuel cycle, except for the severe accident analysis, integrated for a time period of 100,000 years into the future, is 13.1 man.Sv/TWh. A closer look shows that the total local collective dose is about 0.22 man.Sv/TWh and the total regional collective dose is 0.33 man.Sv/TWh, leaving over 95% of the public dose due to the global dispersion of certain radionuclides (C-14, I-129). If the global doses are not included, the occupational doses become a dominant contributor to the overall impacts (about 40% of the doses received).

When all the categories of the doses are considered, the reprocessing stage contributes the largest portion (79%) of the total collective dose (10.3 man.Sv/TWh), followed by the electricity generation stage (18% of the total). If the global collective doses are excluded, the reprocessing stage diminishes in importance and is replaced by the electricity generation (0.38 man.Sv/TWh) and the mining and milling (0.29 man.Sv/TWh) stages. The doses from the enrichment stage are the least important.

On a global scale, C-14 released from the electricity generation and reprocessing stages contributes the largest portion of the dose (more than 12 man.Sv/TWh). It must be stressed that even though this radionuclide is responsible of more than 90% of the total collective dose presented in this report, it is due to the aggregation of very small doses over a large time and space scale (a constant global population of 10 billion people is assumed for 100,000 years).

The average individual dose from the annual atmospheric release of C-14 from the electricity generation and reprocessing stages (8.5E4 MBq per TWh) has been estimated to be 2E-9 mSv/TWh. An individual dose of 1.4E-8 mSv/y is estimated for the operation of one 1300 MW PWR, assuming an electricity production of 7 TWh/y. It can be seen that this dose is insignificant when compared to the average individual dose of 1.2E-2 mSv/year due to natural C-14 or the 2.4 mSv/y average individual dose due to the natural background.

The collective dose of less than 1E-7 man.Sv/TWh due to potential transportation accidents is a very small part of the total 9.5 E-4 man.Sv/TWh public collective estimated for all transportation operations in France.

In case of a severe reactor accident, an indicative total collective dose for the population (for a radius of 3,000 km) for the four accident scenarios has been estimated. The impact of the reference scenario ST21 (core melt with a 1% of the core released) is a collective dose of about 58,000 man.Sv (this can be compared to the 560,000 man.Sv estimated for the USSR and European population as a result of the Chernobyl accident). For the other scenarios considered, the expected risk (consequences x probability of occurrence) varies between 0.001 and 0.08 man.Sv/TWh.

For the workers, the total collective dose for all the different stages of the fuel cycle is about 0.35 man.Sv/TWh. The electricity generation and the mining and milling stages are the operations where the occupational collective dose is the most important (0.2 man.Sv/TWh and 0.11 man.Sv/TWh, respectively).

8.2.4.2. Human Health Impacts

Routine Operations

The radiological health effects resulting from the normal operation of the nuclear fuel cycle are directly proportional to the total collective doses. The expected number of health effects were

calculated assuming no lower threshold for radiological impacts, using internationally accepted data from Publication 60 of the International Commission on Radiological Protection. The total number of expected health impacts per TWh are:
0.65 fatal cancers, 1.57 non-fatal cancers, and 0.13 severe hereditary effects. These results include the long-term global dose assessment.

The number of estimated deaths for the European population due to the routine annual operation of one additional 1300 MWe PWR (about 7 TWh/y), integrated over 100,000 years, would be less than 1 fatal cancer (0.1). This can be compared to the approximate value of 800,000 fatal cancers reported in Europe each year.

It is estimated that the production of 1 TWh will result in 0.02 deaths, 0.96 permanent disabilities and 296 working-days-lost (non-radiological health impacts) in the work force for the nuclear industry. Worker accidents during the construction and the decommissioning of the reactor are the most important contributors to these values.

Accidental Situations

The transportation of the radioactive materials between the different sites and the transportation of the materials involved in the construction and the decommissioning of the reactor result in traffic accidents involving the general public. The number of non-radiological health impacts estimated are: 3E-4 deaths and 1.7E-3 injuries per TWh. Assuming an incremental annual production of 7 TWh, less than 1 death (0.002) can be expected per year. This is insignificant when compared to the nearly 10,000 traffic accident deaths that occur in France each year. In accidental situations occurring during the transportation of hazardous radioactive materials such as UF_6, the toxicological health impacts estimated are even smaller (2E-9 deaths/TWh and 7E-5 injuries/TWh).

The radiological health effects from reactor accidents can be divided into two categories: the immediate health effects (deterministic effects) and the stochastic effects as cancers or severe hereditary effects. For the four accident scenarios considered in this study, only the two most severe accidents lead to deterministic effects, but no deaths are expected for the reference scenario ST21. For the stochastic effects, as for normal operation, they are considered to be directly proportional to the collective doses. Depending on the scenario, the number of expected fatal cancers varies from 1E-4 to 3.9E-3 per TWh.

8.2.4.3. Monetary Valuation

Routine operation

The sub-total of the cost presented for all the stages of the nuclear fuel cycle is about 2.5 mECU/kWh, if no discount rate is applied. When 3% and 10% discount rates are used, the cost is reduced to 0.1 and 0.05 mECU/kWh, respectively. The current base load electricity generating costs in France are on the order of 35-40 mECU/kWh.

The dominant contributor to the total cost is the reprocessing stage (76%), followed by electricity generation (18%), when the 0% discount rate and the global impact assessment are implemented. When the 3% discount rate is applied, the construction of the reactor becomes the most important because discounting does not reduce the costs of the very short-term impacts assessed (40%). This is followed by mining and milling and electricity generation (19% and 17%, respectively). Six percent of the overall cost of the fuel cycle, at 0% discount rate, is due to occupational health impacts. This proportion increases in importance when a discount rate is applied (75% of sub-total for a discount rate of 3% and 95% of sub-total for a discount rate of 10%).

This sensitivity to the discount rate used is due to the relatively large portion of medium and long-term impacts associated with nuclear fuel cycle. For example, it can be seen that for no discount rate, the predominant costs are due to the global assessment, however, if a 3% discount rate is used, the short term, mostly occupational impacts dominate the final result. Another example is the waste disposal stage where the relatively small costs disappear if discount rates are applied. It has been for this reason that the use of this type of impact pathway methodology for the assessment of waste disposal and global impacts has been questioned.

Accidental Situations

The costs assessed for transportation impacts in general are extremely small. The portion attributed to accidental conditions can be considered insignificant due to the low probabilities and transportation packaging.

These results reported for the four accident scenarios are indicative of a risk-based methodology. The reference scenario, considered to represent a core melt accident followed by a release of 1% of the core, resulted in a 0.005 mECU/kWh cost. The risk for the other scenarios varies between

0.02 and 0.0005 mECU/kWh. The portion of these costs that might be internalised by nuclear accident insurance has not been addressed.

Further work must be done to evaluate other potential social impacts and external costs such as, *inter alia*, public perception, risk aversion, disruption of electricity supply, and decommissioning of the destroyed reactor. Besides the difficulty in assessing these impacts and costs, the partition of externalised versus internalised costs must also be evaluated.

8.2.4.4. Uncertainty

Each part of the impact pathway methodology employs different models and input data. The uncertainty of these calculations contributes to the overall confidence in the final results. In general the impacts of normal operations provide results that can be considered to have an uncertainty well within an order of magnitude, except for the estimates of human exposure and dose conversion where an uncertainty of an order of magnitude can be indicated in certain individual extreme cases. The propagation of the error estimates has shown that for the one standard deviation confidence interval, the results are considered to be correct within an order of magnitude.

8.2.4.5. Comparison with other Studies

For the most part, the earliest phases of comparative risk assessments of different fuel cycles options concentrated on deaths and injuries as the indicators for damages. In 1988, Hohmeyer published a report on the social costs of energy consumption. This was followed by a German-American workshop in 1990 on the external environmental costs of electric power and the "Pace University report" on the environmental costs of electricity. The results from these studies included impacts that had not been addressed in previous studies. The emphasis on social costs required that different impacts pathways be considered and it introduced the use of money as an impact indicator.

The range of results that have been reported for the external costs of the nuclear fuel cycle is from 0.1 to close to 100 mECU/kWh. This large range of results can be attributed to: (1) the different number of fuel cycle stages included in each assessment, (2) the methodology for the valuation of the health impacts, (3) the discount rate applied, (4) the inclusion of a global physical impact assessment, and (5) the methodology and assumptions used for the assessment of severe nuclear accidents.

One of the major disadvantages of these studies were that the boundaries of the assessments and methodologies applied varied between the different fuel cycles, therefore it was difficult to objectively compare the final results. The ExternE project set, as one of its main objectives, the goal of analysing different fuel cycles within the same consistent methodological framework in order to allow for direct comparison between fuel cycle options. Since the start of this project, a number of other projects have been initiated on the international and national levels.

8.2.4.6. Limitations of the Results

In attempts to include all impacts within a rather large time and space scale, the limits of valid assumptions have been stretched in order to be as complete as possible in the physical impact assessment. Current day conditions have been assumed to remain constant for 100,000 years - a truly unlikely event. However, with these assumptions it was possible to complete the assessment for the long-lived radionuclides.

No thresholds have been assumed in the calculation of the response to the doses received, so in many cases, the average individual doses to the public fall into a highly uncertain area of the dose-response relationship. The generally accepted collective dose approach, which integrates the average individual doses over the total population to be considered, was implemented. With this approach, the magnitude of the individual risk is masked when the results are presented. The most obvious drawback of this approach has been seen in the evaluation of the long-term global impacts of C-14, where the very small individual doses are summed to a large value over time and space. However, without this assessment, an important part of the overall potential physical impacts from the nuclear fuel cycle would not have been completed.

The assessment of a potential severe nuclear reactor accident was based on a risk-based approach. This methodology has not been accepted by everyone, however, it has been judged as an adequate basis for the calculation of the physical impacts within a range of uncertainty. This does emphasise the need for further methodological work to determine the additional social impacts and costs that have not been included in this type of approach.

Although there are limitations and uncertainties in the methods used for the assessment of the physical impacts, the key methodological issues that remain are for the monetary valuation stage. Before the monetary values of the impacts from the nuclear fuel cycle can be considered to be external costs the following issues must be addressed:

- If the same monetary valuation methodology is used for the evaluation of very small (and quite uncertain) individual risks to a large population and larger individual risks to a smaller population, does the final result really demonstrate the proper weighting of the real risks? Should occupational (voluntary) risks be valued in the same manner as risks to the general public (involuntary risks).

- If the use of a discount rate is not considered to be acceptable for the evaluation of far future impacts, what should be used in its place? The results of this phase of the project should be reviewed in order to determine how to provide a good representation of present day and far future risks.

- How can a method realistically incorporate the societal perceptions in terms of time and space keeping in mind the need for society to balance between the options available? For example, if C-14 is released today, it is diluted and results in low individual risks with no future disposal problems. If the releases are captured, waste repositories must be maintained causing increases in occupational risks and larger local population risks in the far future.

- How can the aversion of certain risks be equitably included in the assessment of external costs? This problem is clearly illustrated in the differences between expert and public perceptions of the risks of potential nuclear accidents and high-level waste disposal.

8.2.5. Conclusions

The systematic assessment of all the stages of the nuclear fuel cycle with a common methodology and the same boundaries has provided a good base of information with which to understand the health and environmental impacts of fuel cycle and preliminary assessment of the costs of these impacts. At this stage, no definitive evaluation has been made to determine to what extent the costs presented in this report are externalities.

In presenting these costs, care has been taken to indicate that they are considered to be a "sub-total" and are not intended to represent the absolute total of all the possible impacts. Within the constraints of available resources and existing methodologies, the priority impact pathways have been analysed. In some cases, the assumptions have been pushed to the limit of validity in an effort to be as complete as possible.

For nuclear accidents most of the work has addressed valuation of health impacts and costs of the countermeasures implemented to limit the possible health impacts. Further work is needed to better estimate some of the other social costs and the extent to which those costs can be considered to be externalities. More research is needed to continue to develop these ideas.

Even though some unresolved issues remain, this study has made important advances in reporting the physical impacts and monetary valuation of these impacts in a manner consistent with other fuel cycles. In addition, many remaining uncertainties in the methodology have been identified, and important parameters that should be considered in the decision making process.

Some key results are summarized in Figs.ES.4 to 6. Fig.ES.4 shows the damage cost for each stage of the nuclear fuel cycle, for three values of the discount rate. The average damage cost of the electricity generation routine operation is 0.44 mECU/kWh for discount rate = 0%. If the construction and the decommissioning costs are taken into account, this average value becomes 0.5 mECU/kWh. The total of the quantified costs (called "sub-total") in this figure is

2.52 mECU/kWh for 0% discount rate,
0.098 mECU/kWh for 3% discount rate,
0.054 mECU/kWh for 10% discount rate.

For comparison, the production cost of nuclear electricity in France is approximately 38 mECU/kWh (0.25 F/kWh) [MdI 1993], and the average retail price of electricity in France is 65 mECU/kWh (0.43 FF/kWh = 0.081 US$/kWh) [EdF 1994]. [14]

[14] The exchange rates are 1 FF = 1/6.585 ECU = 1/5.3 US$.

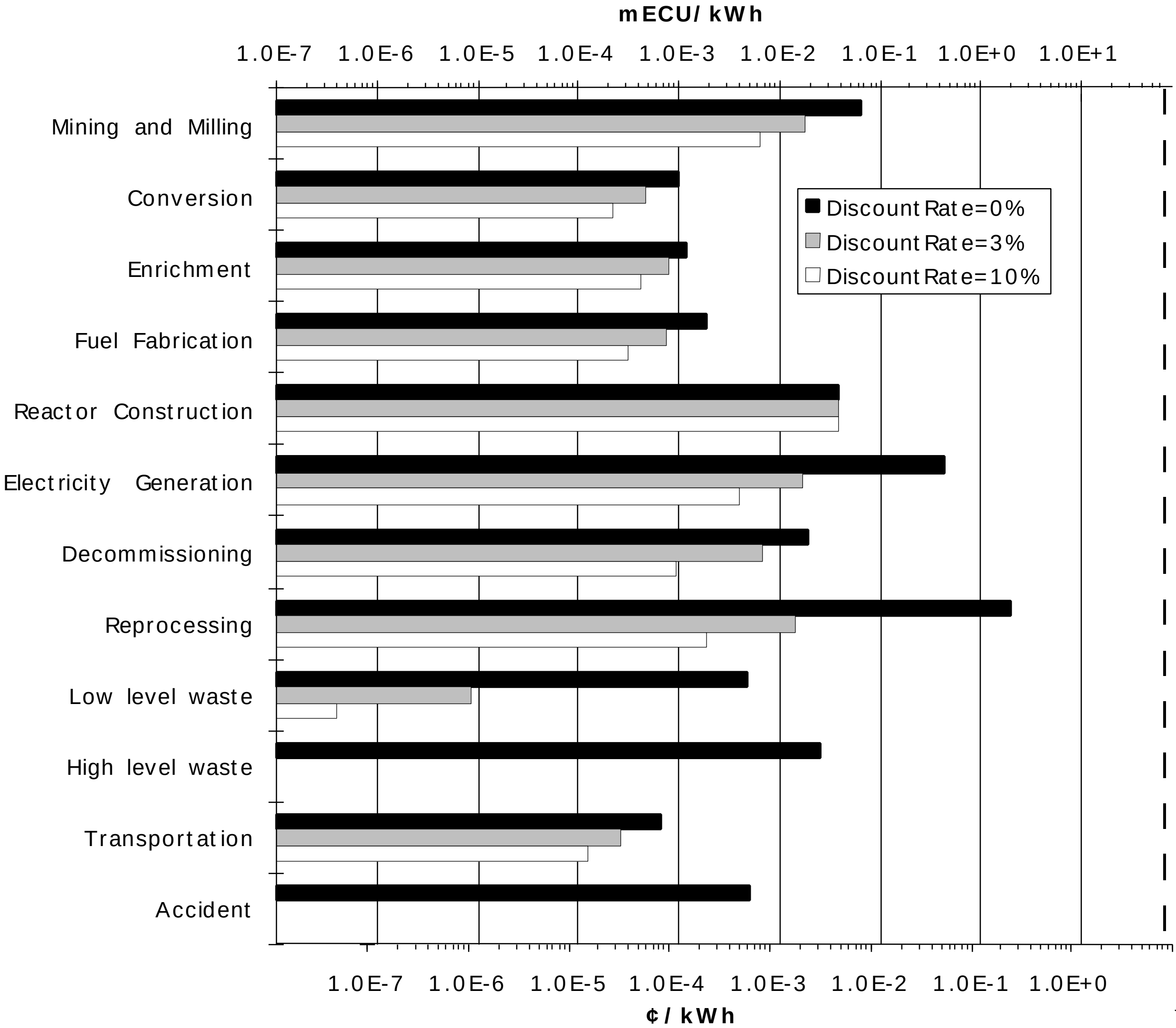


Fig.ES.4. Damage cost for the **nuclear** fuel cycle, by stage of cycle, for three discount rates: 0% (black), 3% (gray), and 10% (white).
Dashed line = average retail price 65 mECU/kWh (0.43 FF/kWh = 0.081 US$/kWh) [EdF 1994].

Also of interest is the breakdown according to occupational and public impacts. That is shown in Fig.ES.5, together with the breakdown by geographical scale. Over all, if no discount rate is used, the occupational impacts comprise about 5.5% of the total damage cost. This proportion increases to over 75% when a 3% discount rate is applied, and over 95% with the 10% discount rate, due to the more immediate nature of some of the occupational impacts.

Finally the sensitivity of the results to the electricity generation site is indicated in Fig.ES.6. The total damage cost for each of the sites are essentially the same except for Nogent due to the differences that are explained in Section 4.1.1.

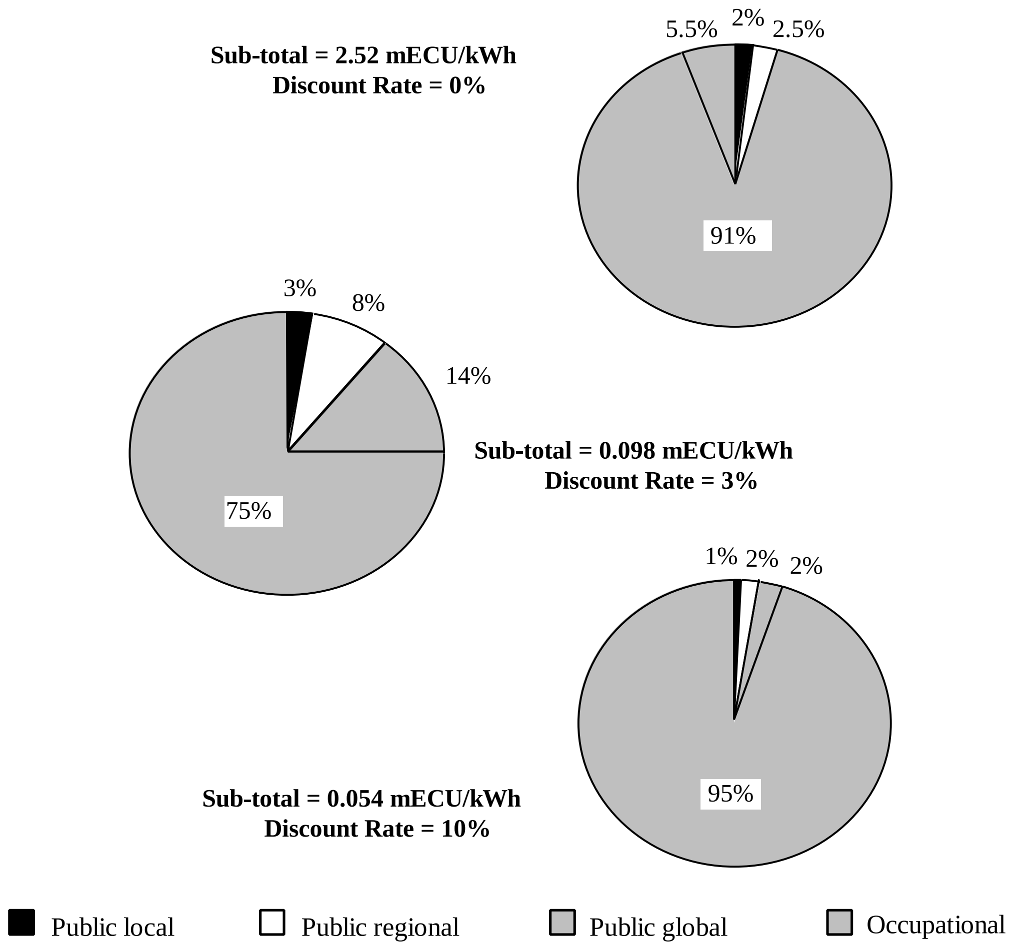


Fig.ES.5. Distribution of the damage costs for the 0%, 3% and 10% discount rates.

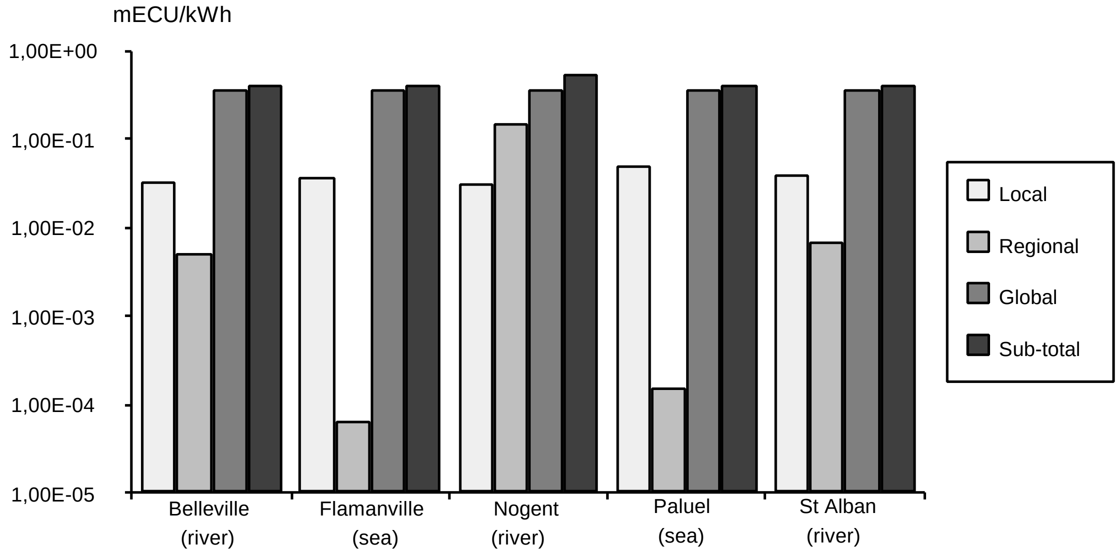


Fig.ES.6. Damage costs of electricity generation for the different sites (0% discount rate).

8.3. IMPLEMENTATION OF THE HYDROELECTRIC FUEL CYCLE FOR FRANCE

Below is the executive summary for the report:

Lesgards, V. (1995) "Assessment of the Externalities of the Hydro Fuel Cycle - Implementation in France," European Commission, DGXII, JOULE Program and US Energy Department, Final Report for contract JOU2-CT92-0080, External Costs of Fuel Cycles.

8.3.1. Introduction

The aim of the External Costs of Fuel Cycles study is to develop methods to measure and monetize all the externalities associated with incremental investments in electric power production, taking account of the different stages of the fuel cycles.

The Damage Function Approach (DFA) was selected by the study team as the basic methodology for assessing the social costs and benefits of fuel cycle.

ENCO, Environmental Consultants in Norway and Electricité de France (EDF) in France have taken on a joint responsability for adapting the methodological framework for hydroelectric fuel cycle analyses in Europe.

In France, in 1993, hydroelectricity contributed 15% to national electricity production (% of TWh produced), as against 75% for nuclear and 10% for conventional thermal (coal + fuel oil).

In the future, although the types of hydroelectric projects and technologies are not expected to change very much, the sites where the installations are to be located are, on the other hand, subject to evolution. The high fall sites (large dams in the mountains), economically viable, are practically all equipped for electricity production.

8.3.2. Description of the reference site and technology

The project decided upon consists of a series of 3 lock type dams, located on the river La Creuse, in the Limousin Region, to the northeast of the Central Plateau (Centre of France).

This type of dam crosses the river from one side to the other, blocks and limits the volume of water which can flow downstream. In back of the dam a small retention pond forms, corresponding to a short period of accumulation which makes it possible to stop the turbine operation during the least loaded hours of the day or of the week and to contribute their production during hours of full activity.

Environmental characteristics : The dams are located in a boxed-in part of the river, in natural gorges, leading downstream to the last dam in the plateau of La Celle Dunoise. From upstream (Champsanglard Dam) to downstream (L'Age Dam), the project extends over 30 km of the river.

In the initial state (before the development of the reference project), the river had the specific characteristics of fast water rivers, i.e. shallow, fast currents, good oxygenation and presence of populations of many invertebrates constituting the food base for the running water fishes (trout, gudgeon, barbel...).

Social economic characteristics : With its 723000 inhabitants, the Limousin region is one of the most thinly populated regions in France. The population density is approximately 43 inhabitants/km2, while the national average is 104 inhabitants/km2.

Technical and energy characteristics :

- Number of power stations :		3
- Capacity (at average total head) in total		20 MW
- Average annual electricity production (total)		51.3 Gwh
- Average energy equivalents (per dam)		0.037 kWh / m^3
- hydraulic capacity at total head (per dam)		45 m^3 / s
- Average total head (per dam)		20 m
- Reservoirs	- total volume :	8 millions m^3
	- total length :	11.3 km
	- total surface :	107 Hectares
- Transmission lines	- power :	20 KV
	- distance :	less than 10 km

These structures were built at the beginning of the 1980s, exclusively for the purpose of generating power

8.3.3. Differences from previous ExternE analyses

There are two main differences between the national implementations of the hydro fuel cycle in France (like in Norway; ENCO,1994) and the previous fuel cycle analysis :

1. A new site and project-specific valuation study was performed.

Since the impacts from hydro fuel cycle are very site and project specific, we decided to conduct a new application of the Travel Cost Method to evaluate the impacts on recreational activities of the plant.
Two surveys were conducted to obtain information needed for the valuation. A demand function for the service of the fast water river was estimated and transferred to the reference site. The value of consumer's surplus associated with the demand curve was finally computed. An uncertainty and sensitivity analysis of the results obtained was conducted.

2. Results of Environmental Impact assessment Study are used as basis for economic valuation.

The hydro fuel cycle is very different from the nuclear and fossil fuel cycle, where the burdens are dominated by radiation and atmospheric emissions.

For many of these burdens, general dose-response and dose-exposure functions from previous studies can be used to estimate the impacts.

Most of the burdens of the hydro fuel cycle are, however, not related to atmospheric emissions, but are direct burdens on aquatic and terrestrial ecosystems, e.g. alteration of river flows. The impacts of these burdens are very site-specific and it would be very difficult (and not pertinent) to construct general dose-response functions. In addition, a single impact might be caused by many burdens and it is often not possible to sort out what part of the impact was caused by what burden.

This is why the Norwegian and French teams suggested to replace the dose-response functions by estimates of Environmental Impact Assessment Study and by expert estimates. In the French study, the results of the Impact study on the reference project form the basis for economic valuation.

8.3.4. Analysis the impact pathway: identification of burdens and priority choices

Two stages of the hydroelectric fuel cycle have been identified :

1. electricity generation
2. transmission

There are three phases of each of these stages : construction, operation and safety unwatering (in general, no dismantling is previous in France).

The construction period was of 7 years (starting in 1979) and the operation period is at least of 50 years. Ten year unwaterings of retention ponds are carried out for safety reasons.

Table ES.1 gives the effects of origin, the receivers and the impact caused by generation and transmission (and for each stages) of electricity from the reference project, as well as a classification of the impacts according to their magnitude and therefore their priority character *(high, medium, low).*

The other notations used are :

- *absence of data* : the relation between the effect of origin and the impact is accepted but not quantified ;
- *not proven* : the relation between the effect of origin and the impact is suggested but not proven ;
- *negligible* : the impact is too low to be taken into account.

Table ES.1: Impact Pathways for hydro fuel cycle: effects of origin, receivers and impacts.

BURDEN	RECEPTOR	IMPACT	PRIORITY
I ELECTRICITY GENERATION **A. CONSTRUCTION** *building site*			
emissions of dust and materials into the stream -increase in matter in suspension and turbidity -	- fish species - drinking water producer - recreational activities	- reduction of fish - variation of producer surplus - losses of activities	absence data absence data absence data
emissions of dust into the air and noise from worksite vehicles and equipment	- public/worker - public/worker	- minor damages - major damages	negligible negligible
accidents due to construction of dams, roads, power plants	- workers	- minor injuries - major injuries	high low
building of roads (noise and emission)	- public - Wildlife/fauna	- improvement of access to recreational area -minor damages - occupation/ loss of lands - loss of housing	low negligible low absence data
creation of reservoirs	- public and recreational activities	-development of activities;	medium
visual intrusion	- public and recreational activities	- damages to the landscape	medium
flooding of lands	- agriculture - Wildlife/fauna	- loss of lands - loss of housing	low absence of data
obstacle to the drifting of	- Fish species	- loss of species	high

invertebrate and to spawning areas downstream,			
obstacle to boating	- recreational activities (kayak...)	- loss of activities	high
alteration of the flow of water : broadening of the stream bed and reduction of the current	- Fish species - Wildlife/fauna - recreational activities : kayak and fast water sports	- loss of species - reduction of biodiversity - loss of activities	high absence of data high

Table ES.1 (cont)**:** Impact Pathways for hydro fuel cycle: effects of origin, receivers and impacts.

BURDEN	RECEPTOR	IMPACT	PRIORITY
<u>B. OPERATION</u> variations of flows and levels of water downstream	- fish population - Wildlife/fauna - drinking water production	- loss of housing - reduction biodiversity - loss of producer surplus	high absence data low
variations of water levels in the reservoirs	- recreational activities - fish and birds species	- reductions of activities days - loss of housing	low absence data
risk of flooding (break in the dam)	- public - infrastructure - agriculture - drinking water production	- bodily injuries - damages to housing, roads... - damages to production - loss of producer surplus	low low low low
<u>C. SAFETY UNWATERING</u> degradation of the water quality downstream (content of sediment and matter in suspension)	- drinking water production - aquatic/fish ecosystem - public/ recreative activities	- loss of prod surplus - damages to ecosystem and fish species - loss of activities	low absence of data absence of data
drop in the water level in the reservoir	- ecosystem - recreative activities	- loss of species - loss of activities	absence data low
II POWER TRANSMISSION <u>A. CONSTRUCTION</u> accidents on building site	- workers	- injuries	low
noise - circulation	- public - ecosystem	- effect on attractiveness - loss of housing	low absence data
occupation of space	- agriculture - ecosystem	- loss of lands - loss of housing	low low
landscape / attractiveness	- public -recreative	- effect on attractiveness	low

	activities		
B. OPERATION electrocution	 - animal species (birds)	 - loss of individuals	 absence data

The main environmental impacts from the project are:

- fish populations,
- recreational activities,
- ecosystems (biodiversity),
- production activities (agriculture + drinking water),
- workers (building site).

8.3.5. Identification of priority impacts

Based on table ES.1 the following priority impact pathways were identified :

1. Impacts on health of workers due to the occupational accidents on building site;

2. Impacts of flow alteration, obstacle to the drifting of invertebrates and obstacle to spawning areas on fish species;

3. Impacts of flow alteration and obstacle to kayaking on fast water sports;

4. Impacts of flow alteration, flows and levels variations on ecosystem and reduction of biodiversity.

Notice that each priority impact pathways may cover two or more of the impacts listed in table ES.1. Some of the impacts are caused by several different type of burden, and in general it is difficult to sort out which part of the impact is due to which burdens.

8.3.6. Damages and benefits

Table ES.2. shows the result from the economic valuation of the impacts derived from the priority impact pathways. It also gives an overview of the other impacts, which have been discussed but not quantified in monetary unit.

Table ES.2: Damages (-) and benefits (+) of the hydroelectric fuel cycle for the Creuse hydro development (Champsanglard, l'Age, les Chezelles) in France. (1 mECU = 0.001 ECU)

Impact category	Damages (-) and benefits (+) (mECU / kWh)	Range of impact	Time of impact	partially or totally internalized
Occupational Health (construction / generation)	**- 0.027 (r=0) - 0.014 (r=3%) - 0.0055 (r=10%)**	**L**	**S**	**I**
Recreational activities (New Travel Cost Method)				
		L	**S**	**E**
kayaking	**- 11.69 (r=0)**	**L**	**S**	**E**
	- 6.01 (r=3%)	**L**	**M**	**E**
	- 2.315 (r=10%)	**L**	**M**	**E**
swimming	**+ NQ**			
fishing	**- IQ**			
Public Health (Dam failure)	**- NQ**	**L**	**L**	**E**
Ecosystem/biodiversity	**- IQ**	**L**	**S**	**E**

NQ = not quantified in this report, though some discussion of effects is given
IQ = impacts have been quantify but not valued
Each set of effects are classified according to the *geographical range* of the impact :

L = local (0-100 km)
R = regional (100-1000 km)
G = global (≥ 1000 km)

and the *time of the impact* :

S = short term (immediate)
M = medium term (1-100 years)
L = long term (100-100.000 years)

Notice that the time of impact is the time where impacts appear but it does not reflect the duration of the impact.
Some of social damages and benefits are already internalized. We introduce a simple notation :

I = effects already internalized
E = Externalities

r = discount rate based on 3 assumptions (0, 3 and 10%)

Table ES.2 shows that most impacts from hydroelectric development are local and immediate (which is different from both the nuclear and fossil fuel cycles). Most impacts are also persist during all the existence of the structures (dams and pounds). The figures in table ES.2. are not added up because many impacts have not been valued and because some of them are already internalized.

Two impacts out of four judged to have priority were economically evaluated. The estimation of the economic cost of working accidents made it possible to determine a measurement of the social cost to health caused by the building of structures. The application of the travel cost method made it possible to determine a general magnitude of the loss of a resource for kayaking and for fast water sports. The reduction of surplus is then estimated at 596,418 ECU per year (3,996000 Francs) , or 14 ECU (95 Francs) per visit to the site (1995 Francs).

Expressed in mECU of damages per kWh (Table ES.2) the social cost due to the loss of a resource for kayaking seems to be quite high (specially compared with other values of the ExternE studies). This is due to a) the specific impact for kayak and fast water sports (very few substitute sites far from the reference site...), and mostly b) by the low level of production of the hydro plants (51 Gwh per year).

The two other priority impacts which are the loss of fish populations (trout and fast water fish) through the impact on fishing activity, and the reduction of biodiversity have been estimated in physical terms (only the contingent evaluation would have made it possible to estimate a monetary value for this latter impact).

8.3.7. Conclusion

Although the Damage Function Approach is pertinent to estimate the priority impact pathways and to analyse the externalities of hydroelectric developments, it deserves however to be adapted to the hydro cycle. The most important modification is to replace the dose-response functions, traditionally used for thermal plants cycles (coal, uranium...) with other physical measures such as those supplied in France by Impact Study or to base oneself directly on the opinions of the experts (according ENCO, 1994).

The analysis of the impact pathways has made it possible to point out the various impacts of the project for each of the operations (construction, operation, safety unwatering), taking place at each step of the sector processes (power generation and transmission). Although hydroelectricity's impacts depend heavily on the technologies and on the sites where the structures are located, the selected priority impacts seem however to be relatively representative of the effects on the environment of this type of structure (in this type of location).