THE INTERNATIONAL ENERGY AGENCY – IMPLEMENTING
AGREEMENT FOR HYDROPOWER TECHNOLOGIES AND
PROGRAMMES

ENVIRONMENTAL AND HEALTH IMPACTS OF ELECTRICITY GENERATION

A Comparison of the Environmental Impacts of Hydropower with those of Other Generation Technologies

June 2002

OTHER TECHNICAL REPORTS IN THIS SERIES

HYDROPOWER UPGRADING TASK FORCE (ANNEX 1)

Guidelines on Methodology for Hydroelectric Turbine Upgrading by Runner Replacement – 1998 (available to non-participants at a cost of US $ 1,000 per copy)

Guidelines on Methodology for the Upgrading of Hydroelectric Generators – to be completed in May 2000.

Guidelines on Methodology for the Upgrading of Hydropower Control Systems – to be completed in 2000.

SMALL SCALE HYDROPOWER TASK FORCE (ANNEX 2)

Small Scale Hydro Assessment Methodologies – to be completed in May 2000 (available to non-participants on request)

Research and Development Priorities for Small Scale Hydro Projects – to be completed in May 2000 (available to non-participants on request)

Financing Options for Small Scale Hydro Projects – to be completed in May 2000 (available to non-participants on request)

Global database on small hydro sites available on the Internet at:
www.small-hydro.com

ENVIRONMENT TASK FORCE (ANNEX 3)

Survey on Positive and Negative Environmental and Social Impacts and the Effects of Mitigation Measures in Hydropower Development – 2000 (available to non-participants on request)

A Comparison of the Environmental Impacts of Hydropower with those of Other Generation Technologies – 2000 (available to non-participants on request)

Legal Frameworks, Licensing Procedures, and Guidelines for Environmental Impact Assessments of Hydropower developments – 2000 (available to non-participants on request)

Hydropower and the Environment: Present Context and Guidelines for Future Action
Volume 1: Summary and Recommendations
Volume 2 : Main Report
Volume 3 : Appendices
– 2000 (available to non-participants on request)

Guidelines for the Impact Management of Hydropower and Water Resources Projects – 2000 (available to non-participants on request)

EDUCATION AND TRAINING TASK FORCE (ANNEX 5)

(All of the following reports are available on the Internet at www.annexv.iea.org Some reports may consist of more than one volume.)

Summary of Results of the Survey of Current Education and Training Practices in Operation and Maintenance – 1998 (available to non-participants on request)

Development of Recommendations and Methods for Education and Training in Hydropower Operation and Maintenance - 2000 (available to non-participants on request)

Survey of Current Education and Training Practice in Hydropower Planning – 1998 (available to non-participants on request)

Structuring of Education and Training Programmes in Hydropower Planning, and Recommendations on Teaching Material and Reference Literature - 2000 (available to non-participants on request)

Guidelines for Creation of Digital Lectures – 2000 (available to non-participants on request)

Evaluation of tests – Internet Based Distance Learning – 2000 – (available to non-participants on request)

BROCHURE

A brochure for the general public is available. It is entitled “Hydropower – a Key to Prosperity in the Growing World”, and can be found on the Internet (www.usbr.gov/power/data/data.htm) or it can be obtained from the Secretary (address on the inside back cover).

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PREFACE

The International Energy Agency (IEA) is an autonomous body, established in November 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD). The IEA carries out a comprehensive programme of energy co-operation among 24 of the OECD's 29 member countries. The basic aims of the IEA, which are stated in the *Agreement on an International Energy Programme*, are the following:

- Co-operation among IEA participating countries to reduce excessive dependence on oil through energy conservation, development of alternative energy sources, and energy research and development
- An information system on the international oil market as well as consultation with oil companies
- Co-operation with oil producing and oil consuming countries with a view to supporting stable international energy trade, as well as the rational management and use of world energy resources in the interest of all countries
- A plan to prepare participating countries against the risk of a major disruption of oil supplies and to share available oil in case of an emergency.

At its inception, the IEA concentrated on issues related to oil. Since that time the Agency has broadened its work to include all forms of energy. More than forty «Implementing Agreements» have been set up to deal with specific energy technology issues. Such Agreements comprise a number of task forces, called "Annexes", which implement specific activities such as collection of data or statistics, assessment of environmental impacts, joint development of technology etc. The work of these Annexes is directed by an Executive Committee» consisting of representatives of the participating Governments.

In 1995, seven IEA member countries agreed to co-operate in a five-year research program focused on hydroelectric power formally called the *Implementing Agreement for Hydropower Technologies and Programmes*. Italy withdrew, but France, United Kingdom and People's Republic of China subsequently joined the remaining countries. This Agreement proposed that four distinct Task Forces ("Annexes") should be set up to address the following topics:

Annex I:	Upgrading of Existing Hydropower Facilities
Annex II:	Small-Scale Hydropower
Annex III:	Hydropower and the Environment
Annex V:	Education and Training

Annex III "Hydropower and the Environment" entered into force in February 1995 with the following principal objectives:

- To arrive at a set of international recommendations for environmental impact assessment of hydropower projects, and criteria for the application of mitigation measures.

- To improve the understanding of hydropower's environmental advantages and suggest ways to ameliorate its environmental drawbacks.
- To forward national experiences regarding environmental effects of hydropower development at a project level and the legislation and decision making process at a national level.
- To provide an environmental comparison between hydropower and other sources for electricity production.

To achieve these goals the following Subtasks have been implemented:

Subtask 1: Survey of the environmental and social impacts and the effectiveness of mitigation measures in hydropower development *(Subtask leader: NVE, Norway)*
Subtask 2: Data base (included in Subtask 1)
Subtask 3: Environmental comparison between hydropower and other energy sources for electricity generation *(Subtask leader: Vattenfall, Sweden)*
Subtask 4: Survey of existing guidelines, legislative framework and standard procedures for environmental impact assessment related to hydropower development *(Subtask leader: UNESA, Spain)*
Subtask 5 Present context and guidelines for future action *(Subtask leader: Hydro-Québec, Canada)*
Subtask 6 Effectiveness of mitigation measures *(Subtask leader: Hydro-Québec, Canada)*

From a scientific perspective, environmental studies are complex because of the many interactions in the ecosystem. In a subject area as wide as hydropower and the environment, it has been important to maintain the scope of the work within the limits imposed by the five-year time schedule and the available financial and human resources. However, several of the topics discussed are very extensive and complex, and as such, ought to have been handled with resources equivalent to an Annex. The main Annex III challenges have been to define the context and focus on the most important environmental and social issues. Two guiding themes have been the relation to government decision-making processes, and the need to ensure the highest possible level of credibility of the work.

Annex III is based on a case study approach combined with experience from a wide range of international experts representing private companies, governmental institutions, universities, research institutions, and international organizations with relevance to the subject. In all 112 experts from 16 countries, the World Bank (WB) and the World Commission of Dams (WCD) have participated in meetings and workshops. Additionally, 29 professional papers have been presented at the meetings. The participating countries are responsible for the quality control of the information given at the national level. Reference groups have been consulted in some countries.

Like all extraction of natural resources, the harnessing of rivers affects the natural and social environment. Some of the impacts may be regarded as positive; others are negative and severe. Some impacts are immediate, whereas others are lingering, perhaps appearing after several years. The important question, however, is the severity of the negative impacts and how these can be reduced or mitigated. The aspect of ecological succession is also of great interest. Through history, the ecosystems have changed, as a result of sudden disasters or more gradual adjustments to the prevailing weather conditions. Any change in the physico-chemical conditions seems to trigger processes that establish a new ecological equilibrium that matches the new ambient situation. Under natural conditions environmental change is probably more common than constancy. Ecological winners and losers, therefore, are found in natural systems as well as those created by man.

Even if the "fuel" of a hydropower project is water and as such renewable, the projects are often quite controversial since the construction and operation directly influences the river systems, whereby the adverse impacts become direct and visible. The benefits, like avoidance of polluting emissions that would have been the unavoidable outcome of other electricity generating options is, however, less easily observed.

Access to water and water resources management will be a very important environmental and social global challenge in the new century, because water is unevenly distributed and there are regional deficits. Dam construction and transfer of rivers and water abstraction are elements in most water management systems. The lessons learned from past hydropower projects may be of great value in future water resources management systems. If a regional water resources master plan or management system is available, then the development of hydropower resources could also contribute to an improved water supply for other uses.

It is necessary to underline that the Annex III reports discuss the role and effects of hydropower projects and how to improve their sustainability. They do not consider the increased energy consumption *per se* since this aspect is a national and political issue. Annex III has developed a set of international recommendations and guidelines for improving environmental practices in existing and future hydropower projects. One main conclusion is the necessity of an environmental impact assessment undertaken by competent experts and forming an integrated part of the project planning.

The Annex III reports have been accomplished based on a cost and task sharing principle. The total costs amount to USD 805 305, while the task sharing part had a budget of 93 man months. The reports which have been completed include 4 Technical reports (Subtasks 1, 3, 4, 6) with Appendices, one Synthesis report (Subtask 5) with Appendices and one Summary report presenting the recommendations and guidelines.

Annex III comprises the following countries and organizations: Canada (Ontario Hydro, 1995-98, Hydro-Québec 1995-2000), Finland (Kemijoki OY 1996-2000); Italy (ENEL 1995-98); Japan (CRIEPI 1995-2000); Norway (NVE 1995-2000); Spain (UNESA 1995-2000) and Sweden (Vattenfall AB 1995-2000).

Oslo 30 March 2000

Sverre Husebye
Operating Agent
IEA-Annex III

ANNEX III ACKNOWLEDGEMENTS

I wish to thank the Annex III team, their companies and experts for the support and constructive and professional participation during all these 5 years. The Expert Meetings and Workshops have been characterized by an open, friendly and informal atmosphere, which have ensured common understanding with regard to professional content and the decisions made. During the 11 meetings the work has progressed steadily, with no steps back caused by misunderstandings or unclear decisions. Special thanks go to the National Representatives, Subtask Leaders and the Annex III Secretary for their enthusiasm, co-operation and achievement. On behalf of all the participants in our meetings and workshops, I would like to express our appreciation to the companies which were our hosts: Vattenfall, ENEL, UNESA, CRIEPI, NEF, Kemijoki OY and Hydro-Québec..

The credibility of the Annex III work has been greatly enhanced by the contributions from the participating experts representing: Ethiopia, Indonesia, Laos, Nepal, Philippines and Vietnam. Japan and Norway supported their participation. All Annex III countries and companies are thanked for financing additional internationally renowned experts in specialized subject areas. This ensured that progress was maintained and credibility was enhanced.

I also wish to thank the professionals who have filled in the comprehensive questionnaires. The participation from the World Bank and WCD has inspired the Annex III team and contributed to the actuality of our results.

The Executive Committee members are thanked for their guidance, support and co-operation.

Even if all names are given in the review of the IEA-Annex III Organization below, I would like to draw special attention to the following persons due to their active participation and support over the years: Mr. Jens Petter Taasen (Annex III secretary and STL 1), Ms. Kirsti Hind Fagerlund (Annex III secretary and STL 1), Mr.Björn Svensson (STL 3), Mr. José M. del Corral Beltrán (STL 4), Ms. Cristina Rivero (STL 4), Mr. Jean-Étienne Klimpt (STL 5), Mr. Gaétan Hayeur (STL 6), Mr. Serge Trussart (STL 6), Mr. Joseph Milewski, Mr. Frans Koch (Executive Committee secretary), Mr. Luc Gagnon, Mr. Raimo Kaikkonen, Mr. Hannu Puranen, Mr. Mario Tomasino, Mr. Shuichi Aki, Mr. Jun Hashimoto, Mr. Tsuyoshi Nakahata, Mr. Kiyoaki Uchikawa, Mr. Yohji Uchiyama, Mr. Svein T. Båtvik, Mr. Rune Flatby, Mr. Geir Y. Hermansen, Mr. David Corregidor Sanz ,and Mr. Magnus Brandel.

Oslo 30 March 2000

Sverre Husebye
Operating Agent
IEA-Annex III

IEA - Annex III Organisation

Operating Agent:

Husebye, Sverre	1995-2000	Norwegian Water Resources and Energy Directorate (NVE), Norway

Secretary:

Taasen, Jens Petter	1997-2000	Norwegian Water Resources and Energy Directorate (NVE), Norway
Fagerlund, Kirsti H.	1995-1997	Norwegian Water Resources and Energy Directorate (NVE), Norway

National representatives:

Hayeur, Gaëtan	1995-1997	Hydro-Québec, Canada
Klimpt, Jean-Etienne	1997-2000	Hydro-Québec, Canada
Kaikkonen, Raimo	1996-2000	Kemijoki Oy, Finland
Aki, Shuichi	1995-2000	Central Research Institute for Electric Power Industry (CRIEPI), Japan
Husebye, Sverre	1995-2000	Norwegian Water Resources and Energy Directorate (NVE), Norway
Corral, Jose del	1995-1998	Hidroelectrica Catalunia, Spain
Rivero, Cristina	1998-2000	UNESA, Spain
Svensson, Björn	1995-2000	Vattenfall SwedPower AB, Sweden
Young, Christopher	1995-1997	Ontario Hydro, Canada
Tomasino, Mario	1995-1998	ENEL, Italy

Subtask leaders:

ST1 Survey of the Environmental and Social Impacts and the Effectiveness of Mitigation Measures in Hydropower Development

Taasen, Jens Petter	1997-2000	Norway
Fagerlund, Kirsti H.	1995-1997	Norway

ST2 Creation of an International Information Data Base Comprising Environmental and Social Impacts, the Effect of Mitigation Measures and the Licensing Procedures Related to World Wide Experience of Hydropower Development (Closed down in 1997, database included in ST1)

Young, Christopher	1995-1997	Canada
Yu, Margaret S.	1997	Canada

ST3 Environmental and Health Impacts of Electricity Generation

Svensson, Björn	Sweden

ST4 Survey of Exisitng Guidelines, Legislative framework and Standard Procedures for EA of Hydropower Projects

Rivero, Cristina	Spain
Corral, Jose del	Spain

ST5 Hydropower and the Environment: Present Context and Guidelines for Future Action

Klimpt, Jean-Etienne	Canada

ST6 Hydropower and the Environment: Effiectiveness of Mitigating Mesures

Trussart, Serge	Canada

Activity list Annex III:

Expert meetings and workshops

March 1995 - Montreal, Canada: :	**18 participants**
October 1995 - Rome, Italy:	**18 participants**

Case-study presentations

February 1996 - Stockholm , Sweden:	**16 participants**
October 1996 - Madrid, Spain:	**19 participants**

Presentations

Review of the national/provincial legislation in:

Canada	Young, Christopher	Ontario Hydro

Finland	Kaikkonen, Raimo	Kemijoki Oy
Italy	Tomasino, Mario	ENEL
Japan	Aki, Shuichi	Central Research Institute for Electric Power Industry
Nepal	Sudesh, Kumar Malla	Energy Development Centre
Norway	Flatby, Rune	Norwegian Water Resources and Energy Directorate
Spain	Rivero, Cristina	UNESA
Sweden	Svennson, Björn	Vattenfall SwedPower AB

General papers:

Kjørven, Olav, World Bank :Environmental Assessment at the World Bank: Requirements, Experience and Future Directions
Haagensen, Kjell, Statkraft: IEA program: Hydro Power and the Environment

April 1997 - Tokyo, Japan: 21 participants

Presentations

Sumitro, Sasmito, Indonesia: The Saguling Hydro Power Electric and Environment Aspects
Manolom, Somboune, Laos: Hydropower and the Environment Lao PDR
Benito, Francisco A., Phillipines: Hydropower Development and the Environmental Impact System in the Philippines
Xayen, Nguyen, K. X., Vietnam: Brief Review on Hydropwer situations in Vietnam

October 1997 - Venice, Italy: 21 participants

March 1998 - Rovaniemi, Finland: 20 participants

October 1998 - Manila, Philippines: 28 participants

Presentations

Merdeka, Sebayang, Indonesia: Environmetnal Aspects on Hydropower Development in Indonesia
Boungnong, Chanchaveng, Laos PDR: Socio-Environmental Impact Assessment of the Nam Ngiep 1Hydroelectric Project
Marasigan, Mario C., Philippines: Status of Mini-Hydropower Development in the Phillippines
Delizo, Tito D., Philippines: Tapping Private Sector for Small and Medium hydroelectricpower Plants in the Phillipines

March 1999 - Madrid, Spain: 25 participants
November 1999 - Paris, France: 19 participants

Technical Seminar

Escorial - Madrid, Spain 15-17 March 1999 55 participants

Presentations

Gagnon, Luc & Bélanger, Camille, Canada: Windpower: More Renewable than Hydropower?
Goddland, Robert, World Bank: What Factors Indicate the Future Role of Hydro in the Power Sector Mix? Environmental Sustainability in hydroprojects.
Henderson, Judy, South Africa: WCD-Strategy and Objectives
Husebye, Sverre, Norway: Status and Progress of the IEA-Annex III Work
Marasigan, Mario C., Philippines: Philippine Perspective: Hydropower and Rural Electrification
Nakamura, Shunroko, Japan: Recent River Ecosystem Conservation Efforts Downstream of Power Dams in a Densely Populated and Highly Industrialized Country: Japan
Oud, Engelebert, Germany: Planning of Hydro Projects
Roy, Louise, Canada: Ethical Issues and Dilemmas
Svensson, Björn, Sweden: A Life Cycle Perspective on Hydroelectric and Other Power Plants
Uchiyama, Yohji, Japan:Life Cycle Assessment For Comparison of Different Power Generating Systems
Pineiro, S.J.L., Spain: El libro blanco del agua en España

Subtask Leader meetings

July 1998 - Montreal, Canada
September 1999 - Montreal, Canada

Participants at the Annex III Expert meetings, Workshops and Technical Seminar (1995-2000):

Canada	Adams, Ken	Manitoba Hydro
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Canada	Egré, Dominique	Hydro-Québec
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Canada	Guertin, Gaétan	Hydro-Québec
Canada	Hayeur, Gaëtan	Hydro-Québec
Canada	Howard, M. Charles D.D.	Charles Howard and Associates Ltd
Canada	Kingsley, Tony	Canadian Electrical Association
Canada	Klimpt, Jéan-Étienne	Hydro-Québec
Canada	Koch, Frans	IEA-Hydropower Agreement
Canada	Lee, Walter	Engineering & Technical Support
Canada	Messier, Danielle	Hydro-Québec
Canada	Milewski, Joseph	Hydro-Québéc
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Canada	Roquet, Vincent	VR Associates Inc.
Canada	Rowsell, Jim	Ontario Hydro
Canada	Roy, Louise	Consensus Inc.
Canada	Trussart, Serge	Hydro-Québéc
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Canada	Yu, Margaret S.	Ontario Hydro
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Ethiopia	Shenkut, Gebresemayat	Ministry of Mines and Energy
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Finland	Kaikkonen, Raimo	Kemijoki Oy
Finland	Nuutinen, Jaana	Kemijoki Oy
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Spain	Cortés, Hernán	ENDESA
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	Goodland, Robert	World Bank
	Kjørven, Olav	World Bank
	Ziegler, Tor	World Bank
	Henderson, Judy	World Commission on Dams
	Haas, Larry	World Commission on Dams
	Skinner, Jamie	World Commission on Dams

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Ms. Gullbritt Malm made the necessary corrections to make the report ready for print.

Finally, I am indebted to the participants and experts in the IEA Hydropower Annex who have made a lot of contributions for the advancement of the report.

Stockholm 00-05-03

Björn Svensson
Sub-task leader

SUMMARY

This report describes the general characteristics of different ways of producing electricity in terms of their environmental impact. Some technologies are described in detail (coal, natural gas and biomass fuel cycles; nuclear power, hydroelectric power and wind power) whereas others (oil, geothermal and photovoltaic means of generating electricity) have been excluded due to time constraints. A so-called life cycle analysis (LCA) methodology has been used to compare different options, but also other means of making such comparison have been adopted.

Chapter 1 describes the life cycle analysis approach with particular reference to its application to energy systems. The systematising of impacts is described and the different impact categories are defined, namely: Use of non-renewable and renewable resources, respectively, as well as land and water; global environmental impacts, viz. climate change and ozone layer depletion. Local and regional environmental impacts include acidification, eutrophication, photochemical oxidant formation, and ecotoxical impact. Environmental aspects that cannot at present be adequately handled by LCAs include habitat alteration, impact on biodiversity and risks. Impacts on humans like health risks, socio-economic consequences, risk perception as well as aesthetic aspects and their possible estimate are also mentioned.

Chapter 2 provides a detailed description of the coal fuel cycle. This fossil fuel accounts for the bulk of electricity production in the World. The main drawback with the use of coal is the inevitable emissions of carbon dioxide to the atmosphere, which are higher for his fuel than for any other alternative. Other emissions are more easily controlled, and the use of the most modern techniques by virtue of their higher conversion efficiencies can cut the emissions considerably. But since the majority of coal-fired power plants represent old and less efficient techniques, average specific emissions of greenhouse gas will remain high, i.e. >1000 g CO_2 per kWh_{el}. Although coal represents a non-renewable energy source, the global reserves are unlimited for all practical purpose.

Chapter 3 treats natural gas, the most rapidly expanding fossil fuel used for electricity generation. Several factors contribute to its increased use of which the expansion of the pipeline distribution networks is the most important. Its combustion gives rise to less amounts of greenhouse gas, because the heat content is high relative to the amount of carbon contained in the fuel. Natural gas should be considered a clean fuel also in other respects, because it contains few hazardous trace substances.

Chapter 4 describes the nuclear fuel cycle. Nuclear power resembles strictly renewable electricity generation alternatives in terms of environmental performance. The emissions of greenhouse gases are for example low despite the fact that highly energy demanding methods of isotope enrichment are sometimes practised. The weakest point in the uranium fuel cycle is undoubtedly the handling of radioactive wastes, including the storage of spent fuel. The public perception of risk also weakens the environmental performance of nuclear power.

Chapter 5 provides an account of the environmental characteristics of using biomass for fuelling power plants. Since biomass is continuously and naturally replenished, this technology represents a strictly renewable energy source. In principle, biomass combustion does not give rise to net emissions of carbon dioxide, provided harvested land is managed in a proper way. Biomass can either be supplied as energy crops, in which case its production is identical to other kinds of agriculture. It can also be extracted as residues following the logging of forests for timber. In the latter case, a proper management can make biomass extraction almost environmentally neutral. The most outstanding feature of biomass burning is the relatively high land requirement. This also means that there is a limit to the distance that it is feasible to transport the fuel.

Chapter 6 gives detailed descriptions of the results from several LCAs on hydropower. Unlike most other means of producing electricity the environmental impacts following the construction of dams, creation of reservoirs and regulation of rivers, are easily observed and understood. Most effects are local although regulation of upstream reaches of rivers has consequences all the way down to the mouth or sometimes even far off the coast. One important conclusion from studies of different hydro projects is that it is not meaningful to try to characterise the environmental performance of hydropower in general terms. The variation between projects is very large for this technology. For example, specific greenhouse gas emissions vary between negative releases; i.e. the creation of an impoundment brings about a net increase in the sequestration of carbon, and releases that appear to come close to emissions from some fossil-fuelled power plants. There are also large geographic variations in terms of impacts on biodiversity.

Chapter 7 deals with wind power. Wind power makes use of a moderate amount of resources according to available LCAs. The establishment of windmills puts constraints on other use of the surrounding land, but localisation of the power plants is usually directed to windy sites that are naturally barren, such as coastal areas.

Chapter 8 presents some observations from studies of risk perception and attitudes to different energy options.

Chapter 9 compares the environmental performance of different technologies in Japan, based on LCA. The comparison includes estimates of electricity per unit area reclaimed as well as energy ratios, i.e. quotients between energy generated during a plant’s life and the amount of energy invested.

Chapter 10 presents the main conclusions of this report:

- The environmental performance of different power plants must be related to the total service that is provided, i.e. the production of electricity for its entire lifetime.

- It is clear that the local and regional environmental conditions determine the extent and sometimes even the direction of environmental changes as a result of the construction and operation of power plants. The differential capacity of ecosystems to withstand stress should be considered in assessments of environmental impact.

- In systems for energy supply where hydroelectric power accounts for the need for peaking power production, facilities that generate non-firm electricity shall share the environmental burden of hydropower.

- The size of different power stations often stands in reverse proportion to the specific consumption of natural resources, that is larger power stations often use fewer natural resources to produce a unit of electricity than do smaller ones. This inverse relationship tends to be particularly strong for hydropower.

- Most of the negative impacts of hydropower are easy to observe and quantify. There is no doubt that this means a problem when trying to compare different options because impacts that can be observed with the naked eye will probably be considered more serious than impacts that can only be predicted on theoretical and statistical grounds. Since the reservoir type of hydroelectric power transforms fairly large areas, comparisons with for example fossil alternatives must have the capacity to calculate land use changes caused by emission of pollutants.

- The differential perception of risks in connection with electricity generation options will likewise weaken the applicability of full chain cost analyses.

- Greenhouse gas emissions from renewable energy sources and from nuclear power, are much lower than GHG emissions from fossil-fuelled power plants. The controversy regarding emission of methane from man-made lakes in some tropical areas and temperate lowlands points to the need of an international research effort to study hydroelectric reservoirs in such areas.

1. INTRODUCTION

The goal of Subtask 3, Annex III of the IEA Hydropower Agreement, is to provide an overview of the environmental performance of different electricity generation options. The project has made use of available systems and models in order to compare the impacts of hydropower with those from other electricity sources.

The following sub-objectives were approved:

(1) To gather life cycle analyses (LCA) or life cycle inventories of hydropower projects.

(2) To collect and systematise existing studies that have been undertaken to compare the impacts of hydropower with those from other electricity sources.

(3) To assemble existing studies on the environmental and social impacts of other forms of electricity generation.

(4) To produce summary documents which describe and compare general social and environmental impacts of hydropower with those of other electricity sources. The impacts should be expressed as a function reflecting the diversity of environmental settings. The reports will refrain from discussions or comparisons of value judgements regarding the performance of other electricity sources.

This report is the result of this work.

The following forms of electricity generation included in this report are coal, natural gas, biomass, nuclear, hydro, and wind power. Most of these options can be further split into sub-categories based on the different technologies available for their utilisation or different sub-classes based on the more exact composition of the actual fuel (e.g. coal can be split into hard coal and brown coal with very different environmental impacts when the fuel is extracted and combusted).

Data compiled for this report derive from various sources. Of particular importance is the Life Cycle Assessment (LCA) data that have been gathered. Such data have been provided by participating countries but we have also used other LCAs, such as the study made by the Swiss Federal Institute of Technology (ETH) Zürich (Frischknecht, *et al.* 1994).

1.1 Means of comparing electricity supply options

The extraction of natural resources, manufacturing of goods and generation of various services that assist humans in their complex societies, and the resulting impacts on the ambient environment and intrusion on future options are not easily described. And yet, comparisons between different options in terms of their benefits and drawbacks are necessary in decision making. The most powerful tools for that purpose have the capacity to compress most important facts into one single measure that makes the comparison and resulting conclusion merely trivial. Unfortunately, such tools are still mainly theoretical constructions that are used in practical situations only exceptionally.

The “emergy analysis”, spelled with “m”, was formulated by Howard T. Odum (Odum 1996) to provide an instrument for such evaluations. Emergy is defined as the total amount of (solar) energy that is directly or indirectly required to generate a product or a service. It summarises a system’s history, i.e. records all the energies involved in the different processes that ultimately generates the goods or services. There is an interesting coupling between emergy and economics that makes the concept challenging to test and develop further. However, the use of the emergy concept is still mainly restricted to academic research activities. It has for example been applied to hydroelectric development in Thailand (Brown and McClanahan 1996) as well as planting of shrub for energy purpose (Hovelius 1997).

The “exergy” concept has been used for similar purpose, either solely or in combination with emergy (there are other concepts with essentially the same meaning). Exergy is the maximum work that can be extracted from a system when it goes towards the thermodynamic equilibrium with a reference state. Hence, “exergy” analysis is based on the laws of thermodynamics, taking into account not only the amount of energy generated but also the quality of this energy. In more or less closed technical systems, the exergy concept is straightforward and operative, c.f. (Bisio & Pisoni 1995). But its applicability on complete fuel cycles for the purpose of making comparisons between options still needs further development.

1.2 The Life Cycle Assessment approach

Life Cycle Assessment (LCA) is a technique for assessing the environmental aspects and potential impacts associated with a product from the cradle to the grave. All societal effects, especially environmental impacts, are evaluated for each step throughout the lifecycle. By delineating the individual components of the often complex environmental impacts, LCA can assist decision-makers and stakeholders in designing specific measures to reduce environmental burdens. This method constitutes a kind of bookkeeping by which to accurately describe the detailed track of the flow of material and energy used in the construction, operation and finally the scrapping of an electricity supply system. It also includes the manufacturing of its components, the possible extraction and supply of fuels as well as waste generated in these processes.

In order to make a fair comparison between the environmental performance of two or more electricity supply options one has to consider all the impacts and the total use of resources for each technology over its entire lifetime. It is also necessary to relate the measured variables to the total service provided during this period of time. For example, in order to compare the environmental impact from a wind power plant with that of a nuclear power plant, one has to take into account the fact that the output of electricity from a nuclear power station is probably much larger than from a single wind power plant. It is therefore customary to express impacts in relation to the total service provided. Thus, the specific contribution to the heating of the atmosphere is expressed as amount of greenhouse gas released into the air, usually transformed to carbon dioxide equivalents, per unit electricity produced, i.e. g CO_2-equiv./kWh. Even if impacts are calculated per unit of electricity produced (kWh) there are often features of power generation that might bring additional services to the system that are not accounted for. For example, the ability of satisfying demands for peaking power, that usually add particular burdens on the environment, is still not adequately handled in traditional LCAs.

The importance of LCA lies mainly in its ability to assist decision-makers in identifying measures to reduce environmental disturbance. LCA is particularly useful when applied to the manufacturing of consumer durable goods where it can assist in identifying and refining steps that pose a particular strong burden on resource use or the environment. However, LCA is also useful for evaluating the effects of large-scale technologies and services such as power generation and transportation systems.

Power plants and their support systems are made up of many discrete units, and it is necessary to inventory these parts in order to understand where the greatest impacts lie in the overall lifecycle of the facility. An LCA of a fossil fuel power plant includes the mapping of resource use and environmental impact of equipment such as boilers, turbines, condensers, feedwater pumps, pipes, as well as auxiliary and electric equipment. Nowadays, there is an international standard, ISO 14040, available that describes the principles for conducting and reporting LCA studies (International Organisation for Standardisation, 1998). The ISO 14040 LCA framework requires that the goal and scope of the LCA be clearly defined. It also requires that an inventory analysis (LCI) is performed that includes data collection and calculation to generate results that relates to the defined functional unit and the allocation of flows and releases. Regarding "the elementary flows associated with production of electricity, account shall be taken of the production mix and the efficiencies of combustion, conversion, transmission and distribution". The reporting of the LCA procedure shall be made so as to allow a full comprehension of all its details and possibly adjusted following a peer review procedure.

With respect to LCA on electricity generation it has so far been customary to stop after the LCI step (see below). It is also doubtful if there currently are any complete LCI on electricity generation that complies with ISO 14040, because the standard was established only recently.

The present report is a summary of some life cycle inventories on electricity production that have been carried out so far. The goal in this case is to concentrate on general features. It is limited to emissions of air pollutants including greenhouse gases, land use aspects and efficiencies. However, a comprehensive LCI on hydropower has been included to illustrate the principles, possibilities and limitations of the method. To understand the system boundaries and other limitations of the underlying studies it is necessary to consult the references.

1.3 Description of the LCA method

General description

LCA is often applied to consumer durable goods such as beverage containers, automobiles and home electric appliances. However, LCA is also useful for evaluating the effects of large-scale societal technologies and services such as power generation and transportation systems. Extensive resources are used every year to develop the social infrastructure that supports our life. With increased development and investment in public resources the environmental impacts on society from these systems have also gradually increased. In the future, ideal urban development will conserve resources and energy and maintain a balance with the natural environment. For this to occur, however, it is necessary to accurately analyse the resources and energy needs for construction and maintenance of new and existing developments and survey the environmental effects resulting from these systems. With this information it is then possible to complete the assessment portion of an LCA and weigh the different economic and environmental costs and benefits of different alternatives.

The term "social infrastructure" refers to the resources, including capital, which constitute the needs and their interdependencies in the human society. These include traffic and communication facilities, water supply and sewage facilities, energy-related facilities, agricultural, forestry and fishery facilities, cities and parks, educational, cultural and welfare facilities, and land conservation facilities (e.g. rivers and seashores). Unlike the general consumer durable goods, the infrastructure indirectly affects the life and activities of individuals and companies, and this impact is large. Also, unlike basic consumer products, the operation of these public facilities is complex. Most facilities are made up of many discrete units, and it is necessary to make inventories of these parts in order to understand where the greatest impacts lie in the overall lifecycle of the facility. For example, when completing an LCA for a fossil fuel power plant, it is necessary to investigate the resource use and environmental impact of equipment such as boilers, turbines, condensers, feedwater pumps, pipes, auxiliary equipment and electric equipment. In addition, it is also necessary to map the effects of less obvious components such as power plant buildings and fuel transportation, and waste disposal. Table 1.1 compares the characteristics of social infrastructure facilities and consumer durable goods.

Table 1.1 Social Infrastructure Facilities and Consumer Durable Goods

	Social Infrastructure Facilities	**Consumer Durable Goods**
Examples	Buildings, Ports and Harbours, Communications Facilities, Roads, Bridges, Railways, Airports, Utilities (Electricity, Gas, Water and Sewage Facilities)	Home Electric Appliances, Gas Equipment, Office Equipment, OA Supplies, Foodstuffs, Containers, Automobiles
Characteristics	- Facilities as stock - Available for public use - Difficult to export/import services - Made up of many products and/or services (large scale) - Long life (maintenance required)	- Direct service to individuals and companies - Mainly for use by individuals - Easy to export/import products - Single products (small) - Short life (expendables)

International Standard ISO 14040 describes the principles for conducting and reporting LCA studies. The ISO 14040 LCA framework requires: 1) definition of goal and scope, 2) inventory analysis, 3) impact assessment and 4) interpretation of results as shown in Figure 1.1.

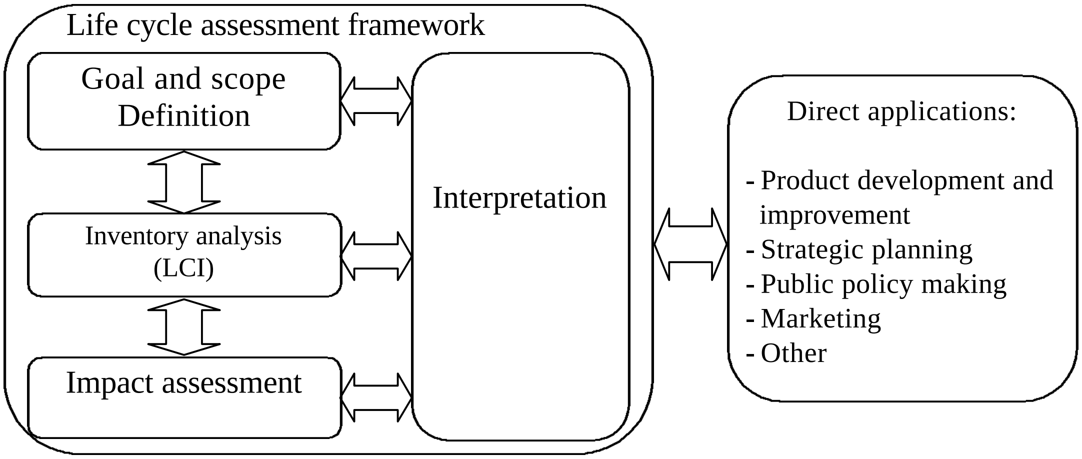

Figure 1.1 Phases of an LCA

LCA is a technique for assessing the environmental aspects and potential impacts associated with a product. The LCA phases are iterative in nature and many studies will undergo several iteration cycles. For example, inventory data collections need to be considered in the light of impact assessment results. This circular process of analysing the data and then assessing what follows from that interpretation is indicated by the bi-directional nature of the arrows between LCA phases in Figure 1.1. LCA results may be useful inputs to a variety of decision-making processes. Examples for applications of LCA, which are outside the scope of the International Standard, are illustrated in the Figure. Additional considerations such as social, economic and safety assessment, economic rates of return, technical feasibility, etc., are outside of the LCA framework.

The goal and scope definition identifies specific work objectives for the LCA phases. The following items shall be considered and clearly described as part of this LCA phase:

- the functions of the product system
- the functional unit
- the product system to be studied
- the product system boundaries
- allocation procedures
- types of impact and the impact assessment methodology
- data requirements
- assumptions
- limitations
- initial data quality requirements
- type of critical review, if any
- type and format of the report required for the study

The scope should be sufficiently well defined to ensure that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal. It should be recognised that an LCA study is iterative and various aspects of the scope may need to be modified in order to meet the original goal of the study.

An inventory phase precedes the actual analysis. The life cycle inventory analysis (LCI) is concerned with the data collection and calculation procedures for quantifying relevant inputs and outputs of a product system. These inputs and outputs may include the use of resources and environmental burdens such as air, water and land pollution associated with the system. The schematic diagram in Figure 1.2 illustrates a sample product inventory. These data also constitute the input to the life cycle impact assessment.

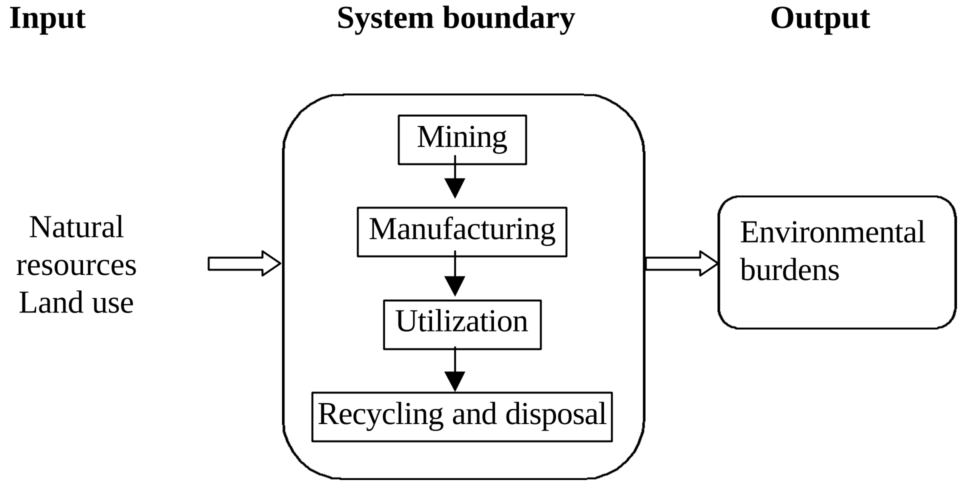

Figure 1.2 Inventory of a Product

The procedures used for data collection may vary depending upon the scope, unit process or intended application of the study. Allocation procedures and energy flow are significant factors to consider when collecting the quantitative data for the LCI. When dealing with systems involving multiple products such as gasoline, naphtha, kerosene, or heavy oil from petroleum refining, allocation procedures are needed in order to ensure that the materials and energy flows, as well as associated environmental releases, are assigned to the appropriate product. Energy flow calculations should take into account the different fuels and power sources used as well as the conversion efficiency and energy flow distribution.

Large amounts of process data are necessary to complete a typical LCI. Raw material use, energy use and environmental releases must all be quantified for each process step of the system. Often these data are not available from the literature, but companies and utilities will generally provide it. Sometimes site-specific data are needed for an inventory analysis of a project level study.

The LCI and the impact assessment phases of the LCA are interdependent. The impact assessment is intended to evaluate the significance of potential environmental impacts with respect to the results of the inventory analysis. The impact assessment is composed of three main elements:

- *classification*: assigning inventory input and output data to the impact categories
- *characterisation*: modelling inventory data assigned to impact categories to express the impacts in terms of numerical indicator for each category
- *valuation*: possibly aggregating the results and looking at the data while taking into account some aspects of public perception which may not correspond with scientific assessments.

Comparisons between different overall facilities or systems can be made by contrasting characteristics of individual components within the larger systems. Currently, a standard method for completing an impact assessment has not been developed, although fairly standard methods are accepted for completing the life cycle inventory.

The findings from the inventory analysis and the impact assessment are combined together in the interpretation phase. Using the findings from the interpretation of the LCI and impact assessment in conjunction with the goal and scope of the study decision-makers can develop conclusions and recommendations. The interpretation phase may involve the iterative process of reviewing and revising the scope of the LCA. A sensitivity analysis may also be employed at this stage.

LCA Methodology for Electricity Generation Options

Among social infrastructure facilities, power generation facilities often affect society the most in terms of energy consumption and environmental atmospheric impact. The LCA of an electric power generation system must address not only the power plants but also the entire system including the fuel cycle and power transmission and distribution. An example of an LCA analytical procedure is as follows:

1) Selection of the processes to be analysed

For a specific electric power generation system, the characteristics of the processes from fuel extraction, transportation, processing, generation, waste treatment/disposal and electricity transmission/distribution should be specified (Figure 1.3). It is best to analyse the entire process, however some assessors omit the electricity transmission/distribution process.

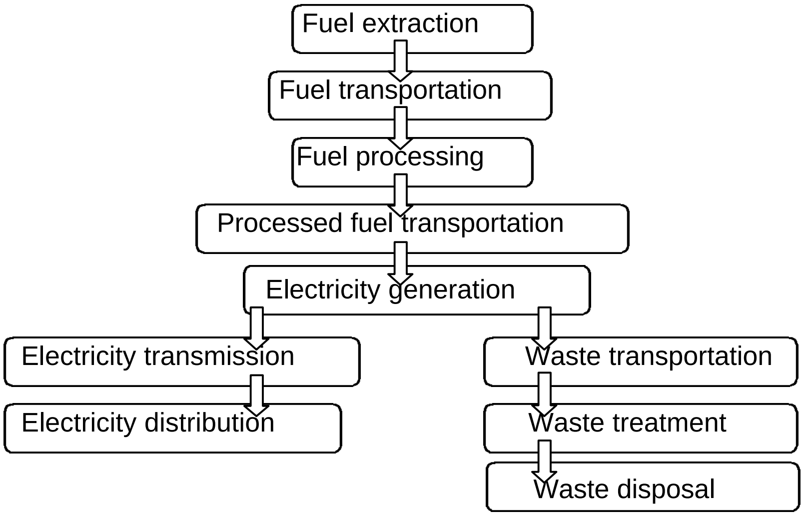

Figure 1.3 Energy Chain Processes of Electric Power Generation System

2) Inventory analysis

For each of the selected processes, the LCI data, such as information on the input materials and energy used throughout the life cycle and the environmental burden caused by equipment manufacturing, facility construction, operation and maintenance, and the dismantling of facilities, should be analysed in detail (Figure 1.4). To make the inventory analysis more accurate, it is desirable to examine the processes by dividing them into smaller units. For instance, the equipment and materials required by power generation facilities are manufactured through diverse industrial activities from ore extraction and refining to processing, assembly and transportation. Ideally, the amount of the energy consumed and the environmental burden produced in all of these processes should be analysed. However, the more detailed the scope of analysis, the more data must be collected. Data acquisition can be both difficult and time consuming. When assessing some complex processes it may not be necessary to analyse each distinct phase of the life cycle since some components may contribute little to the overall understanding of the costs and benefits.

For instance, when analysing CO_2 emissions produced by a coal fired power plant throughout life cycle, over 90% of the emissions are derived from coal combustion at the time of power generation. The CO_2 indirectly emitted through construction of the equipment used for coal extraction is less than 0.2% of all emissions. Therefore, there may not be a need to increase the analytical accuracy by including this term in the analysis. Yet, in order to obtain an informative estimate of the environmental effect of a coal powered plant it is essential to consider the CO_2 emitted by the fuel consumed and the fuel transported while operating the power plant.

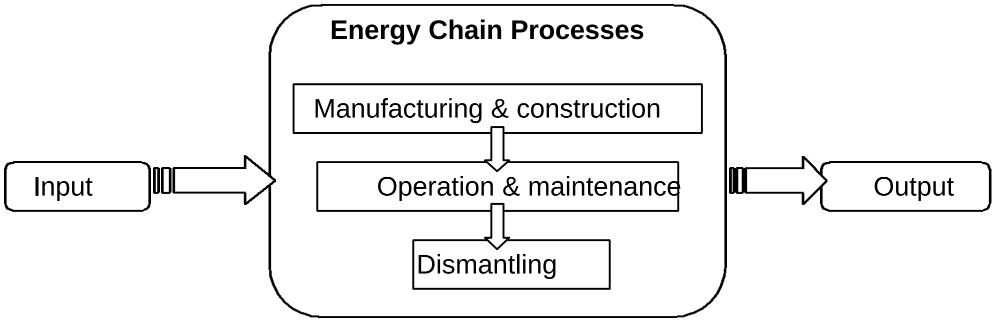

Figure 1.4 Inventory Analysis of Electricity Generation System

The kinds of inventories that are generated through input and output depend on the study targets. In general when completing an LCA for an electricity generation system, the input data include fossil fuels, minerals, water and land use. The environmental burdens that, in effect, are the output data include air pollution, water pollution, soil contamination and noise. Air pollution is further divided into carbon dioxide, sulfur dioxide, nitrogen oxides, hydrocarbons, carbon monoxide, particles, ethylene, CFCR22, hydrogen, etc. When water and soil pollutants are included, the number of environmentally harmful substances to evaluate becomes enormous. Therefore, data should be selected prudently based on the study targets.

In general, to complete an LCA it is necessary to add up all the pollutants generated, i.e. all deviations from an undisturbed state. For this reason, LCA has merit for use in analysing substances that are emitted in quantities that greatly affect the environment (e.g. substances that cause acid rain and ozone layer depletion). However, in the case of harmful substances discharged by a specific company, such as environmental hormones, it suffices to evaluate the emissions from that specific company and there is no need for LCA. In this case an LCA will not add additional information to help understand such a simple system. In addition, an LCA should not be used for pollutants, such as harmful substances, that affect the environment through their density, or noise. These should be assessed based on factors such as location and time.

3) Calculation of inventory values

The quantity per kWh is obtained by calculating the generated output that a power plant supplies to the society during its lifetime and dividing the value of each inventory item, such as the life cycle energy consumption and the environmental burden, by that value. The work so far can obtain the inventory per kWh of different electric power generation systems, therefore enabling comparisons of the amount of environmental burden. It is also possible at this stage to examine the methods for reducing the environmental burden caused by specific inventory items.

An electric power generation system manufactures energy as a produced good. Therefore, it is of value to analyse the system’s overall efficiency in terms of energy gained per unit of energy invested. By dividing the input energy by the output energy one gets the energy analysis ratio, that denotes this efficiency. An alternative means of expressing the same thing is to calculate the time lapse before a power plant has generated the same amount of usable energy that was required for its construction, maintenance and final dismantling. This, so-called pay-back time, is usually presented as number of months or years.

4) Impact Assessment

In theory, impact assessment converts the results from an LCI to a set of common impact measures such as mortality, habitat disruption, etc., that can be used to evaluate the total effect of the system in question. Impact assessment consists of three parts: classification, characterisation and valuation.

Classification involves identifying the inventory items of a system that are related to specific impacts (e.g. the inventories that affect global warming include greenhouse gases such as carbon dioxide, methane, nitrous oxide (N_2O), SF6 and CFC.). Studying the types of impacts produced from electricity generating systems in more detail shows that there are several different categories of impacts including: resource depletion, global warming or climate change, ozone layer depletion, acidification, eutrophication, photochemical oxidant formation, human health damage, other ecotoxic effects, etc.

The ultimate objective of an LCA is to assess the impacts of the catalogued inventory items on relevant natural resources and the environment as objectively as possible. One way to examine the environment and human activities is to divide the Earth into several spheres including: the atmosphere, the geosphere, the aquasphere, the biosphere and the technosphere. By TC 203 standards, the technosphere is defined as “all technical energy systems and products produced by them to extent that they have not been discarded as release”. The technosphere is a man-made sphere that functions to supply services. The technosphere consumes natural resources in other spheres and then releases substances in gaseous, liquid, or solid form back into the other spheres. The environmental burden from the technosphere is greatly damaging to the biosphere, which is made up of the portion of the other spheres (atmosphere, geosphere and aquasphere) that support human life (Figure 1.5). An impact assessment will quantitatively clarify and evaluate the environmental impacts that substances generated throughout the life cycle of the energy supply system have on the biosphere.

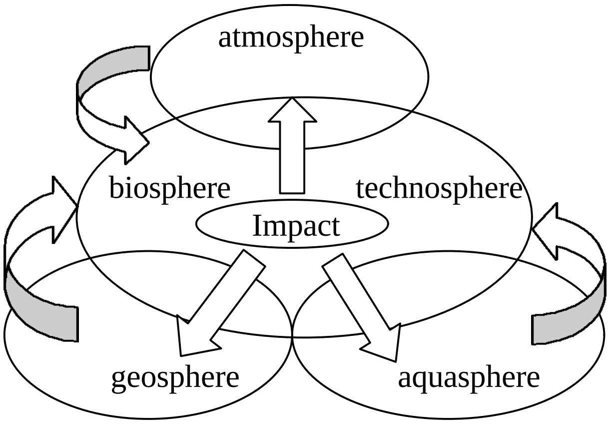

Figure 1.5 Impact among Different Spheres

5) Characterisation

Characterisation refers to quantifying the relative contribution to an effect that is exerted by a specific impact. For instance, in the case of global warming, characterisation requires clarifying the effects of each greenhouse gas. The emission of greenhouse gases contributes to global warming. The "global warming potential" of a green house gas depends on its atmospheric residence time and absorption properties. The longer the atmospheric residence time and the more efficient the absorption properties of a trace gas are, the larger the contribution to radiate forcing and climate change will be. The atmospheric residence times of the gases determine what the atmospheric build up will be over time. The absorption properties of the gases will determine the contribution to the radioactive forcing from the mixing ratios. Anthropogenic greenhouse gas emissions will add to the overall atmospheric concentration of the gas. And will also either immediately or after some time be involved in sink processes in the atmosphere.

Greenhouse gases have the property of absorbing and emitting thermal infrared radiation, due to rotation or vibration-rotation bands in their spectra. These radioactive properties are directly responsible for the greenhouse effect. Each gas is assigned an index describing the contribution to radioactive forcing from an emission of the gas taking into consideration the differences between the gases in atmospheric lifetimes and absorption properties. The index is defined as the Global Warming Potential (GWP) as established by the International Panel on Climate Change (IPCC). The GWP stands for the time integrated commitment to climate forcing from the instantaneous release of 1 kg of a trace gas expressed relative to that from 1 kg carbon dioxide. Its current value for a given gas is provided by IPCC (Houghton *et al.* 1996).

Therefore, through this characterisation process, global warming potentials can be assigned to each inventory item (gas) and therefore the overall contribution to global warming can be assessed for each process being evaluated. The next step, valuation, is needed to compare and contrast different energy producing alternatives based, in part, on the global warming potentials.

6) Valuation

The inventories obtained throughout the life cycle through classification and characterisation quantitatively represent their effects on the impact categories. Valuation is an attempt to weight to the different impact categories so that they can be compared. The problem here is how to assess the different impact categories. It is necessary, yet sometimes difficult, to assess the importance of one impact category, such as resource depletion, global warming or climate change, ozone layer depletion, acidification, eutrophication, photochemical oxidant formation, human health damage and ecotoxic activity, in relation to another. The methodological problems are still immense when comparing and valuing different impacts. For the time being and probably also in the future, it is ultimately the decision-makers together with other interest groups that make these valuations.

In essence, an LCA can break down a system into discrete steps so that significant impacts can be identified and scrutinised. LCA can assist in identifying places where a material or fuel substitution and/or an investment in product or technology development may make sound environmental sense. LCAs give decision-makers and stakeholders tools for identifying environmental harm and comparing alternatives for producing the same goods.

Function and Functional Unit

The systems' function is electricity production. The functional unit of 1 kWh (1 kWh = 3.6 MJ) electricity output from the power plant was chosen because it has been common practice to use this unit in the contexts of LCA. In addition, kWh is the unit that is most familiar to individuals since utilities make use of this unit when measuring household electricity consumption. In the categories 'accidents' and 'health risks' 1 GWa (GigaWatt and year) was chosen as the functional unit, as this is a functional unit commonly used in such contexts.

Impact Categories

The LCA method requires that impacts be categorised. However, not all important impacts can as yet be considered in life cycle analyses. They must nevertheless be mentioned and described in order to provide a full account of negative effects. Some impacts on the natural environment, such as influence on complex ecosystem functions are not easily identified or quantified, but also many potential impacts on human health are difficult to describe accurately and in quantitative terms. An overview of means of describing different impact categories is given in Table 1.2.

Table 1.2 Main impact categories and sub-categories and their respective assessment method in this report.

Use of resources	
Non-renewables	Life Cycle Impact Assessment (LCIA)
Renewables	LCIA
Land	LCIA
Water	LCIA
Global environmental impact	
Greenhouse effect	LCIA
Ozone layer depletion	LCIA
Local and regional environmental impact	
Acidification	LCIA
Eutrophication	LCIA
Photochemical oxidant formation	LCIA
Ecotoxic impact	LCIA
Habitat alteration	qualitative
Impact on biodiversity	qualitative, based on above LCIAs
Accidents	qualitative; statistics; quantitative risk assessment (QRA)
Impact on humans	
Health risks	QRA
Social and socio-economic impact	qualitative
Risk perception	qualitative; risk perception studies
Aesthetic impact	qualitative

1.4 Definition of impact categories and outline of the technical descriptions used in this report

Each major technology, i.e. fossil-fuelled thermal power production (coal, oil and natural gas), nuclear thermal and renewable options (biomass, hydro, wind and photovoltaic), is briefly described. Unfortunately it is not possible to provide a full account of the most modern facilities and their technical and environmental performance not the least because LCAs are not as yet available. The frame conditions of each power option also include a short description of the geographic perspective that might be relevant for the selection of a certain technology. Some economic considerations are also provided where this information is particularly relevant.

Use of resources

Non-renewables

Non-renewable resources are resources that do not regenerate themselves naturally, or that take a very long time to do so. To assess the relative value of the used non-renewable resources, the EPS-approach (Environmental Priority Strategies) has occasionally been used in this report (c.f. Steen & Ryding, 1992). Use of non-renewable resources is then valued in Environmental Load Units (ELU). One ELU corresponds to approximately one ECU. Weighting factors were calculated using the amount of known reserves and the current use (Lindfors *et al.*, 1995).

Renewables

Renewables are resources that are considered to be unlimited or restorable in a short time. Water, its inherent power potential and wood were the renewable resources listed in the ETH life cycle inventories (Frischknecht *et al.*, 1994). Land use is in this report handled separately, although land could be considered a renewable resource.

Land

Land can in some ways be considered as a renewable resource, as it can be used and altered but is not actually consumed. However, history has taught us that some human activities make future alternative use of land more problematic than others do. One way to assess the value of a piece of land is to consider what its present use is. In the ETH study, four different quality classes of land were defined:

- class I: natural (human influence since industrial revolution not bigger than influence of other species)
- class II: modified (human influence bigger than other species' influence, but mostly uncultivated, e.g. natural forest)
- class III: cultivated (human influence bigger than other species' influence, mostly cultivated, e.g. agriculture, fuel forest
- class IV: built (dominated by buildings, roads, dams, mines etc.)

Land use was assessed in land class change categories, e.g., building a road into agricultural land would change the land class from III to VI. Land change is given in m^2a (annual appropriation of a unit area), considering average time of use and time needed to re-cultivate the land. It was assumed that class IV land takes 5 years to be re-cultivated to class III land, class III land 50 years to be re-cultivated to class II, and class II 100'000 years to turn into class I land again. It would have been of great value to be able to adopt this or a similar approach throughout this report, but this was not possible.

Global environmental impacts

Climate change

The greenhouse effect means the absorption of some of the heat radiated from the Earth's surface by so-called greenhouse gases (water vapour, CO_2 and other compounds in the lower atmosphere). If the levels of, e.g., CO_2 in the atmosphere progressively increase as a result of human activity, it is thought that this will eventually increase the natural greenhouse effect and result in a rise of temperature in the lower atmosphere leading to wide-spread climate change.

In this report using Global Warming Potentials (GWPs) that was mentioned above assesses the effect of greenhouse gases on global warming. GWP might vary depending on the time horizon considered. In this report, a residence time of 100 years has been adopted throughout.

Ozone layer depletion

Ozone layer depletion is the destruction of the stratospheric ozone layer that shields the earth from ultraviolet radiation that is harmful to life. This destruction of ozone is mainly caused by the breakdown of certain chlorinated, brominated or other halogenated hydrocarbons. These compounds break down when they reach the stratosphere and then catalytically destroy ozone molecules.

The potential destruction of the ozone layer is in this report assessed by using Ozone Layer Depletion Potentials (ODPs) presented by the WMO (World Meteorological Organisation) in 1992. ODPs are weighting factors to assess the effect of gases on ozone layer depletion in terms of CFC-11-equivalents. ODPs are dependent on the atmospheric lifetime of the compounds, the release of reactive chlorine or bromine from the compounds and the corresponding ozone destruction within the stratosphere. The used ODPs are steady-state ODPs for a wide range of substances. For some substances, it may however take hundreds of years before the steady state ODP is reached. For HCFCs and many halons the time-dependent ODPs will for short-time periods be higher than the steady-state ODPs (Lindfors *et al.*, 1995). Thus the range of values using minimum ODPs and maximum ODPs is calculated in this report as well. Other compounds than the ones listed may also contribute to ozone layer depletion. Combined effects are very complex and not yet wholly understood. They are not included.

Local and regional environmental impact

Acidification

The environment can either be acidified by direct emissions of acids to aquatic or terrestrial systems or through a complex chemical reactions. Such reactions occur when emissions of sulphur and nitrogen compounds and other substances are transformed in the atmosphere, often far from the original sources, and then deposited on earth in either wet or dry form. The wet forms, popularly called ‘acid rain’, can fall as rain, snow, or fog. The dry forms are acidic gases or particles. Acidification is linked to adverse effects on aquatic ecosystems and terrestrial plant life, especially in areas with poor neutralising (buffering) capacity. Acids can also leach out poisonous trace metals from the rock matrix in the soil, thus causing damage to flora, fauna and humans. The effects are very site-specific.

Here an approach, in which the effect is defined as the amount of protons (H^+) released in a terrestrial system in SO_2-equivalents, is used (Lindfors *et al.*, 1995). The standard weighting factors adopted here are used calculate the maximal acidification potential. In addition, minimal acidification potentials are calculated.

Eutrophication

There are two main issues of eutrophication. The first is the adverse effect from a decline in dissolved oxygen levels in the aquatic environment. This can happen either when the introduction of a limiting nutrient (generally P or N) leads to increased growth of algae (sometimes leading to blooms of toxic species) and thus to more biomass, or when more biomass is introduced directly. The decay of this biomass may lead to a decrease in oxygen levels. The second issue of eutrophication is the fertilisation of terrestrial plants, due to the introduction of nitrogen species (NO_X, NH_3 or NH_4^+) (International Organisation for Standardisation, 1998).

Assessing the eutrophication potential is a difficult task, as the effects are very site-specific, i.e. dependent on the limiting nutrient (Finnveden & Potting, 1999). Here the maximum-scenario is used, in which it is assumed that all types of discussed emissions contribute (Lindfors *et al.*, 1995). Additionally, calculations on the eutrophication for N-limited and P-limited ecosystems are included.

Photochemical oxidant formation

Photochemical smog affects human health, as well as plants and animals. Its production is the result of a highly complex combustion or mineralisation reaction of organic materials in the atmosphere (volatile organic compounds, VOCs). The reaction occurs when the organic molecules are combined with NO_X. The active component is ozone, a by-product of the above reaction (International Organisation for Standardisation, 1998). For large parts of Europe, NO_X is expected to be more important for photochemical ozone production than VOCs. NO_X availability is thus a precondition for the formation of photochemical smog.

The emissions contributing to photochemical ozone formation are divided into two classes:

1. VOCs, aggregated with Photochemical Ozone Creation Potentials (POCPs) as weighting factors
2. Nitrogen oxides, aggregated as NO_X

POCPs are generally expressed in ethene-equivalents from the average of three trajectories in Europe (Lindfors *et al.*, 1995). It is assumed that VOCs released to water will later evaporate and thus contribute to photochemical oxidant formation too. Additionally, POCPs using minimal and maximal weighting factors are calculated.

Ecotoxic impact

In this sub-category all (e.g., carcinogenic, pathogenic) substances that can have a toxic effect on the environment, i.e. flora, fauna or humans, are aggregated.

Ecotoxicity is aggregated in three classes:

1. toxically contaminated soil
2. toxically contaminated water
3. radioactivity

Contamination of air is not considered in this approach.

For the first two classes, using the provisional ecotoxical method (CML) assesses ecotoxicity. In CML no consideration is given to the fate of the chemicals. The effect (weighting) factor is the inverse of the calculated 'maximum tolerable concentration' (MTC) for water (mg/m^3) or soil (mg/kg soil). The weighting factor for water is called ECA (ecotoxicological classification factor for aquatic systems) and for soil ECT (ecotoxicological classification factor for terrestrial systems) (Lindfors *et al.,* 1995). The product of the emission and the weighting factor gives the maximum potential amount of water or soil that could be polluted above the MTC. Emissions to air can either be washed out to soil or to water and emissions to water can be deposited on soil. Because of this, no difference was made, where the pollutants entered the environment. All emissions, i.e. those to air, soil, and water, were aggregated in order to assess the total maximal potential amount of water or soil polluted.

Toxicity calculations are only included where they have formed part of the original LCAs.

Total radioactivity was assessed at the time of emission. To get a more complete picture, decline of radioactivity over time should be assessed as well. However, this task was beyond the resources available for the production of this report.

Habitat alteration

Habitat alternation is addressed from three viewpoints: Change in local climate, geophysical change and change in aquatic systems, excluding indirect changes induced by impacts of all above impact categories. Possible alterations are reported qualitatively.

Accidents

In addition to environmental and health impacts arising during normal operation, account must be taken of the risks associated with potential severe accidents, particularly as these are accompanied by a considerable degree of public trauma and alarm. A severe accident is usually defined as an incident causing a certain minimum number of casualties. The studies used in this report set this number either at 5 or 10 casualties. Sometimes it would probably be more appropriate to use another definition which also take into consideration major accidents that do not lead to casualties, such as oil tanker catastrophes. Hirschberg & Spiekerman (1996) suggest the following definition:

An accident is considered to be severe if one or more of the following applies:

1. at least 5 casualties
2. at least 10 injured
3. at least 200 evacuees
4. extensive ban on consumption of food
5. release of hydrocarbons exceeding 10’000 tonnes
6. enforced clean-up of land and water over an area of at least 25 km^2
7. economic loss of at least 5 million US$

It is much more difficult to ascribe any single quantitative measure to compare severe accidents than it is to most other impacts. In the first place, severe accidents are comparatively rare events, which do not conform to any one pattern. Secondly, a number of immediate fatalities are not an adequate expression of the consequences of large-scale accidents affecting large numbers of people. Ideally, disasters should be described by: immediate fatalities and serious injuries; long-term health and psychological effects; all immediate economic damages; costs and consequences of social disruption, e.g. evacuation and resettlement; and ecological damage, with consideration to extent and reversibility (Roberts & Ball, 1996). This data is seldom available in full, and this report will concentrate on an assessment of past severe accidents and fatalities connected, and thus statistically try to assess accident risks.

It is clear that there are a number of problems connected with making generalised risk estimates from statistics. A single incident may change such risk estimates dramatically. When making risk estimates of a power option (e.g., hydro power) from world-wide statistics one also needs to take proper consideration to the specific local or regional conditions (e.g. geology, earthquake frequency, flood frequency distribution, dam type, technology etc.). Otherwise, the analysis will not deliver any useful data on the risk coupled to a single power plant and is thus not particularly informative.

Impact on biodiversity

Global, regional, as well as local environmental changes can have impacts on biodiversity. The cause and effect chains of impact on biodiversity by local and regional environmental changes can usually be far more easily assessed because they are much more direct. How much local and regional global impacts can influence biodiversity is strongly dependent on geographic circumstances. Impact on biodiversity due to global environmental changes, on the other hand, can be described independently of the geographical setting of an emitter. But here cause and effect chains are immensely more complex, which makes the assessment of the actual relevance of a single emission type much more difficult and the assessment of the relevance of a single emitter even more so. Thinking globally in terms of effects, as well as in terms of causes, is a prerequisite for the assessment of impact on biodiversity due to global environmental changes. This report tries to list the most outstanding impacts on the local and regional, as well as the global biodiversity, as the scientific community perceives them today.

Impact on humans

Health risks

Assessing health risks is a very complex task, especially when the whole life cycle is to be included. It is necessary to consider disparate health risks, ranging from those of acute mortality associated with construction activities to chronic risks of occupational and public disease. Estimation of some of these risks presents serious technical and philosophical challenges, which cannot always be met in full (Roberts & Ball, 1995). The risks of severe accidents are excluded here. They are dealt with in the category 'accidents'.

This report is based on the following studies:

- A profound British study (Roberts & Ball, 1995) assessed and compared occupational and public health impacts of seven electricity options for British standards, which can probably be applied to most OECD countries. It excluded many regional and global scale risk, e.g., associated with acidification and greenhouse gas emissions, as well as cancer risk by chemical carcinogens and risks arising from trace metal pollution and airborne particles.
- A German study (Thöhne & Kallenbach, 1988) compared different risk assessment studies, normalised them and adjusted them to (West) German conditions. It was remarked that neither of the evaluated studies included health risks due to emission of NO_X, trace metals and hydrocarbons or risks due to long term or global impacts, except radioactivity. The figures can only be partly compared to those of the British study, as severe accidents and injuries were included.
- Another German study (Fritzsche, 1989), in some respects a pioneer study, which served as a basis for many later assessments, listed acute and late (disease) occupational and public mortality risks of most electricity options. Effects resulting from the emission of greenhouse gases were excluded. Severe accidents were also excluded.

Risk perception

Impact Category

Experts usually try to assess risks of hazards by quantifying probabilities in a strictly rational way. The public's perception of these risks often differs greatly from such calculated figures, which has lead scientists to distinguish between 'actual' and 'perceived' risk. 'Actual risk,' as assessed by experts, is thought to be a precise measure of risk while 'perceived risk' is postulated by laypersons and is thought to be merely a distortion of 'actual risk' due to bias and lack of knowledge.

But there are several arguments, which show that it is seldom adequate to attribute all discrepancies between 'actual' and 'perceived' risk to public misconceptions. First, risk probabilities do not reflect hazard frequencies. They are always very rough and imprecise because of data lack and incomplete assumptions and models. Due to this, expert judgements are not always better. Moreover, experts are often overconfident, as their results are based on scientific methods. Secondly, experts in their expert roles primarily use probabilities and negative consequences when dealing with risks.

Laypersons, on the other hand, perceive risks with reference to many different attributes, such as controllability or catastrophic potential. These important aspects of hazards are not easily quantifiable. A third argument is that risk perceptions often affect risk probabilities and vice versa. If, for example, I perceive my chances of getting cancer as being high, then my perceptions can exacerbate stress and therefore increase the probability that I do actually become a cancer victim. Negative correlation is maybe more common: If I know something to be risky, I will take greater care when dealing with it and thus lower the risk. Finally, the distinction between 'actual' and 'perceived' risk is misconceived. The assertions typically called 'actual risks' inevitably contain some elements of judgement on part of the scientists that produce them. Thus, both scientific risk assessment and popular perceptions derive from judgements, the former made with the assistance of formal and sometimes reproducible methodology, and the latter elicited through more informal and perhaps broader cognitive processes. In other words, all risks are perceived risks. If a hazard is not perceived, then we don't know it, and if we know it, we also perceive it (Shrader-Frechette, 1990; Fischhoff *et al.*, 1981; Kates, Hohenemser *et al.*, 1985).

This leads to the conclusion that 'perceived risk' is not merely an erroneous misunderstanding or imprecise expression of 'actual risk' but that they are two different conceptions of risk (Thompson & Dean, 1996), both with their separate advantages and limitations, which shall be discussed briefly.

The public conception of risk

The main advantage of the public conception of risk is that it is more complete than the expert's conception. It not only takes into account the probability of mortality or morbidity, but also considers other important aspects of risk, such as catastrophic potential, how voluntary a risk is, whether a risk is certainly fatal, controllability, familiarity, equity, and possibility of long term consequences. Questions about moral principles and ethics are included in several of these aspects. Whether a risk is publicly considered to be tolerable or not often depends much more on the aspects listed above than on mere risk probabilities.

Of course, public conceptions of risk are also subject to a number of limitations. Most importantly, public risk perception is prone to be biased in several ways. There seem to be a number of very general inferential rules, known as heuristics, that people use when judging risks. One heuristic aspect that has a special relevance for risk perception is called availability. People using this heuristic judge an event as likely if instances of it are easy to imagine or remember. An implication of this is that discussion of a low-probability hazard may increase its perceived risk. Among other aspects, this leads to a systematic tendency to overestimate the frequencies of low-probability hazards and underestimate those of high-probability hazards. In addition, there are sizeable specific biases to overestimate dramatic and sensational causes of death and to underestimate unspectacular causes, which claim one victim at a time and are common in a nonfatal form. The role mass media plays in biasing risk perceptions is debated. Most risk researchers take an influence, which could be explained by the availability heuristic, for granted. But the influence occurs in the other direction too, i.e. people's opinions about what is important influence mass media contents. Newer research claims that even for heavy users, media are not a strong casual factor in risk perception. Another heuristic aspect that plays an important role in risk perception is overconfidence in judgements based on heuristics. Interpreting new data in a manner consistent with one’s prior beliefs is one consequence of such overconfidence (Slovic *et al.*, 1985; Wåhlberg & Sjöberg, 1997).

The expert conception of risk

A typical risk assessment expert’s definition of risk is that it is the ‘probability of a negative consequence (of an activity).’ To exemplify, a possible negative consequence of driving a car is to die in an accident. The probability of dying in an accident is the ‘risk of dying in an accident’ (Svenson, 1990). Such risks are often expressed in a relative scale, e.g., the probability to die in a car accident per km driven.

The advantages of expert risk assessments are well known: The expert conception of risk is mainly a quantitative one based on scientific methods like Quantitative Risk Assessment (QRA), Probabilistic Risk Assessment (PRA) or Probabilistic Safety Assessment (PSA). In QRA, PRA and PSA the risks that could result from a particular hazardous technological system are estimated from considerations of the likely failure rates of each component of the total system. Dose-effect threshold models are used to estimate the effect on human health from standard operation and accidents. Expert risk estimates are especially useful when comparing similar hazards and for identifying items that could or should be improved.

Nevertheless, there are several severe limitations to expert risk perception. Just like a layperson’s risk perception, an expert risk perception can also be biased and thus inaccurate. Experts seem to be less prone to be influenced by the availability aspect of heuristics, although they too tend to fail to appreciate the limits of the available data. Overconfidence is an aspect that more often biases expert judgements. Studies have shown that experts, as soon as they have to go beyond their data and rely on judgement, may be just as likely to be overconfident as laypersons. Some common ways in which experts may overlook or misjudge pathways are listed below (Slovic *et al.*, 1985):

- Failure to consider the ways in which human errors can affect technologies.
- Overconfidence in current scientific knowledge.
- Failure to appreciate how technological systems function as a whole.
- Slowness in detecting chronic and cumulative effects.
- Failure to anticipate common-mode failures that simultaneously afflict systems that are designed to be independent.

Conclusions

Public acceptance of an energy option in general or of a power plant in particular depends greatly on how the hazards of the technology are perceived (DeLuca *et al.*, 1986). Moreover, when fears are ignored, stress or psychosomatic effects can result. Thus, aside from being a complementary risk conception, perceived risk concerns could be considered as being a psychological part of human health. It is therefore wise to consider both conceptions of risk in order to get a complete picture of the health risks of a technology.

Methodology

The main items that contribute to the way the risks of each technology are perceived will be discussed qualitatively in Chapter 8. To compare risk perceptions of different electricity options, we will employ a psychometric paradigm study, carried out in the USA (Slovic *et al.*, 1985), and a study comparing risk and benefit perception, carried out in Austria (Thomas, 1981).

The psychometric paradigm study

In the late 70's Slovic *et al.* developed and carried out a number of psychometric paradigm studies. In this report we will concentrate on a survey among U.S. college students in 1979. The psychometric paradigm approach uses psychological scaling and multivariate analysis techniques to produce quantitative representations or 'cognitive maps' of risk perceptions. Within the psychometric paradigm, people make quantitative judgements about different risk characteristics of diverse hazards. Factor analysis of risk perception studies has shown that the broad domain of risk characteristics can be condensed to a small set of higher-order factors. These are mortality and morbidity probability, 'unknown risk', and 'dread'. As probabilities have been assessed in the categories 'accidents' and 'health risks', we will here concentrate on the two other main factors, 'dread' and 'unknown risk', which are made up of combinations of the following risk characteristics:

dread factor

controllable	-uncontrollable
not dread	-dread
not global catastrophic	-global catastrophic
consequences not fatal	-consequences fatal
equitable	-not equitable
individual	-catastrophic
low risk to future generations	-high risk to future generations
easily reduced	-not easily reduced
voluntary	-involuntary
does not affect me	-affects me

unknown risk factor

observable	-not observable
known to those exposed	-unknown to those exposed
effect immediate	-effect delayed
old risk	-new risk
risks known to science	-risks unknown to science

The mean results for the ‘unknown risk’ and the ‘dread’ factors are projected on the two-dimensional factor space, using an xy-graph (see Figure 8.1). The dread factor is projected on the x-axis, with dread increasing towards the right, and the unknown risk factor on the y-axis, with unknown risk increasing upwards. Thus, as one goes from the bottom to the top of the space, the hazards are judged to pose risks that are less well known, less voluntary, less familiar, and more delayed in effect. As one goes from left to right, the risks are increasingly characterised as dread and certain to be fatal, possibly for large number of people (Slovic *et al.*, 1985).

The risk-benefit perception study

The second study that will be examined closely bases on a survey of beliefs and attitudes of the general public towards the use of coal, oil, hydro, solar and nuclear energy. It was carried out in Austria in 1977 and 1978 at a time of increasing concerns with energy strategies and of controversies surrounding Austria’s first nuclear power plant (which was, as a result of these controversies, never put to operation).

A broad questionnaire on overall attitude objects, attribute evaluations and belief strengths was evaluated using several statistical techniques. The two most interesting results for our purposes are a frequency distribution of attitudes towards energy systems (see Figure 8.2) and the comparison of five risk and benefit belief dimensions for each energy system: economic benefit, environmental risk, indirect (future-oriented risk), technological development, and psychological and physical risk (see Figure 8.3). The underlying specific beliefs of these dimensions are the following:

economic benefit
good economic value
increased standard of living
increased employment
the industrial way of life
increasing Austrian economic development

environmental risk
air pollution
water pollution
production of noxious waste
making Austria dependent on other countries
exhausting our natural resources

indirect (future-oriented) risk
changes in man’s genetic make-up
increasing rate of mortality
(not) a technology that I can understand
formation of extremist groups
a police state

technological development

new forms of industrial development
new methods in medical treatment
dependency on small groups of experts
technical spin-offs
(not) exhausting natural resources

psychological and physical risk

accidents that affect a large number of people
exposure to risk I cannot control
rigorous physical security measures
hazards caused by human failures
hazards caused by material failures

As can be deduced from these belief dimension, health risk concerns stemming from routine operation are here considered a part of ‘environmental risk’ and not ‘physical and psychological risk’, as the name could suggest (Thomas, 1981).

Social and socio-economic impact

Producing electricity has a wide range of social impacts, many of which are closely related to local economics, politics etc. To try to assess all of these impacts is not an aim of this report, even more so as many of them are not immediately linked to processes of electricity production life cycles. Here only the immediate social impacts due to the construction of the power plant and its necessary infrastructure - the prime example is resettlement - will be discussed qualitatively. In the final study, the wider range of impacts should be discussed in each power option’s section dealing with frame conditions, which was omitted in this report.

Aesthetic impact

Electricity generation options have many potential aesthetic, i.e. visual and acoustic, impacts on human beings. Judging the relevance and size of these is a difficult issue, as aesthetic preferences vary across cultures and people. Nevertheless, this report will try to list the most important possible aesthetic impacts of the coal power and hydro power life cycles.

1.5 Data collection and accuracy

Life cycle impact assessments

For the first three main categories (Table 1.2) the life cycle impact assessment method (LCIA) is used to assess impacts. Data gathered in the inventory phase are generally of good quality. However, when interpreting results of different LCAs it becomes obvious that some factors have a too large influence on the overall result in relation to the certainty by which they are quantified. One such factor is the life expectancy. For hydroelectric reservoir dams, for example, the true life span is rarely known. At the same time, the dam and the flooding of the reservoir constitute the most significant structures in terms of resource use and environmental impact, so only small adjustments of the longevity would have a strong influence on the overall environmental performance.

Another problem that need to be resolved in future LCAs on energy supply systems is the differential emissions of air pollutants and their usually very different retention times. This problem have been specifically addressed in relation to methane emissions from some tropical hydro reservoirs by Rosa & Schaeffer (1995). Also emissions of radionuclides and their potential health impacts need further elaboration.

Risk assessments

The categories ‘accidents’ and the sub-category ‘impact on human health’ base on statistics and quantitative risk assessment (QRA). Nuclear power is the only energy system, for which quite many QRAs have been carried out, i.e. where accident risk assessments base not solely on statistics. Risk assessments for all other energy systems rely heavily on statistics. It is questionable how well these statistic conform to today’s technologies and frame conditions.

The discipline of quantitative risk analysis (QRA) has been increasingly used since the 1950’s to assess the likelihood of serious accidents, to describe the possible (human health) consequences and to assign probability figures to them. However, risk analysis is not an exact science and QRA is subject to several limitations, due to incomplete data, the imprecise allowance that has to be made for human error, and doubts over whether all accidents have been considered. The results are therefore subject to uncertainty and should best be expressed as a range of probabilities (Roberts & Ball, 1996).

Risk perception studies

Methodological

The use of verbal terms to represent technologies in the risk perception studies and the use of brief descriptions for obtaining impressions and evaluations of societal decision approaches suffer from possible methodological limitations. Responses to these brief verbal terms or descriptions may not be representative of reactions that occur in everyday life. Nevertheless, making the sets of hazards more specific (e.g., partitioning nuclear power into radioactive waste transport, uranium mining, and nuclear reactor accidents) has had little effect on the factor structure or its relationship to perceived risk probabilities (Slovic *et al.*, 1985; Buss *et al.*, 1986).

Geographical

Exposure to risk varies from country to country, depending on economic conditions, technological infrastructure, public health priorities, and natural hazards, among other things. Perceptions of risk are also likely to vary from one country to another, depending upon what the people choose to discuss, what the news media choose to report, what cultural norms are viewed as important, and what technical and political opportunities exist for the control of risk (Haddad & Dones, 1991). One study (Hoefer & Raju, 1989) indicates that American citizens generally perceive more risk than French citizens do, especially with respect to nuclear power generation. Another study (Englander *et al.*, 1986) shows that Americans also generally perceive more risk than Hungarians do. Hungarians tended to rank common, everyday risks higher than Americans did, who were more concerned about newer risks from chemicals and radiation. Thus, Hungarians also tended to rank most electricity options worse but the nuclear option better than the Americans did. Nevertheless, the Hungarian factor structure did not radically differ from the American one and the location of electricity options in the two-dimensional factor space also did not differ very greatly. In summary, it can be said that the factor space has been quite robust over different investigations and subjects.

Social

The factor space only shows the average risk perception of the studied groups (U.S. college students i.e. cross section of Austrian population). Of course, there are big differences in individual risk perceptions. It has been shown that risk perception is influenced by: knowledge, personality, political orientation, cultural biases, hierarchy, individualism, and egalitarianism. It has also been suggested that risk perception is a social process: Individuals choose what to fear to support their preferred way of life. Women seem to generally perceive more risk than the men do (Hoefer & Raju, 1989; Dake & Wildavsky, 1989).

Temporal

Risk perception will vary with time and available information. How these variables could have influenced risk perceptions since the studies have been performed and how they might do so in the future is out of the scope of this compilation. As the studies used here are already rather old (1977-1979) and much scientific research on impacts of technology has been done recently, it is well possible that perceptions of risks have changed substantially since. Newer data would be welcome and may present a better picture of current public risk perceptions.

Qualitative assessments

The categories ‘habitat alterations’, ‘impact on biodiversity’, ‘social and socio-economic impact’, ‘aesthetic impact’ and partly ‘risk perception’ describe impacts qualitatively, partly because quantification is not practicable, and partly because no quantitative data exists. In this report, it was tried to include all relevant aspects. In order to do this, a wide range of literature was reviewed and experts were consulted.

2 COAL POWER

2.1 Frame conditions

Coal is the raw fuel that provides 42% of the world's electricity (Maden & Mole, 1996). This distinguishes coal as the world's primary energy source for electricity generation. In 1997, China, the United States, India, Australia, and Russia together produced 68 percent of total amount of coal mined world-wide (U.S. Department of Energy, 1999).

The name coal refers to a family of solid, organic fuels with different properties. Coal is mainly composed of elemental carbon and is formed by the conversion of deposited organic (primarily plant) material. In most cases this transformation takes place under water. The lowest grade of coal formed is peat. Under the influence of high pressures and temperatures, peat is, with time, transformed to lignite. Lignite is subsequently transformed to sub-bituminous coal, bituminous coal and finally anthracite. This chain of conversion also implies that the original organic matter is gradually converted to higher grades of coal that have increasing elemental carbon contents. The environment of formation thus plays a role in determining coal quality. For example, coal with a lower sulphur content is considered to be of higher quality since it burns cleaner. Coal formed in a marine environment has higher sulphur content than coal formed in a non-marine environment. As coal is transformed to higher grades, the percent carbon increases and the water content is reduced. Consequently, the energy content increases, as well. Therefore, the use of Anthracite and bituminous coals for energy production is much more environmentally benign than burning lignite.

Normally a distinction is made between hard coal and lignite in terms of energy potential. Hard coal is defined as coal with an energy content greater than 23.8 MJ/kg on ash-free dry weight bases (Van Engelenburg & Nieuwlaar, 1992). Hard coal consists of anthracite, bituminous coal and some sub-bituminous coal. Lignite and sub-bituminous coals with a heat content of less than 23.8 MJ/kg, on ash-free weight basis, are often referred to as brown coal. In the UCPTE[1] countries, a substantial portion of coal power is fuelled by brown coal. Consequently, the authors of a Swiss study (Frischknecht *et al.,* 1994) have differentiated between two sub-categories of coal power: brown coal power and hard coal power. This report will utilise these coal power sub-categories throughout.

The coal power lifecycle is summarised in the schematic diagram below. In general, the combustion of coal gives rise to the majority of coal related emissions, but substantial quantities of particulate emissions are also produced during coal mining, processing and transport.

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[1] Union for the Coordination of Production and Transmission of Electricity, i.e. Belgium, Germany, Spain, France, Greece, Italy, Slovenia, Croatia, Federal Republic of Yugoslavia, Former Yugoslav Republic of Macedonia, Luxembourg, The Netherlands, Austria, Portugal and Switzerland.

Technology

Using coal to generate power or heat is an old technique. Therefore, the technology is conventional and well proven. Below are descriptions of some of the main technologies in the coal power generation lifecycle.

Mining

In the USA, Canada, South Africa and Australia, coal is mined by the room and pillar method. When using this process large amounts of coal are left in the mine as pillars to support the roof. In European and American mines, line mining (or long-wall mining) is often used. During line mining the coal is extracted along a section up to 250 meters in length while hydraulic shields support the roof. The shields are removed as the milling machine continues along the coal seam and the roof slowly subsides behind. This method allows for more complete recovery of the coal than possible with room and pillar mining. In Canada, the USA, Australia and elsewhere there are also open cast (or open pit) mines. The technique used there is similar to other mining activities that occur on the land surface (Swedish State Power Board 1983). In the eastern USA a process called Mountaintop Removal Mining is practised where entire hilltops are removed by enormous drag lines to expose one or several coal seams for recovery. This process is quite controversial due to the extensive environmental effects caused by depositing large quantities of overburden material in stream and valley fills.

Transports, handling and storage

Coal is expensive to transport compared to its market value. Exported coal is often transported by ship to re-loading harbours and then on to import-harbours. From the import-harbours smaller boats, trains or trucks transport the coal to storage areas or to the consumers. The coal is often stored (Swedish State Power Board, 1983) in large piles in open areas. Generally barriers or water sprinkling systems are used in coal storage areas, during loading operations and at conveyor transfer points to prevent wind from spreading coal dust, but some dust is usually present unless the coal is stored in an enclosed warehouse with a roof.

Enrichment

Coal is enriched in order to lower the content of impurities such as ash, sulphur and trace elements. Several methods can be used to enrich the coal. These include: 1) methods based on density differences (e.g. ash minerals have a higher density than coal), 2) methods based on magnetism (many impurity compounds are paramagnetic), and 3) methods based on chemical properties (such as sulphur oxidation). Mining companies attempt to produce coal with an ash content of 10-15 %. The most cost-effective way to enrich coal is to reduce the ash content. Methods to lower the sulphur content of coal are not commonly used today due to a lack of sulphur emission regulations in most countries (Swedish State Power Board, 1983).

Combustion

The oldest and most well proven technique for coal burning is a method that utilises a grate boiler. In this process, the burning bed of coal rests on a grid, called a grate, and the boiler is continuously supplied with air. Grate boilers have a low efficiency, but they are reliable, simple and not very sensitive to coal quality. Pulverised coal firing is commonly used in larger plants today. This technique is simple and optimal combustion of the fuel can be achieved. In addition, with pulverised coal firing the plant can safely and rapidly react to the load demand. Coal firing in a fluidised bed is a modern technique. In this method, the fuel is mixed with incombustible material, e.g. sand or limestone. When air is blown through the bed the particles are loosened from each other under a temperature of about 850°C which allows for a fairly complete and efficient combustion of the fuel. The advantages of the fluidised bed are that 1) the bed can be fed with limestone to lower the emission of sulphur, 2) the use of lower combustion temperature reduces the tendency to form nitrogen oxides (Swedish State Power Board, 1983) and 3) the boilers are able to satisfactorily utilise different qualities of coal.

Advanced Coal Technologies

Traditionally, the burning of coal has been used to produce heat and the technology has therefore adapted towards this use. Today, coal is a major source of world electricity and therefore there is an interest in developing new techniques that will produce higher electricity generating efficiency.

Currently, more efficient coal burning technologies are available. Advanced, high-efficiency coal plants and co-generation systems improve efficiency and therefore reduce CO_2 emissions per unit of produced electricity. Target efficiency values for these advanced technologies are 45% for an Integrated Gasification Coal-fired combined cycle (IGCC) plant and 55% for a Coal Gasification Molton Carbonate Fuel Cell Combined Cycle (IG-MCFC-CC) plant (Uchiyama, 1994).

One example of an IGCC plant is a test project operated by the U.S. Department of Energy called the Piñon Pine IGCC Power Project in Reno, Storey County, Nevada (U.S. Department of Energy, 1999). The plant was dedicated in April 1998. At the Piñon Pine plant an air-blown pressurised fluidised-bed gasifier is loaded with dried and crushed coal and limestone. The limestone reacts with the sulphur in the coal to form calcium sulphide, a removable landfill product. The limestone also helps to prevent the conversion of nitrogen (in the coal) to ammonia. After leaving the gasifier, the gas is cleaned with a hot gas system. This system removes virtually all of the particulate matter (with ceramic candle filters) and sulphur (by reaction with metal oxide). The cleaned gas then enters the combustion turbine. The generator connected to the turbine is designed to produce 61 MWe. Then a heat recovery system used the exhaust gas to produce steam that drives a steam turbine-generator designed to produce about 46 MWe (U.S. Department of Energy, 1999).

The NO_x emissions are reduced by 94 % (0.069 lb/10^6 Btu) and SO_2 emissions are reduced by 90% (0.069 lb/10^6 Btu). Currently, the Piñon Pine plant uses 880 tons/day of coal and generates 107 MWe (gross), or 99 MWe (net). The coal is supplied from

Southern Utah and has a relatively low sulphur content (0.5-0.9% sulphur) (U.S. Department of Energy, 1999).

Future plants based on this design are expected to have a net heat rate of 7,800 Btu/kWh (43.7% efficiency). This design is expected to produce an approximately 20% increase in thermal efficiency as compared to a conventional coal plant with a scrubber (U.S. Department of Energy, 1999).

Geography

Coal is the most abundant fossil fuel on earth and world-wide coal reserves are estimated to last far into the future. A 1995 estimate predicts that proven coal reserves will last for 235 years at 1995 production levels (Anonymous, 1995).

According to the United States Department of Energy, the production of coal declined by 16 million short tons between 1988 and 1997 (U.S. Department of Energy, 1999). In 1997, China produced the most coal with 1.55 billion short tons followed by the United States with 1.09 billion short tons, India with 329 million short tons, Australia with 293 million short tons, and Russia with 288 million short tons (U.S. Department of Energy, 1999). For coal consumption in 1997, China ranked first. China consumed 1.53 billion short tons, followed by the United States with 1.03 billion short tons, India with 342.45 million short tons, Russia with 284.24 million short tons, and Germany with 277.33 million short tons (U.S. Department of Energy, 1999). Coal production summaries by region are listed in Table 2.1. The main hard coal exporting countries are Australia, the USA and South Africa, whereas Japan imports the most coal. Germany is the world's largest producer of brown coal (International Energy Agency, 1996). Not all of the produced coal is for electricity generation. Much of it is used in the steel industry. Coal is also used for heating households.

Table 2.1 *World Coal production and consumption, 1997 (Million short tons) (U.S. Department of Energy, 1999)*

Region	*Production*	*Consumption*
World Total	5,218.35	*5,269.21*
North America	*1,186.97*	*1,101.61*
Central & South America	*48.56*	*35.06*
Western Europe	*526.68*	*708.72*
Eastern Europe & Former USSR	*840.92*	*821.45*
Middle East	*1.32*	*11.40*
Africa	*251.11*	*183.72*
Asia & Oceania	*2,362.78*	*2,407.25*

About 90% of the coal produced world-wide is consumed in the region where it is produced (International Energy Agency, 1998). However, the environmental emissions related to the transportation of coal are still high. Most of the coal mined in China, for example, is consumed within this country. Due to the largely non-overlapping geographical distribution of coal resources vs. production and consumption in China extensive transportation is required. The south-eastern region of China has a high rate of coal consumption but few resources, while the north-western side has a low rate of consumption and plentiful coal resources (International Centre for Energy and Environment Technology, 2000).

The Chinese economy has developed very rapidly in recent years. The energy demand is higher than the energy produced and statistics indicates that the deficit of electricity is 20 percent (Kang 1998) Currently, coal is the main electricity generating resource in China, and the use of coal power as the primary source of electricity is expected to continue. There is currently no alternative to coal in terms of the energy needs it has capacity to satisfy. In 1990, the total installed power capacity in China was 137,890 MW. Of that 36,046 MW were produced by hydropower and the rest was produced by coal power. China has 15 large coal-mining areas that produced a combined total of 219.6 Mt of coal in 1990. Most of the mines are underground mines and the environmental effects of these operations are mainly caused by discharge of large quantities of acid drainage, subsidence, and wild fires. Most of the coal in China (about 83 percent) is burned without prior processing (Luo *et al.*, 1996).

Economics

Fossil fuels may supply most of the world's energy needs, but with the international interest in reducing greenhouse gas emissions enthusiasm for coal energy is waning, especially in western countries. In order to meet Kyoto greenhouse gas emission reduction targets some coal electricity generation will have to be replaced with cleaner sources of power.

In the current European coal market, cheap imports are beating domestic coal prices by a large margin (Anonymous, 1997). With electricity reform customers are increasingly able to choose suppliers and therefore avoid the high cost of coal supplied from local monopolies. If often makes good economic sense to purchase cheap, imported coal to fill peak winter energy needs even if this reduces local coal production profits. Overall, European coal mining is shutting down. Several countries including France, Belgium, Portugal and the Netherlands have already made plans to stop mining coal domestically and the German, British, and Spanish coal industry is looking less and less profitable (Anonymous, 1997). Coal industry subsidies are also draining government budgets.

Unfortunately, closing mines leads to a loss of rural jobs. This problem is prevalent in the Appalachian region in the United States. The eastern U.S. coal mines are still open, but to cut costs workers have been replaced with efficient machines. These areas are some of the poorest in the U.S., and attempts to revive the local economies in parts of West Virginia, central Pennsylvania, and western Kentucky have been disappointing.

Natural gas is a prime choice for replacing phased out coal power pants. According to the Economist, a British news magazine, coal accounted for 70% of the raw fuel used for electricity generation in the UK in 1990 (Anonymous, 1998). In 1998, coal accounted for only one third of raw fuel with natural gas filling in the gap (Anonymous 1998). This quick shift has created employment strains and competing interests between the old British coal producers and new natural gas plant investors and builders (Anonymous 1998).

Life cycle analysis

Data from several different LCA studies is used for this survey. In a Swiss study completed by the Swiss Federal Institute of Technology (ETHZ) and the Paul Scherrer Institute (PSI) lifecycle resource use was analysed for many different energy systems. Values were reported as UCPTE country averages using 1992 values. This data is reported in several publications and the data is also relied on heavily in a 1994 report by Det Norske Veritas (Sandgren & Sorteberg, 1994). In the ETH study, in addition to the calculation of the average UCPTE life cycle inventory, the following countries were analysed:

Brown Coal Power: Austria, Germany, Spain, Ex-Yugoslavia, France and Greece
Hard Coal Power: Austria, Belgium, Germany, Spain, Ex-Yugoslavia, France, Italy, Greece and Portugal)

A Chinese LCA report estimates the environmental impacts from coal power in China under the conditions present in 1990. This lifecycle analysis includes coal mining, coal processing, coal transportation and coal power generation.

Lifecycle analysis data from Japan are also included in this chapter. The entire energy process in this case includes recovery and extraction, refining and processing, transportation, electricity generation and ash disposal. In Japan, there are three types of power plants: conventional pulverised coal fired power plants, ultra-super critical power plants and integral coal gasification combined cycle power plants. The total power output of the plants is 1,000 MW and the net efficiency factor is 36.1, 39.8 and 41.6 percent respectively. The lifetime of the plants is assumed to be 30 years (Uchiyama, 1995).

Available LCA studies on coal are too few to allow a general picture of resource use and emissions to emerge since they probably represent power plants with better than average environmental performance. On the other hand, since much of the specific emission from coal-fired power plants is coupled to the energy efficiency of the chosen technique it is possible to get accurate estimates of the extremes.

2.2 Use of resources

Non-renewables

In the following table the total amount of resources used in an average UCPTE coal power life cycle are listed and evaluated. Resource use contributing to less than 0.1% of the total relative use of both brown coal and hard coal power sub-categories is omitted.

Table 2.2 The use of non-renewable resources of the average UCPTE coal power life cycle (Gantner & Hofstetter, 1996) for Brown Coal Power and Hard

Coal Power, respectively. Static reserve life refers to the expected time before the now known reserve of the resource in question is fully used (Lindfors et al., 1995).

Resource	**Unit**	**Brown Coal Power**	**Hard Coal Power**	**static reserve life (years)**
lead (Pb)	$g\cdot kWh^{-1}$	$1.42\cdot10^{-4}$	$9.00\cdot10^{-4}$	20
iron (Fe)	$g\cdot kWh^{-1}$	1.15	3.08	119
copper (Cu)	$g\cdot kWh^{-1}$	$1.97\cdot10^{-2}$	$1.54\cdot10^{-2}$	36
silver (Ag)	$g\cdot kWh^{-1}$	$5.44\cdot10^{-6}$	$2.92\cdot10^{-5}$	1
oil gas	$g\cdot kWh^{-1}$	$9.76\cdot10^{-2}$	$5.29\cdot10^{-1}$	40
Methane	$g\cdot kWh^{-1}$	$9.50\cdot10^{-2}$	4.36	60
brown coal	$g\cdot kWh^{-1}$	$1.49\cdot10^{3}$	7.02	390
hard coal	$g\cdot kWh^{-1}$	5.04	$6.59\cdot10^{2}$	390
natural gas	$g\cdot kWh^{-1}$	$9.76\cdot10^{-1}$	1.35	60
Oil	$g\cdot kWh^{-1}$	1.72	9.29	40

As clearly shown in Table 2.2, the use of non-renewable resources other than fuel is, of course, negligible compared to the use of coal. Nevertheless, considerable amounts of oil, natural gas, copper and silver are used. Table 2.3 displays the use of steel, aluminium, copper and concrete in Japan (Uchiyama, 1995).

Table 2.3 The use of non-renewable resources in Japanese coal power plants.

Material	**Unit**	**Conventional pulverised**	**Ultrasuper critical**	**Coal gasification combined system**
Steel	$g\cdot kWh^{-1}$	2.35	2.26	2.34
Aluminium	$g\cdot kWh^{-1}$	$1.50\cdot10^{-2}$	$1.49\cdot10^{-2}$	$1.62\cdot10^{-2}$
Copper	$g\cdot kWh^{-1}$	$7.74\cdot10^{-3}$	$7.01\cdot10^{-3}$	$6.72\cdot10^{-3}$
Concrete	$g\cdot kWh^{-1}$	4.44	4.19	4.22

Renewables

Coal power is not a renewable energy system, and as such does not use renewable resources to a large extent. Some wood is used, mainly during mining of hard coal. For Hard Coal Power, it amounts to 4.75 $g\cdot kWh^{-1}$, while Brown Coal Power uses only $9.90\cdot10^{-2}$ $g\cdot kWh^{-1}$ in the UCPTE average.

Only a small amount of energy is used for water supply to the power plant. It amounts to $6.24\cdot10^{-3}$ $kWh\cdot(kWh)^{-1}$ and $8.83\cdot10^{-3}$ $kWh\cdot(kWh)^{-1}$ for Brown Coal Power and Hard Coal Power, respectively. On a weight basis, $1.18\cdot10^{5}$g and $1.67\cdot10^{5}$ g, of water are utilised in the turbines per kWh to produce this energy for Brown Coal Power and Hard Coal Power, respectively (Gantner & Hofstetter, 1996). The water is mainly used for generating steam or as cooling medium.

During the mining activities, water is pumped out of the mining area. Up to 8.5 m^3 of water per ton feed coal is used in the coal handling plants, independent of method. Most of the water is used in the cooling systems of power plants. In so called once-through systems, especially large amounts are needed. In evaporative cooling systems, i.e. different kinds of cooling towers, the continuous need of water is greatly reduced since the cooling water is circulating in a loop (Golob & Brus, 1993). Normally, only a few percent of the water is lost to the atmosphere when circulating through a cooling tower (Perry & Green, 1997).

Water is also consumed inside the power plant, e.g. in the treatment of ash or in the flue gas cleaning system. In total, the use of water, exclusive of water passed through the turbines, amounts to $4.86 \cdot 10^4$ $g \cdot kWh^{-1}$ and $3.85 \cdot 10^4$ $g \cdot kWh^{-1}$ for Brown Coal Power and Hard Coal Power, respectively. Roughly two thirds of this water is used in mining and one third is used in the power plants.

For both Brown Coal Power and Hard Coal Power the water quality is reduced considerably between the intake to, and release from the power plants. Part of the deterioration is due to the addition of dissolved solids (mineral compounds) from the different sub-processes and the use of additives in certain applications. Thus, anti-fouling (in essentially all kinds of cooling water facilities) and anti-corrosive (in cooling towers) chemicals are added when the water is released back into the natural environment or man-made water bodies.

Large differences in the use of renewable resources persist between the investigated countries. The extremes are listed in the table below.

Table 2.4 Extremes in the use of renewable resources in the coal power life cycle in UCPTE-countries (Gantner & Hofstetter, 1996). Abbreviations: BCP = Brown Coal Power; HCP = Hard Coal Power; A = Austria; Ex-Yu = Ex-Yugoslavia; GR = Greece; NL = the Netherlands.

Resource	**Unit**	**BCP min.**	**country**	**BCP max.**	**country**	**HCP min.**	**country**	**HCP max.**	**country**
Pot. Energy water	$kWh \cdot kWh^{-1}$	$3.41 \cdot 10^{-3}$	A	$9.52 \cdot 10^{-3}$	GR	$7.30 \cdot 10^{-3}$	NL	$1.12 \cdot 10^{-2}$	A
Turbine water	$g \cdot kWh^{-1}$	$6.44 \cdot 10^4$	A	$1.80 \cdot 10^5$	GR	$1.38 \cdot 10^5$	NL	$2.12 \cdot 10^5$	A
Other water use	$g \cdot kWh^{-1}$	$4.10 \cdot 10^4$	A	$5.44 \cdot 10^4$	Ex-Yu	$3.59 \cdot 10^4$	NL	$4.61 \cdot 10^4$	Ex-Yu
Wood	$g \cdot kWh^{-1}$	$5.65 \cdot 10^{-2}$	A	$1.48 \cdot 10^{-1}$	GR	2.24	NL	5.54	GR

Land Use

For the purposes of this LCA analysis it is assumed that class I land (natural, i.e. insignificantly influenced by man) is not affected by coal power life cycles in the UCPTE region. Mining, which requires land use of at the most extreme level, changes class II (modified, i.e. uncultivated but with human influence) or class III (cultivated) land into class IV land, or uses land that is already class IV. The amount of land per kWh used for mining depends on the mining method, i.e. open cast versus underground. It is assumed that class IV (mining) land is used for 10 years and that it takes 5 years for re-cultivation to class III land. If the original land use was class II, it is anticipated that another 50 years will pass before that class is reached again.

Table 2.5 The change between land use types of UCPTE average. Abbreviations: BCP = Brown Coal Power; HCP = Hard Coal Power.

land use type	**Unit**	**BCP area**	**HCP area**
area benthos II-III	$m^2a{\cdot}kWh^{-1}$	$1.48{\cdot}10^{-4}$	$6.84{\cdot}10^{-4}$
area benthos II-IV	$m^2a{\cdot}kWh^{-1}$	$1.52{\cdot}10^{-5}$	$7.06{\cdot}10^{-5}$
area benthos III-IV	$m^2a{\cdot}kWh^{-1}$	0.00	0.00
area II-III	$m^2a{\cdot}kWh^{-1}$	$6.62{\cdot}10^{-3}$	$4.79{\cdot}10^{-3}$
area II-IV	$m^2a{\cdot}kWh^{-1}$	$3.45{\cdot}10^{-4}$	$1.56{\cdot}10^{-3}$
area III-IV	$m^2a{\cdot}kWh^{-1}$	$6.52{\cdot}10^{-4}$	$7.70{\cdot}10^{-4}$
area IV-IV	$m^2a{\cdot}kWh^{-1}$	$5.11{\cdot}10^{-7}$	$1.76{\cdot}10^{-6}$
Total	$\mathbf{m^2a{\cdot}kWh^{-1}}$	$\mathbf{7.78{\cdot}10^{-3}}$	$\mathbf{7.88{\cdot}10^{-3}}$

The UCPTE averages of $7.78{\cdot}10^{-3}$ m^2a[2] (Brown Coal Power) and $7.88{\cdot}10^{-3}$ m^2a (Hard Coal Power) of land directly affected per kWh of electricity are derived from mining activities. However, land use variations were extreme between the studied countries. These big differences are likely to reflect the consequences of different mining techniques (which, in turn, largely relate to the vertical distribution of coal in the ground) and energy conversion efficiency.

• Brown Coal Power, minimum:	$4.18{\cdot}10^{-3}$ $m^2a{\cdot}kWh^{-1}$ (Austria)
• Brown Coal Power, maximum:	$1.20{\cdot}10^{-2}$ $m^2a{\cdot}kWh^{-1}$ (Greece)
• Hard Coal Power, minimum:	$6.44{\cdot}10^{-3}$ $m^2a{\cdot}kWh^{-1}$ (Germany)
• Hard Coal Power, maximum:	$1.06{\cdot}10^{-2}$ $m^2a{\cdot}kWh^{-1}$ (Italy)

2.3 Global environmental impact

Greenhouse effect

Coal power life cycles lead to larger emissions of greenhouse gases (GHG) than any other electricity generation option. Most of the emissions stem from combustion. This is unavoidable since burning coal is essentially turning carbon into CO_2. Other fossil fuels, i.e. oil and natural gas, contain additional elements that are oxidised to other compounds during combustion which means that the overall emission of greenhouse gases, from purely stoichiometric reasons, are lower than those formed when coal is burned. The amount of GHG released per kilowatt-hour also depends on power plant efficiency, which is to a large extent related to the heat content of the fuel. Fairly large quantities of the greenhouse gas methane are also released by hard coal mining

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[2] m^2a is the annual approriated unit area.

activities. In addition, emissions also occur during fuel transport. When hard coal is transported internationally over long distances significant emissions can result. For the coal LCA, the emission of CO_2 from transport amounts to a few percent of the total when the coal is imported from abroad (29); the magnitude of the emissions depending on the transport distance. The quantity of gases contributing to the greenhouse effect for the UCPTE-countries are listed below expressed as global warming potentials (GWP). Substances causing a GWP of under 0.1% of the total in both Brown Coal Power and Hard Coal Power sub-categories were omitted.

Table 2.6 Emissions of greenhouse gases for UCPTE average (Gantner & Hofstetter, 1996). Greenhouse warming potential (GWP) obtained from (Houghton et al., 1996). Abbreviations: BCP = Brown Coal Power; HCP = Hard Coal Power; m = emissions from transport (mobile); p = process specific emissions, often diffuse, e.g., leakage, evaporation etc.; s = stationary emissions, e.g., from combustion, flue gases.

Substance	**Unit**	**BCP**	**HCP**	**GWP 100 years (g CO_2-eq./g)**	**BCP CO_2-eq.**	**HCP CO_2-eq.**
CH_4 p	$g{\cdot}kWh^{-1}$	$1.01{\cdot}10^{-1}$	3.60	21	2.12	75.6
CO_2 m	$g{\cdot}kWh^{-1}$	$3.06{\cdot}10^{-1}$	16.2	1	$3.06{\cdot}10^{-1}$	16.2
CO_2 p	$g{\cdot}kWh^{-1}$	3.22	-2.40	1	3.22	-2.40
CO_2 s	$g{\cdot}kWh^{-1}$	$1.33{\cdot}10^{3}$	$9.79{\cdot}10^{2}$	1	$1.33{\cdot}10^{3}$	979
N_2O s	$g{\cdot}kWh^{-1}$	$6.05{\cdot}10^{-3}$	$5.51{\cdot}10^{-3}$	310	1.88	1.71
total	**$g{\cdot}kWh^{-1}$**				**$1.34{\cdot}10^{3}$**	**$1.07{\cdot}10^{3}$**

For Hard Coal Power, releases of methane contribute approximately 7% and releases of CO_2 contribute approximately 93% of the total GWP. For Brown Coal Power, CO_2 contributes over 99%. N_2O has only a very minor effect in both sub-systems, and the other released greenhouse gases are negligible under average UCPTE conditions.

The total GWP in CO_2-equivalents is $1.34{\cdot}10^{3}$ $g{\cdot}kWh^{-1}$ for Brown Coal Power and $1.07{\cdot}10^{3}$ $g{\cdot}kWh^{-1}$ for Hard Coal Power. Calculations of 20 or 500 year GWPs for the UCPTE average lead to the following results. These values do not differ significantly from the 100-year perspective, since CO_2 contributions constitute the bulk of the emissions:

- Brown Coal Power, 20 year GWP:	$1.34{\cdot}10^{3}$ $g{\cdot}kWh^{-1}$
- Brown Coal Power, 500 year GWP:	$1.34{\cdot}10^{3}$ $g{\cdot}kWh^{-1}$
- Hard Coal Power, 20 year GWP:	$1.20{\cdot}10^{3}$ $g{\cdot}kWh^{-1}$
- Hard Coal Power, 500 year GWP:	$1.02{\cdot}10^{3}$ $g{\cdot}kWh^{-1}$

When the greenhouse gas emissions of the observed countries are compared, great differences of up to over 30%, due to technology differences, are revealed.

- Brown Coal Power, minimum: $1.11{\cdot}10^{3}$ $g{\cdot}kWh^{-1}$ (Austria)

- Brown Coal Power, maximum: $1.47 \cdot 10^3$ g·kWh^{-1} (Ex-Yugoslavia)
- Hard Coal Power, minimum: $9.83 \cdot 10^2$ g·kWh^{-1} (the Netherlands)
- Hard Coal Power, maximum: $1.25 \cdot 10^3$ g·kWh^{-1} (Ex-Yugoslavia)

The greenhouse gas emissions data from Japan are shown in Table 2.7. The emissions from Japanese power plants are generally lower than emissions from the UCPTE countries according to these estimations.

Table 2.7 Emissions of greenhouse gases from Japanese power plants (Uchiyama, 1995).

Emission	**Unit**	**Manufacturing and construction**	**Operation and maintenance**	**Total**
Conventional pulverised coal fired power plant				
CO_2	g (CO_2) ·kWh^{-1}	4.00	939	943
CH_4	g (CO_2) ·kWh^{-1}	0.18	46.3	46.5
Ultrasuper critical power plant				
CO_2	g (CO_2) ·kWh^{-1}	3.78	851	855
CH_4	g (CO_2) ·kWh^{-1}	0.15	42.0	42.2
Integral coal gasification combined cycle power plant				
CO_2	g (CO_2) ·kWh^{-1}	3.78	816	820
CH_4	g (CO_2) ·kWh^{-1}	0.15	40.3	40.4

Ozone layer depletion

Table 2.8 lists the ozone layer depletion potentials (ODP) resulting from the coal power life cycles in the UCPTE. Substances contributing to less than 0.1% of the total ODP of both sub-systems are omitted here, but included in the appendix.

Table 2.8 Emissions of ozone layer depleting substances for the UCPTE average (Gantner & Hofstetter, 1996) p = process specific emissions, often diffuse, e.g., leakage, evaporation etc. HCP = Hard Coal Power; BCP = Brown Coal Power.

Substance	**Unit**	**BCP emission**	**HCP emission**	**ODP factor**	**BCP CFC-11 equiv.**	**HCP CFC-11 equiv.**
H 1301 halon p	g·kWh^{-1}	$6.70 \cdot 10^{-7}$	$3.60 \cdot 10^{-6}$	16	$1.07 \cdot 10^{-5}$	$5.76 \cdot 10^{-5}$
R11 FCKW p	g·kWh^{-1}	$1.08 \cdot 10^{-7}$	$1.52 \cdot 10^{-7}$	1	$1.08 \cdot 10^{-7}$	$1.52 \cdot 10^{-7}$
R114 FCKW p	g·kWh^{-1}	$2.85 \cdot 10^{-6}$	$4.00 \cdot 10^{-6}$	0.8	$2.28 \cdot 10^{-6}$	$3.20 \cdot 10^{-6}$
R12 FCKW p	g·kWh^{-1}	$2.32 \cdot 10^{-8}$	$3.26 \cdot 10^{-8}$	1	$2.32 \cdot 10^{-8}$	$3.26 \cdot 10^{-8}$
Tetrachlormethane p	g·kWh^{-1}	$1.25 \cdot 10^{-7}$	$2.08 \cdot 10^{-7}$	1.08	$1.35 \cdot 10^{-7}$	$2.25 \cdot 10^{-7}$
Total	**g·kWh^{-1}**				**$1.33 \cdot 10^{-5}$**	**$6.12 \cdot 10^{-5}$**

The average UCPTE total ODP from coal power in CFC-11-equivalents is $1.33 \cdot 10^{-5}$ and $6.12 \cdot 10^{-5}$ $g \cdot kWh^{-1}$ for Brown Coal Power and Hard Coal Power, respectively. Halon is the major contributing substance, but R114 also contributes substantially. For minimum and maximum ODP factors in the UCPTE countries, the following results were recorded:

- Brown Coal Power, minimal ODP: $8.57 \cdot 10^{-6}$ $g \cdot kWh^{-1}$
- Brown Coal Power, maximal ODP: $1.45 \cdot 10^{-5}$ $g \cdot kWh^{-1}$
- Hard Coal Power, minimal ODP: $3.85 \cdot 10^{-5}$ $g \cdot kWh^{-1}$
- Hard Coal Power, maximal ODP: $6.55 \cdot 10^{-5}$ $g \cdot kWh^{-1}$

The best average ODPs in the investigated UCPTE countries were:

- Brown Coal Power, minimum: $7.99 \cdot 10^{-6}$ $g \cdot kWh^{-1}$ (Austria)
- Brown Coal Power, maximum: $1.91 \cdot 10^{-5}$ $g \cdot kWh^{-1}$ (Greece)
- Hard Coal Power, minimum: $3.42 \cdot 10^{-5}$ $g \cdot kWh^{-1}$ (Germany)
- Hard Coal Power, maximum: $1.19 \cdot 10^{-4}$ $g \cdot kWh^{-1}$ (the Netherlands)

2.4 Local and regional environmental impact

Acidification

Acidification is one of the main problems arising from existing coal power. It takes place during many steps in the life cycle of electricity produced by coal combustion. Pumped mine water contains mud, dissolved sulphate and metal ions. It is also acidic and, therefore, needs to be neutralised before being discharged (Stjernquist, 1986). Drainage water from refuse piles with excavated and residual minerals can be very acidic, particularly if the rocks contain pyrite (ferric sulphide) that undergoes oxidation processes when exposed to the atmosphere. These oxidation processes take place in natural environments, but are greatly accelerated by mining activities, especially when no alkaline rocks are present to neutralise the acid formed. The result is low pH values and a release of certain elements, which are normally encapsulated within the bedrock matrix such as aluminium, copper, cobalt, and/or lead (Gantner & Hofstetter, 1996). Trace elements are also released when acid drainage percolates through a rock and soil waste pile (spoil pile). This is partly due to ion exchange processes as a consequence of the buffering caused by the carbonates and silicates from the overburden material present in the spoil (European Commission, 1995). Wastewater from coal handling plants may be acid due to presence of soluble salts of iron carbonates and pyrite from the coal. Coal combustion gives rise to airborne emissions of sulphur dioxide (SO_2) and nitrogen oxides (NO_X), both kinds of compounds being readily dissolved in water and transformed into sulphur and nitric acid, respectively. There are a number of NO_X reducing systems and desulfurisation systems available to the electric utility industry that can markedly lower these emissions (Sloss, 1998).

Table 2.9 shows the maximum acidification potential (AP) from coal power in the UCPTE countries. Emissions contributing less than 0.1% of the total AP for both Brown Coal Power and Hard Coal Power were omitted.

'Table 2.9. Emissions of maximum acidification compounds for UCPTE-countries (Gantner & Hofstetter, 1996). BCP = Brown Coal Power HCP = Hard Coal Power; m = emissions from transport (mobile); p = process specific emissions, often diffuse, e.g., leakage, evaporation etc.; s = stationary emissions, mainly in the form of flue gases from combustion.

Substance	**Unit**	**BCP emission**	**HCP emission**	**max. factor (g SO_2-equiv./g)**	**BCP max. AP (SO_2-equiv.)**	**HCP max. AP (SO_2-equiv.)**
HCl s	$g\cdot kWh^{-1}$	$4.90\cdot10^{-1}$	$2.16\cdot10^{-1}$	0.88	$4.32\cdot10^{-1}$	$1.90\cdot10^{-1}$
NH_3 p	$g\cdot kWh^{-1}$	$6.48\cdot10^{-3}$	$5.36\cdot10^{-3}$	1.88	$1.22\cdot10^{-2}$	$1.01\cdot10^{-2}$
NOx as NO_2 m	$g\cdot kWh^{-1}$	$3.82\cdot10^{-3}$	$2.20\cdot10^{-1}$	0.7	$2.67\cdot10^{-3}$	$1.54\cdot10^{-1}$
NOx as NO_2 p	$g\cdot kWh^{-1}$	$3.38\cdot10^{-3}$	$9.00\cdot10^{-3}$	0.7	$2.37\cdot10^{-3}$	$6.30\cdot10^{-3}$
NOx as NO_2 s	$g\cdot kWh^{-1}$	2.00	1.40	0.7	1.40	$9.79\cdot10^{-1}$
SOx as SO_2 m	$g\cdot kWh^{-1}$	$4.32\cdot10^{-3}$	$3.23\cdot10^{-1}$	1	$4.32\cdot10^{-3}$	$3.23\cdot10^{-1}$
SOx as SO_2 p	$g\cdot kWh^{-1}$	$8.39\cdot10^{-3}$	$1.61\cdot10^{-2}$	1	$8.39\cdot10^{-3}$	$1.61\cdot10^{-2}$
SOx as SO_2 s	$g\cdot kWh^{-1}$	13.0	3.48	1	13.0	3.48
total	**$g\cdot kWh^{-1}$**				**14.9**	**5.15**

The total maximum acidification potential in SO_2-equivalents is $14.9 g\cdot kWh^{-1}$ and $5.15 g\cdot kWh^{-1}$ for Brown Coal Power and Hard Coal Power, respectively. The main contributors are SO_X and NO_X formed in the combustion process. Depending on the type of soil or ecosystem affected by the subsequent fallout of these substances, the actual acidification potential will vary between the maximum and the minimum potential:

- Brown Coal Power, minimal potential: 13.5 $g\cdot kWh^{-1}$
- Hard Coal Power, minimal potential: 4.00 $g\cdot kWh^{-1}$

Between the observed countries, the maximum acidification potential values vary extremely. The differences of up to one order of magnitude are a consequence of technology differences, i.e. denitrification and desulfurisation, and differences in the quality of the coal used.

- Brown Coal Power, minimum: 11.2 $g\cdot kWh^{-1}$ (Germany)
- Brown Coal Power, maximum: 37.1 $g\cdot kWh^{-1}$ (Spain)
- Hard Coal Power, minimum: 16.3 $g\cdot kWh^{-1}$ (Austria)
- Hard Coal Power, maximum: 280 $g\cdot kWh^{-1}$ (Ex-Yugoslavia)

A compilation of the chemical composition of coal and subsequent emission factors is provided by (UNECE-EMEP Task Force on Emission Inventories, 1996).

Eutrophication

The following table shows the maximum eutrophication potentials (EP) of UCPTE coal power life cycle emissions. Emissions contributing less than 0.1% of the total EP of both sub-systems were omitted.

Table 2.10 *Emissions of eutrophication compounds for UCPTE-countries (Gantner & Hofstetter, 1996). Abbreviations: BCP = Brown Coal Power; HCP = Hard Coal Power; m = emissions from transport (mobile); p = process specific emissions, often diffuse, e.g., leakage, evaporation etc.; s = stationary emissions, mainly in the form of flue gases from combustion; f = to freshwater*

Substance	**Unit**	**BCP emission**	**HCP emission**	**max. eutr. factor (g O_2 /g)**	**BCP max. EP In O_2 decrease**	**HCP max. EP in O_2 decrease**
NH_3 p	$g{\cdot}kWh^{-1}$	$6.48 \cdot 10^{-3}$	$5.36 \cdot 10^{-3}$	16	$1.04 \cdot 10^{-1}$	$8.57 \cdot 10^{-2}$
NOx as NO_2 m	$g{\cdot}kWh^{-1}$	$3.82 \cdot 10^{-3}$	$2.20 \cdot 10^{-1}$	6	$2.29 \cdot 10^{-2}$	1.32
NOx as NO_2 p	$g{\cdot}kWh^{-1}$	$3.38 \cdot 10^{-3}$	$9.00 \cdot 10^{-3}$	6	$2.03 \cdot 10^{-2}$	$5.40 \cdot 10^{-2}$
NOx as NO_2 s	$g{\cdot}kWh^{-1}$	2.00	1.40	6	12.0	8.39
P phosphorus s	$g{\cdot}kWh^{-1}$	$2.28 \cdot 10^{-4}$	$4.64 \cdot 10^{-4}$	140	$3.19 \cdot 10^{-2}$	$6.52 \cdot 10^{-2}$
ammonium as N f	$g{\cdot}kWh^{-1}$	$1.54 \cdot 10^{-4}$	$1.09 \cdot 10^{-3}$	16	$2.47 \cdot 10^{-3}$	$1.75 \cdot 10^{-2}$
nitrates f	$g{\cdot}kWh^{-1}$	$1.69 \cdot 10^{-4}$	$1.93 \cdot 10^{-2}$	4.4	$7.42 \cdot 10^{-4}$	$8.46 \cdot 10^{-2}$
phosphates f	$g{\cdot}kWh^{-1}$	$4.97 \cdot 10^{-4}$	$6.30 \cdot 10^{-2}$	46	$2.29 \cdot 10^{-2}$	2.90
nitrogen total f	$g{\cdot}kWh^{-1}$	$9.79 \cdot 10^{-5}$	$9.72 \cdot 10^{-4}$	20	$1.96 \cdot 10^{-3}$	$1.94 \cdot 10^{-2}$
Total	**$g{\cdot}kWh^{-1}$**				**12.2**	**13.0**

All emissions of nutrients add up to the maximum total eutrophication potential corresponding to an O_2-consumption of 12.2 g/kWh for Brown Coal Power and 13.0 g/kWh for Hard Coal Power. For Brown Coal Power, the main contribution is NO_X from combustion. For Hard Coal Power, the release of phosphates into surface waters contributes significantly to the total discharge of fertiliser compounds. The actual eutrophication depends greatly on the kind of ecosystem that receives the compounds. The Eutrophication potential was recorded for two types of ecosystems in UCPTE countries, Nitrogen limited (N-limited) and phosphorus limited (P-limited):

• Brown Coal Power, P-limited ecosystem:	$5.51 \cdot 10^{-2}$ $g{\cdot}kWh^{-1}$
• Brown Coal Power, N-limited ecosystem:	12.2 $g{\cdot}kWh^{-1}$
• Hard Coal Power, P-limited ecosystem:	2.97 $g{\cdot}kWh^{-1}$
• Hard Coal Power, N-limited ecosystem:	9.97 $g{\cdot}kWh^{-1}$

The range of emission of fertiliser compounds among the UCPTE countries is:

- Brown Coal Power, minimum: 4.46 g·kWh^{-1} (Austria)
- Brown Coal Power, maximum: 20.3 g·kWh^{-1} (Ex-Yugoslavia)
- Hard Coal Power, minimum: 8.64 g·kWh^{-1} (Germany)
- Hard Coal Power, maximum: 30.6 g·kWh^{-1} (Ex-Yugoslavia)

Photochemical oxidant formation

Photochemical ozone creation potentials (POCP) are calculated in the following table. Substances contributing less than 0.1% of the total POCP for both Brown Coal Power and Hard Coal Power sub-categories were omitted.

Table 2.11 Emissions of photochemical ozone creation compounds for UCPTE countries (Gantner & Hofstetter, 1996). Abbreviations: BCP = Brown Coal Power; HCP = Hard Coal Power; m = emissions from transport (mobile); p = process specific emissions, often diffuse, e.g., leakage, evaporation etc.; s = stationary emissions, e.g., from combustion, flue gases; sw = to the sea.

Substance	**Unit**	**BCP emission**	**HCP emission**	**POCP fact. (g ethene-equiv./g)**	**BCP POCP in ethene-equiv.**	**HCP POCP in ethene-equiv.**
Alkanes s	g·kWh^{-1}	$2.62\cdot10^{-3}$	$2.31\cdot10^{-3}$	0.398	$1.04\cdot10^{-3}$	$9.22\cdot10^{-4}$
Alkene s	g·kWh^{-1}	$2.55\cdot10^{-3}$	$2.24\cdot10^{-3}$	0.906	$2.31\cdot10^{-3}$	$2.03\cdot10^{-3}$
Butane p	g·kWh^{-1}	$1.45\cdot10^{-4}$	$7.27\cdot10^{-4}$	0.363	$5.29\cdot10^{-5}$	$2.64\cdot10^{-4}$
Butane s	g·kWh^{-1}	$2.54\cdot10^{-4}$	$2.41\cdot10^{-4}$	0.363	$9.22\cdot10^{-5}$	$8.75\cdot10^{-5}$
CH_4 methane p	g·kWh^{-1}	$1.01\cdot10^{-1}$	3.60	0.007	$7.09\cdot10^{-4}$	$2.52\cdot10^{-2}$
CH_4 methane s	g·kWh^{-1}	$1.22\cdot10^{-2}$	$1.17\cdot10^{-2}$	0.007	$8.53\cdot10^{-5}$	$8.17\cdot10^{-5}$
CO carbon monoxide m	g·kWh^{-1}	$6.73\cdot10^{-4}$	$3.28\cdot10^{-2}$	0.036	$2.42\cdot10^{-5}$	$1.18\cdot10^{-3}$
CO carbon monoxide p	g·kWh^{-1}	$1.72\cdot10^{-2}$	$4.25\cdot10^{-2}$	0.036	$6.19\cdot10^{-4}$	$1.53\cdot10^{-3}$
CO carbon monoxide s	g·kWh^{-1}	$1.45\cdot10^{-1}$	$1.29\cdot10^{-1}$	0.036	$5.22\cdot10^{-3}$	$4.64\cdot10^{-3}$
Ethane s	g·kWh^{-1}	$4.90\cdot10^{-4}$	$4.90\cdot10^{-4}$	0.082	$4.03\cdot10^{-5}$	$4.03\cdot10^{-5}$
Ethene p	g·kWh^{-1}	$1.65\cdot10^{-4}$	$6.48\cdot10^{-4}$	1	$1.65\cdot10^{-4}$	$6.48\cdot10^{-4}$
Ethene s	g·kWh^{-1}	$1.95\cdot10^{-5}$	$1.55\cdot10^{-4}$	1	$1.95\cdot10^{-5}$	$1.55\cdot10^{-4}$
Ethylbenzol s	g·kWh^{-1}	$2.56\cdot10^{-3}$	$2.22\cdot10^{-3}$	0.593	$1.52\cdot10^{-3}$	$1.31\cdot10^{-3}$
Formaldehyde s	g·kWh^{-1}	$7.34\cdot10^{-4}$	$6.80\cdot10^{-4}$	0.421	$3.09\cdot10^{-4}$	$2.87\cdot10^{-4}$
Heptane p	g·kWh^{-1}	$3.16\cdot10^{-5}$	$1.69\cdot10^{-4}$	0.529	$1.67\cdot10^{-5}$	$8.93\cdot10^{-5}$
Hexane p	g·kWh^{-1}	$6.62\cdot10^{-5}$	$3.54\cdot10^{-4}$	0.421	$2.79\cdot10^{-5}$	$1.49\cdot10^{-4}$
NMVOC m	g·kWh^{-1}	$2.57\cdot10^{-4}$	$1.11\cdot10^{-2}$	0.416	$1.07\cdot10^{-4}$	$4.61\cdot10^{-3}$
NMVOC p	g·kWh^{-1}	$1.64\cdot10^{-2}$	$7.52\cdot10^{-2}$	0.416	$6.80\cdot10^{-3}$	$3.13\cdot10^{-2}$
NMVOC s	g·kWh^{-1}	$3.67\cdot10^{-3}$	$9.83\cdot10^{-3}$	0.416	$1.53\cdot10^{-3}$	$4.10\cdot10^{-3}$
Pentane p	g·kWh^{-1}	$1.67\cdot10^{-4}$	$8.93\cdot10^{-4}$	0.352	$5.90\cdot10^{-5}$	$3.14\cdot10^{-4}$
Pentane s	g·kWh^{-1}	$1.77\cdot10^{-3}$	$1.57\cdot10^{-3}$	0.352	$6.26\cdot10^{-4}$	$5.51\cdot10^{-4}$
Propane p	g·kWh^{-1}	$1.84\cdot10^{-4}$	$7.74\cdot10^{-4}$	0.42	$7.74\cdot10^{-5}$	$3.25\cdot10^{-4}$
Propane s	g·kWh^{-1}	$4.32\cdot10^{-4}$	$4.25\cdot10^{-4}$	0.42	$1.81\cdot10^{-4}$	$1.79\cdot10^{-4}$
Propene s	g·kWh^{-1}	$1.90\cdot10^{-4}$	$1.85\cdot10^{-4}$	1.03	$1.96\cdot10^{-4}$	$1.90\cdot10^{-4}$
Toluol s	g·kWh^{-1}	$1.29\cdot10^{-3}$	$1.13\cdot10^{-3}$	0.563	$7.27\cdot10^{-4}$	$6.37\cdot10^{-4}$
Xyloles p	g·kWh^{-1}	$1.64\cdot10^{-5}$	$1.70\cdot10^{-4}$	0.849	$1.39\cdot10^{-5}$	$1.44\cdot10^{-4}$
Xyloles s	g·kWh^{-1}	$1.09\cdot10^{-2}$	$9.43\cdot10^{-3}$	0.849	$9.22\cdot10^{-3}$	$7.99\cdot10^{-3}$
Aromatic CHs total sw	g·kWh^{-1}	$4.79\cdot10^{-5}$	$2.53\cdot10^{-4}$	0.761	$3.64\cdot10^{-5}$	$1.92\cdot10^{-4}$
Total	**g·kWh^{-1}**				**$3.20\cdot10^{-2}$**	**$8.96\cdot10^{-2}$**

The best estimate for the POCP in the average UCPTE country is $3.20\cdot10^{-2}$ g ethene-equivalents per kWh of produced electricity based on the Brown Coal Power life cycle and $8.96\cdot10^{-2}$ g·kWh^{-1} according to the Hard Coal Power life cycle. For Brown Coal Power, non-methane volatile organic compounds (NMVOC), carbon monoxide, and xylole emissions are the main contributors. For Hard Coal Power they are NMVOC and methane. These substances are emitted throughout the lifecycle of the power system. Combustion only contributes around 30% (Gantner & Hofstetter, 1996). Using minimum and maximum POCP factors leads to the results listed below. The big differences are due to extreme assumptions in factors such as sunlight, NO_X-availability and ozone concentration.

- Brown Coal Power, minimum POCP: $1.92 \cdot 10^{-2}$ g·kWh^{-1}
- Brown Coal Power, maximum POCP: $6.01 \cdot 10^{-2}$ g·kWh^{-1}
- Hard Coal Power, minimum POCP: $3.59 \cdot 10^{-2}$ g·kWh^{-1}
- Hard Coal Power, maximum POCP: $2.28 \cdot 10^{-1}$ g·kWh^{-1}

The range of values that represent the best estimates for POCP are listed below:

- Brown Coal Power, minimum: $2.70 \cdot 10^{-2}$ g·kWh^{-1} (Austria)
- Brown Coal Power, maximum: $3.45 \cdot 10^{-2}$ g·kWh^{-1} (Greece)
- Hard Coal Power, minimum: $7.67 \cdot 10^{-2}$ g·kWh^{-1} (Germany)
- Hard Coal Power, maximum: $1.13 \cdot 10^{-1}$ g·kWh^{-1} (the Netherlands)

In addition to the other photochemical smog forming emissions, coal power gives rise to rather high NO_X emissions of 2.01 g·kWh^{-1} (Brown Coal Power) and 1.63 g·kWh^{-1} (Hard Coal Power) These NO_X emissions enable and accelerate photo-oxidant formation (Gantner & Hofstetter, 1996).

Ecotoxic impact

Water contamination and soil contamination potentials are calculated in the Table 2.12 and Table 2.13, respectively. Substances contributing less than 0.5% of the total contamination for Brown Coal Power and Hard Coal Power both sub-categories were omitted.

Table 2.12. Emissions of ecotoxic compounds to water for UCPTE-countries (Gantner & Hofstetter, 1996). Abbreviations: BCP = Brown Coal Power*; HCP =* Coal Power; *p = process specific emissions, often diffuse, e.g., leakage, evaporation etc; s = stationary emissions, e.g., from combustion, flue gases; f = to freshwater; sw = to the sea.*

Substance	**Unit**	**BCP emission**	**HCP emission**	**ECA (m^3 water/mg)**	**BCP max. water contaminated (m^3/kWh)**	**HCP max. water contaminated (m^3/kWh)**
Cd cadmium s	$g\cdot kWh^{-1}$	$3.29\cdot10^{-5}$	$5.36\cdot10^{-6}$	200	$6.59\cdot10^{3}$	$1.07\cdot10^{3}$
Cu copper s	$g\cdot kWh^{-1}$	$1.49\cdot10^{-4}$	$9.61\cdot10^{-5}$	2.00	297	192
Hg mercury s	$g\cdot kWh^{-1}$	$6.98\cdot10^{-5}$	$1.17\cdot10^{-4}$	$5.00\cdot10^{2}$	$3.49\cdot10^{4}$	$5.83\cdot10^{4}$
PAH s	$g\cdot kWh^{-1}$	$1.28\cdot10^{-5}$	$1.23\cdot10^{-5}$	60.0	767	742
Zn zinc s	$g\cdot kWh^{-1}$	$6.08\cdot10^{-4}$	$3.23\cdot10^{-4}$	$3.80\cdot10^{-1}$	231	123
ion lead f	$g\cdot kWh^{-1}$	$6.91\cdot10^{-5}$	$5.33\cdot10^{-3}$	2.00	138	$1.07\cdot10^{4}$
ion cadmium f	$g\cdot kWh^{-1}$	$9.40\cdot10^{-7}$	$5.65\cdot10^{-5}$	200	188	$1.13\cdot10^{4}$
ion chromium-III f	$g\cdot kWh^{-1}$	$8.46\cdot10^{-5}$	$1.05\cdot10^{-2}$	1.00	84.6	$1.05\cdot10^{4}$
ion copper f	$g\cdot kWh^{-1}$	$5.62\cdot10^{-5}$	$5.29\cdot10^{-3}$	2.00	112	$1.06\cdot10^{4}$
ion nickel f	$g\cdot kWh^{-1}$	$4.21\cdot10^{-5}$	$5.29\cdot10^{-2}$	$3.30\cdot10^{-1}$	13.9	$1.75\cdot10^{3}$
ion mercury f	$g\cdot kWh^{-1}$	$1.39\cdot10^{-7}$	$1.35\cdot10^{-6}$	500	69.5	673
ion zinc f	$g\cdot kWh^{-1}$	$1.40\cdot10^{-4}$	$1.07\cdot10^{-2}$	$3.80\cdot10^{-1}$	53.3	$4.03\cdot10^{3}$
Total	$\mathbf{m^3\cdot kWh^{-1}}$				$\mathbf{4.43\cdot10^{4}}$	$\mathbf{1.13\cdot10^{5}}$

Table 2.13. Emissions of ecotoxic compounds to soil for UCPTE countries (Gantner & Hofstetter, 1996). Abbreviations: BCP = Brown Coal Power; HCP = Hard Coal Power; p = process specific emissions, often diffuse, e.g., leakage, evaporation etc; s = stationary emissions, e.g., from combustion, flue gases; f = to freshwater; sw = to the sea.

Substance	**Unit**	**BCP emission**	**HCP emission**	**ECT (kg soil/mg)**	**BCP max. soil contaminated**	**HCP max. soil contaminated**
As arsenic s	$g\cdot kWh^{-1}$	$4.28\cdot10^{-5}$	$7.63\cdot10^{-5}$	3.60	154	275
Cd cadmium s	$g\cdot kWh^{-1}$	$3.29\cdot10^{-5}$	$5.36\cdot10^{-6}$	13.0	428	69.8
Co cobalt s	$g\cdot kWh^{-1}$	$9.68\cdot10^{-5}$	$2.89\cdot10^{-5}$	$4.20\cdot10^{-1}$	40.7	12.2
Cr chromium s	$g\cdot kWh^{-1}$	$1.02\cdot10^{-4}$	$1.14\cdot10^{-4}$	$4.20\cdot10^{-1}$	42.8	48.2
Cu copper s	$g\cdot kWh^{-1}$	$1.49\cdot10^{-4}$	$9.61\cdot10^{-5}$	$7.70\cdot10^{-1}$	114	74.2
Hg mercury s	$g\cdot kWh^{-1}$	$6.98\cdot10^{-5}$	$1.17\cdot10^{-4}$	29.0	$2.03\cdot10^{3}$	$3.38\cdot10^{3}$
Ni nickel s	$g\cdot kWh^{-1}$	$1.22\cdot10^{-4}$	$1.10\cdot10^{-4}$	1.70	207	187
Pb lead s	$g\cdot kWh^{-1}$	$9.94\cdot10^{-5}$	$2.20\cdot10^{-4}$	$4.30\cdot10^{-1}$	42.8	94.7
toluol s	$g\cdot kWh^{-1}$	$1.29\cdot10^{-3}$	$1.13\cdot10^{-3}$	$6.30\cdot10^{-1}$	814	713
Zn zinc p	$g\cdot kWh^{-1}$	$2.22\cdot10^{-5}$	$5.69\cdot10^{-5}$	2.60	58.0	148
Zn zinc s	$g\cdot kWh^{-1}$	$6.08\cdot10^{-4}$	$3.23\cdot10^{-4}$	2.60	$1.58\cdot10^{3}$	839
aromatic HCs total f	$g\cdot kWh^{-1}$	$5.44\cdot10^{-6}$	$2.80\cdot10^{-5}$	10.0	54.4	280
aromatic HCs total sw	$g\cdot kWh^{-1}$	$4.79\cdot10^{-5}$	$2.53\cdot10^{-4}$	10.0	479	$2.53\cdot10^{3}$
ion arsenic f	$g\cdot kWh^{-1}$	$1.64\cdot10^{-5}$	$2.12\cdot10^{-3}$	3.60	59.0	$7.63\cdot10^{3}$
ion lead f	$g\cdot kWh^{-1}$	$6.91\cdot10^{-5}$	$5.33\cdot10^{-3}$	$4.30\cdot10^{-1}$	29.7	$2.29\cdot10^{3}$
ion cadmium f	$g\cdot kWh^{-1}$	$9.40\cdot10^{-7}$	$5.65\cdot10^{-5}$	13.0	12.2	734
ion chromium-III f	$g\cdot kWh^{-1}$	$8.46\cdot10^{-5}$	$1.05\cdot10^{-2}$	$4.20\cdot10^{-1}$	35.5	$4.43\cdot10^{3}$
ion cobalt f	$g\cdot kWh^{-1}$	$1.61\cdot10^{-5}$	$2.10\cdot10^{-3}$	$4.20\cdot10^{-1}$	6.77	882
ion copper f	$g\cdot kWh^{-1}$	$5.62\cdot10^{-5}$	$5.29\cdot10^{-3}$	$7.70\cdot10^{-1}$	43.2	$4.07\cdot10^{3}$
ion nickel f	$g\cdot kWh^{-1}$	$4.21\cdot10^{-5}$	$5.29\cdot10^{-3}$	1.70	71.6	$9.00\cdot10^{3}$
ion zinc f	$g\cdot kWh^{-1}$	$1.40\cdot10^{-4}$	$1.07\cdot10^{-2}$	2.60	364	$2.77\cdot10^{4}$
phenols f	$g\cdot kWh^{-1}$	$8.42\cdot10^{-6}$	$2.88\cdot10^{-5}$	5.30	44.6	153
phenols sw	$g\cdot kWh^{-1}$	$8.89\cdot10^{-6}$	$4.86\cdot10^{-5}$	5.30	47.2	258
Total	**$g\cdot kWh^{-1}$**				**$6.88\cdot10^{3}$**	**$6.66\cdot10^{4}$**

The total potential water contamination arising from the production of 1 kWh of electricity is $4.43\cdot10^{4}$ m^3 water for Brown Coal Power and $1.13\cdot10^{5}$ m^3 water for Hard Coal Power. In the Brown Coal Power life cycle, only cadmium and mercury contribute significantly to the overall ecotoxic pollution. Yet, many substances contribute to ecotoxic water pollution in the Hard Coal Power life cycle. Mercury contributes over 50%, and lead, cadmium, chromium, copper and zinc are also present in high enough concentrations to be of environmental concern. The water contamination potentials vary in the following way among the UCPTE countries:

- Brown Coal Power, minimum: $1.48 \cdot 10^4$ m^3 (Austria)
- Brown Coal Power, maximum: $1.20 \cdot 10^5$ m^3 (Greece)
- Hard Coal Power, minimum: $6.37 \cdot 10^4$ m^3 (the Netherlands)
- Hard Coal Power, maximum: $1.75 \cdot 10^5$ m^3 (Spain)

The total maximum potential soil contamination arising from the production of 1 kWh of electricity is $6.88 \cdot 10^3$g soil for Brown Coal Power and $6.66 \cdot 10^4$g soil for Hard Coal Power. Many substances contribute to these totals. In the Brown Coal Power life cycle, these are mainly cadmium, mercury, toluol and zinc. In the Hard Coal Power life cycle, the main contributors are mercury, arsenic, chromium, copper, nickel and zinc. The soil contamination potential extremes are listed below:

- Brown Coal Power, minimum: $2.85 \cdot 10^3$ g (Austria)
- Brown Coal Power, maximum: $1.23 \cdot 10^4$ g (Greece)
- Hard Coal Power, minimum: $5.58 \cdot 10^4$ g (the Netherlands)
- Hard Coal Power, maximum: $8.14 \cdot 10^4$ g (Spain)

Total radioactive emissions are also given in the Swiss LCA, but these emissions need to be revised so they have been omitted from this compilation

Since radionuclides differ with respect to composition of emitted radiation and also behave differently after uptake in living organisms, it is not possible to sum up their specific contributions to the overall radioactivity. Most of the radionuclides released in the coal cycle are found in the ash (U.S. Department of Energy, 1997). One should also bear in mind that the combustion of coal results in emissions of carbon dioxide with lower than average amounts of ^{14}C-isotopes, so that air-borne radioactivity becomes diluted.

Habitat alteration

Local climate

Coal mining and burning has been found to release 0.929 g (Brown Coal Power) and 1.16 g (Hard Coal Power) of particles per kWh of produced electricity (Gantner & Hofstetter, 1996). This atmospheric load has the potential to influence habitats. Local climate can be affected by the formation of haze and by the increased availability of condensation cores in the atmosphere. In addition, local climate will be affected by heat emissions to the air and to water. Brown Coal Power releases 2,47 kWh/kWh of heat to the air and 0,455 kWh/kWh to water. Hard Coal Power releases 1,76 kWh/kWh to the air and 0,367 kWh/kWh to water.

Geophysical

Acid mine drainage can result from interaction between of air, sulfur (in the coal), bacteria, and water. Acid drainage can lead to reductions in biodiversity in acidified soil and surface waters. Mining processes that use acids to dissolve solid minerals are not used for coal extraction.

Wildlife habitat and the natural landscape are directly altered by mining activities. The effects will remain unless land reclamation is implemented after mining. The success of reclamation efforts depends on the composition and placement of spoil (fill) material as compared to the characteristics of the original, pre-mining land surface. Over-compaction of the surface by heavy equipment during reclamation can reduce the permeability and therefore hinder the growth of new vegetation on post-mining land (Gantner & Hofstetter, 1996). In addition, since the protective topsoil layer is removed during mining, erosion will increase until new vegetation is established. The extent of erosion depends, among other things, on climate, precipitation, slope and the design of the mining area. Mining can also induce seismic activity and cause subsidence.

Aquatic

During mining activities is often necessary to pump large quantities of water out of the mining area. Excessive pumping will lower the groundwater table thereby causing nearby wells to run dry. Even if the groundwater level is ultimately restored following the termination of mining, the specific soil hydraulic conditions will be permanently altered. The results are often similar for surface and underground mining (Gantner & Hofstetter, 1996) and the effects will remain if no reclamation takes place. When reclamation does take place, the consequence of pumping ground water depend on the composition and permeability of the landfill and how much the new conditions differ from the original site characteristics Mining activities can also cause subsidence, which may affect groundwater and Heated effluents from coal combustion plants (sometimes called “thermal pollution”) may adversely affect aquatic environments especially if once-through systems are used. Again, Brown Coal Power releases 0,455 kWh/kWh to water and Hard Coal Power releases 0,367 kWh/kWh.

2.5 Accidents

Fatalities related to coal mining have decreased in recent years. A dramatic improvement in mine safety has been achieved by improved methane gas and dust control measures. Both methane and dust have been responsible for numerous explosions and fires. Heavy air pollution episodes in the past have caused thousands of deaths, e.g. the infamous smog in London, England in December of 1952. Today’s technical advances in pollution control have eliminated such hazards considerably. The public can also be affected by subsidence due to mining, but casualties are rare. The following severe accidents have been recorded by different studies and are presented in Table 2.14. Post-traumatic casualties and severe injuries are not included:

Table 2.14 Severe accidents related to coal mining based on (Roberts & Ball, 1996) (upper data set) and (Hirschberg & Spiekerman, 1996) (lower data set).

Study period	number of events	Fatalities per event	total immediate fatalities	total late fatalities	energy produced GWa	Fatalities per GWa
1969-1986	62	10-434	3600		10,000	0.34
1969-1992		5-				0.3

2.6 Impact on biodiversity

Global

In global terms, the main environmental effect of electricity produced by coal combustion is probably related to the ubiquitous emission of greenhouse gases. The release to the atmosphere of such gases is larger from coal use than for any other fuel used for generating electricity. It is a general contention that any additional increase of greenhouse gases in the atmosphere will exacerbate global warming. This can lead to rapid changes in local weather conditions and can thus have many and profound influences on biodiversity. Organisms that cannot adapt or migrate successfully under changing climate conditions will be adversely effected. Some species that are endangered because of other anthropogenic disturbances can be especially at risk since their habitats have already been reduced.

Local and regional

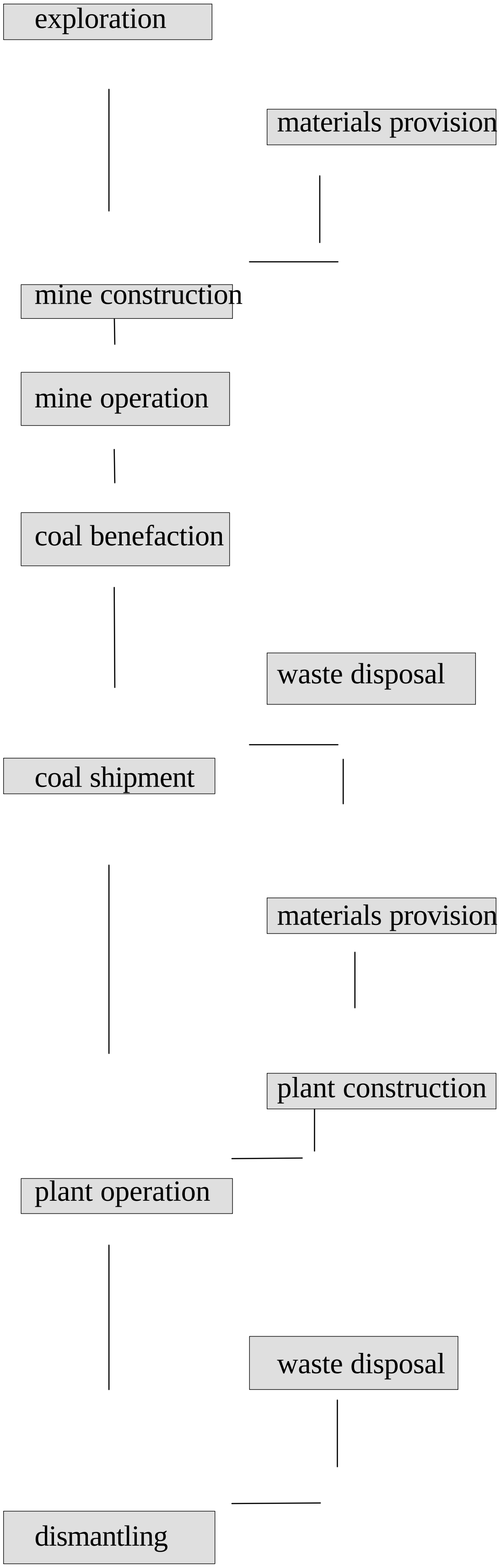
On a local and regional scale coal power generation also influences biodiversity in several different ways:

- Acidification can destroy biotopes and render ecosystem inhospitable to organisms that do not tolerate a low pH. The ultimate outcome of such changes is impaired ecosystem functions, such as reduced productivity, and a lowered rate of nutrient turnover.
- Endangered species may not be able to survive.
- Eutrophication can severely affect aquatic ecosystems as a consequence of the depletion of dissolved oxygen.
- Photochemical smog can damage plants and lead to lowered production or the local extinction of some species.
- Mining activities often change aquatic conditions irreversibly which leads to habitat alteration. When mining takes place in marsh and swamp areas the effects of drainage tend to be especially large.
- Ecotoxic emissions can cause serious environmental health problems. Some substances such as mercury and other heavy metals can accumulate in food chains, and thus especially harm predators (and human beings).

2.7 Impact on humans

Health risks

Each stage of the coal life cycle has associated health concerns, as is shown in the following figure (Roberts & Ball, 1995):



exploration	*acute occupational*
materials provision	*acute occupational, occupational disease, acute public risk in material transport, public risk from pollution*
mine construction	*acute occupational*
mine operation	*acute occupational, pneumoconiosis, radon-induced cancer*
coal benefaction	*acute occupational, public risk from air and water pollution*
waste disposal	*transport-related risk, radon emissions*
coal shipment	*public and occupational transport-related risk*
materials provision	*acute occupational, occupational disease, transport-related risk, and public disease from pollution*
plant construction	*acute occupational*
plant operation	*occupational risk, public disease from air pollution, public risk from global climate change*
waste disposal	*occupational and public risk from transport of waste and waste emissions and leachates*
dismantling	*acute occupational*

In recent decades, occupational health hazards have been reduced in many countries. This has been achieved mainly by improved safety and control measures, but automation, leading to a reduction in manpower, and the younger average age of the work force have also been contributory factors.

*Table 2.16 The health risks of the coal power life cycle for British conditions (Roberts & Ball, 1995). 0 - Not calculated or negligible on a GWa basis; * - Depending on assumptions made.*

Cycle stage	**Acute occupational fatality risk per GWa**	**Occupational disease and carcinogenic risk per GWa**	**Fatal public risks per GWa**
fuel extraction	0.25 - 0.7	0.2 - 0.9	0
fuel preparation/reprocessing	0	0	0
materials/component fabrication	0	0	0
plant construction	0.1 - 0.2	0	0
power plant operation	0.01 - 0.2	0	0 - 6
transport	0	0	0.002 - 0.06
decommissioning	0	0	0
waste disposal	0	0	<2 – 4*
Total	**0.36 - 1.1**	**0.2 - 0.9**	**<2 - 10.1**

Fatal public risks from waste disposal are noted to have a lower boundary of -2 fatalities/GWa. This is due to the use of coal ash in building materials, which could actually reduce public radiation exposure depending on assumptions made. Fatal public risks from power plant operation (flue gas emissions) have by some studies been estimated to be potentially much higher, i.e. up to 77 fatalities/GWa (Roberts & Ball, 1995).

The following two tables (2.17 and 2.18) list health risks of the coal power life cycle calculated in two German studies (Thöhne & Kallenbach, 1988; Fritzsche, 1989). In the second table, the numbers in brackets indicate risk calculations for extreme conditions, e.g., very bad mining conditions.

Table 2.17 Occupational and public health risks from all stages of the coal power life cycle (Thöhne & Kallenbach, 1988)

Acute occupational fatalities per GWa	4.0
Occupational disease and injuries in missing days of work per GWa	19 - 200
Public fatalities per GWa	0.2 – 23.2
Public diseases and injuries in cases per GWa	5.8 - 90

Table 2.18 The occupational and public mortality risks from all stages of the coal power life cycle according to (Fritzsche, 1989).

Acute occupational risk per GWa	0.4 - 3.0 (- 6.5)
Late occupational risk (disease) per GWa	0.1 - 1.0 (- 4.9)
Acute public risk per GWa	0.1 - 1.0 (- 2.3)
Late public risk (disease) per GWa	1.9 - 6.0 (- 15)

All three studies (i.e. Roberts & Ball, 1996; Thöhne & Kallenbach, 1988, and Fritzsche, 1989) indicate that coal power is the electricity option with the greatest health risks. Yet, if new technology is used to generate coal power these risks are very small as compared to everyday health risks. Nevertheless, health risks from diffuse emissions and complex cause and effect chains that are not included in the studies could be considerable. A Norwegian study (Vogt, 1986), for example, suggests that there are increased mortality rates from Alzheimer's disease due to the washing out of aluminium into drinking water by acid rain (Probert & Tarrant, 1989). However, other epidemiological studies have failed to establish such relationships or pointed to the existence of confounding factors (Industrial Disease Standards Panel, 1992). Airborne particles from coal mines and coal combustion could also pose considerable health risks (Edwards, 1997), as well as the consequences from greenhouse gas induced global warming. In general, it can be said that technologies with large effects on the natural environment will also bear large health risks.

Risk perception

In the psychometric paradigm study carried out by Slovic, *et al.* (1979), fossil electric power options rate lowest on the 'unknown risk' factor. With respect to the "dread" factor measured in the study, only nuclear power is perceived to be (far) worse than all other power options. Coal power is comparable with hydropower in terms up public dread. Since this 1979 study, much research has been completed that may have changed the public's perception of risk with respect to different power generation options. The following are examples of the kinds of information that have recently been made available to the public:

- Public discussions about acidification and its effects have only been initiated on a broad scale since 1980 when the first International scientific conference on acid rain took place in Norway. (Although the topic was introduced to the world community at the UN environmental conference in Stockholm 1972).
- Recent research on global warming has lead to scenarios that predict large potential catastrophes. But this same research has also revealed much uncertainty about the consequences of greenhouse gas emissions.
- Much research has been done in recent years on carcinogenic substances, including those arising from the coal combustion process.
- Newer research has shown that human health impact pathways (e.g., of photochemical smog, acidification, carcinogens) are often not known well enough to allow quantification of the total contribution from individual substances.

Such ‘new’ hazards to human health are diffuse, not easily observed, involuntary, partly global, potentially catastrophic, sometimes delayed in their effects, and almost impossible to avoid. These characteristics greatly influence risk perception. The presence of these new hazards would probably lead to a higher score on the ‘dread’ scale as well as on the ‘unknown risk’ factor scale if the study were repeated today. On the other hand, some very substantial improvements have taken place during the two decades that have passed since this study, which might, in fact, counter the higher risk perceptions somewhat. These are:

- New technologies are available which can substantially reduce many emissions
- Occupational health conditions have been greatly improved in many coal mines

Even though scientific insight into the possible health effects of coal power has and will increase, it is not likely that the ‘unknown risk’ factor score will decrease soon. In contrast, scientific research continually uncovers new risks associated with coal power (e.g., health threats from dust from open-cast coal mines) that have to be evaluated. This continuous process of uncovering new public disadvantages stemming from the use of coal power may lead to further increases in public’s perception of ‘unknown risk’. With such new insight into the possible effects of global or regional problems like global warming or acidification, the ‘dread’ factor is almost certainly bound to increase, as well. This development is probable in spite of recent technological developments because even with the new technologies it is not likely that the sum total of world-wide carbon dioxide emissions will be cut.

Social and socio-economic impact

Resettlements

Coal power generation requires extensive land use due to mining. In sparsely populated areas, this is not a large social problem. In densely populated areas, however, resettlements are required, but the number of individuals affected can be reduced if the operation is well planned.

Culture

New mines as well as new power plants in formerly non-industrialised, rural regions will lead to changes in culture. Mining offers an alternative to farming and other occupations. The implications of such changes are topics for future research.

Aesthetic impact

Visual

Mines and the infrastructure that accompanies them (e.g., access roads) are not usually considered aesthetically pleasing. Due to their extended land use, they can change the view and thus the aesthetic value of whole landscapes. If land reclamation does not take place, this change is more or less permanent, and even if the land is reclaimed, the scars will still be seen for decades. Coal power plants can also be considered as a visual intrusion and particulate emissions can alter the appearance of the sky daily. Coal waste disposal sites and access roads may also be unattractive.

Acoustic

The acoustic impact from mines can be considerable, especially in populated areas. To operate the power plant, coal must constantly be transported from the mine to the power plant, which also gives rise to noise. Yet, the operation of power plants and the coal handling plants will only cause noise problems in the local areas.

3 NATURAL GAS

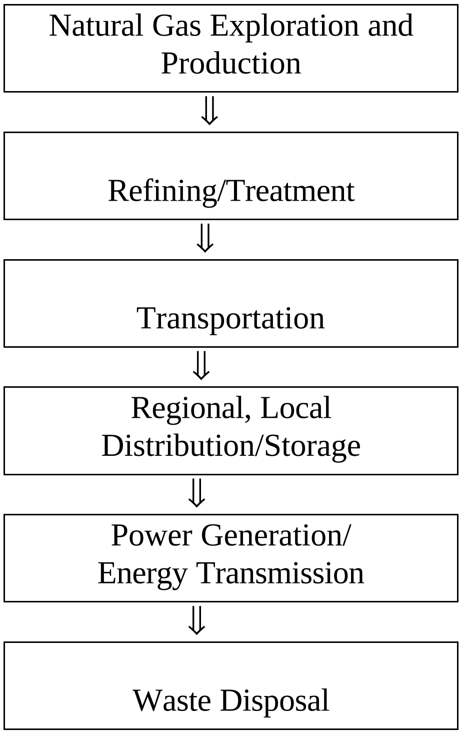
3.1 Frame conditions

In 1990, Natural gas accounted for 23% of all non-renewable fuel used world-wide (Golob & Brus, 1993) and was responsible for 12% of all electricity generation (Maden & Mole, 1996). Natural gas is a naturally occurring mixture of hydrocarbons found in porous geological formations, often in association with petroleum. The principal compound is methane (75-95 percent of volume) but there are also small quantities of other gases such as nitrogen oxide and carbon dioxide. Natural gas is a variety of fossil fuel together with coal, petroleum and their derivatives. Natural gas is formed as a product of anaerobic decomposition of dead organic matter. The gas becomes entrapped in underground pockets and is therefore isolated from further transformation. Natural gas and oil are often found in the same well and therefore they are often produced in conjunction with one another. The equipment used for the exploration, drilling and production of oil and natural gas is usually identical.

Natural gas has a large specific energy content. In fact, twice the amount of coal or 1.25 times the amount of oil on a weight basis is required to provide the same amount of energy as one unit of liquid natural gas (LNG). This is because both the carbon and the hydrogen atoms of methane are oxidised during combustion. Natural gas is a more versatile energy source than oil and coal due to this large specific energy content. Natural gas can also be decarbonised and the resulting hydrogen gas produced can be used as an energy carrier. The cost of generating electricity from natural gas is similar to that from coal, whereas the cost of H_2 production from natural gas is about half that from coal (International Energy Agency, 1997). However, usually natural gas per se is used as an energy carrier. Pipelines are then used to transport the gas from the wells to the end-user, and the gas is mainly used for heating. The following discussion is restricted to life-cycle settings where natural gas is used as the fuel in thermal power plants.

For natural gas, the life-cycle begins at gas wells. After processing, the gas is compressed and distributed through pipelines. The overall efficiency of natural gas from source to appliance is about 91% (U.S. Department of Energy, 2000) which is high compared to most other systems that use electricity as the energy carrier. A simple schematic of the gas lifecycle is presented in Figure 3.1 (Schleisner & Nielsen, 1997).

Figure 3.1 Natural Gas Life Cycle Energy Chain (modified from Schleisner & Nielsen, 1997).



Technology

Methods of Natural Gas Electricity Generation

Several natural gas technologies exist for generating electricity and equipment required, efficiency, and emissions vary. All of these technologies use at least a simple gas turbine to generate electricity. The most common technique for burning the gas uses nozzle-mixing pressure air burners. In this method pressurised air is discharged through a nozzle and gas ports supply the air stream with gas. Combustion takes place in a burner tunnel and the pressure generated turns the turbine. Summaries of the specific natural gas electricity generation technologies follows:

1) Cogeneration

Cogeneration produces electricity and usable heat instead of just electricity. This process allows for a higher overall energy efficiency and reduced emissions per unit of fuel used to produce energy since the "waste" heat is recovered (Beals & Hutchinson, 1993).

One method of cogeneration uses natural gas turbines to generate electricity and then recovers heat from exhaust and cooling water with heat exchangers to generate steam or hot water. This recovered heat can be used for heating local buildings, water heating and other thermal needs (Beals & Hutchinson, 1993). The recovered heat energy must be used locally since it cannot be transferred over long distances.

2) Combined Cycle Technology

Combined Cycle technology is a specific method of cogeneration. In this process, electricity is generated by a gas turbine, which is linked to a steam cycle generator. The heat exhaust from the gas turbine is converted through a heat exchanger to produce the steam, which drives the steam turbine (Beals & Hutchinson, 1993). Efficiencies of more than 50% can be achieved with combined cycle technology as compared to 33% with a basic natural gas powered turbine (Ryder, 1997).

3) Reburning

Natural gas reburning is a process that uses natural gas in a traditional boiler meant for other fuels. After the other fuel is combusted the boiler is heated to a higher temperature and natural gas is injected. This process generates additional energy from the natural gas and reduces the total amount of SO_2 and NO_x emissions at the same time (National Gas Supply Association, 1998).

4) Co-firing

Co-firing is essentially the same process as reburning, but the natural gas is burned at the same temperature as the traditional fuel. This process reduces SO_2 and NO_x emissions, as well (National Gas Supply Association, 1998).

Gas to Liquid Conversion Technology – LNG

When building a natural gas pipeline is not an economically feasible option, liquid natural gas (LNG) may be an alternative state for transporting this fuel. LNG is natural gas cooled to – 260 degrees F at atmospheric pressure (National Gas Supply Association, 1998). Under these conditions natural gas is a liquid. LNG is combustible at concentrations of 5-15% when mixed with air (National Gas Supply Association, 1998). LNG must be stored below 117 degrees F in special insulated tanks to stay in liquid form. The process of cooling of natural gas to reach its liquid state generates heat that can be put into productive use or vented away. Depending on the selected method in this respect the overall energy efficiency of the system will be affected.

While expensive, there is currently a market for LNG. Sometimes the total cost, including environmental costs, for building a natural gas pipelines between countries can be more expensive than building LNG facilities and paying to import LNG fuel. Japan is currently the world largest importer of LNG and other countries are discovering regional LNG markets, as well.

<u>Transportation</u>

Natural gas requires more technical and expensive transportation accommodations than oil or other fuels since it exists as a gas at standard pressure and temperature. Therefore, for natural gas to be transported in an economically feasible manner it must be compressed/cooled for transport by container as LNG or it must be transported by pipeline. As a result, most natural gas is consumed in close proximity to the production site. Natural gas produced for export only totals 15% (Golob & Brus, 1993). Natural Gas is primarily transported by pipeline (75%), and a smaller percentage (25%) is shipped as LNG (Golob & Brus, 1993).

Alternative Sources of Natural Gas

1) Coal Bed Methane (CBM)

Methane is often associated with coal deposits in concentrations of up to 200 m^3 of methane per tonne of coal (Freund *et al.*, 1998). Methane captured directly from coal beds that have not previously been mined is often more than 90% pure. It is possible to use this source of methane to operate generators since the technologies to capture methane are available, but very little CBM is currently used to generate electricity. Most captured CBM (about 25%) is vented of flared since facilities to utilise the methane are not available or economically feasible to install (Freund *et al.*, 1998). In some cases, however, the cost of capturing and utilising CBM for electricity generation is cheap enough to generate a net profit (Freund *et al.*, 1998).

2) Methane Hydrates

Although not always a considered a natural gas "reserve", methane does exist in vast quantities in continental permafrost and in the ocean floor sediment (Golob & Brus, 1993). At high pressures and low temperatures, methane gas can become trapped in solid water-ice "cages". This structure is called a methane hydrate. Large methane hydrate deposits have been found in Siberia, Northern Canada, Alaska and off the coasts of Japan, India and the Eastern coast of the U.S.A., to name a few locations. Currently, countries such as Japan and India that do not have extensive domestic energy resources are actively researching ways to produce methane hydrates for fuel. Yet, at this time the methods available to extract methane from hydrates are too expensive to be economically viable. The amount of methane stored in hydrate form is estimated at two times the amount of traditional natural gas reserves and, therefore, the deposits may become an important source of natural gas for future generations.

Innovative Natural Gas Technologies

Some innovative technologies related to natural gas production, transportation, and power generation beyond the traditional natural gas power plant lifecycle may have interesting implications for future world energy supply.

For example, one argument in favour of using natural gas to fuel vehicles advocates that the wide-spread use of such vehicles would liberate large quantities of oil for other energy needs. While environmental savings may be noted in terms of car exhaust emissions, what new, environmental impacts could result if, for example, 20% of cars used fuel cells or LNG? Complete lifecycle assessments should consider all of these factors and tradeoffs.

A summary of two innovative natural gas technologies follows:

1) *Natural Gas Vehicles (NGVs).*

According to the Natural Gas Supply Association, gasoline powered vehicles contribute 75% of the urban carbon monoxide pollution along with a whole suite of other air pollutants (National Gas Supply Association, 1998). Tests of NGVs by the Gas Research Institute indicate that they emit virtually no particulate matter and can reduce carbon monoxide emissions by more than 80% over gasoline fuelled vehicles (National Gas Supply Association, 1998).

The two kinds of natural gas vehicles currently in use are compressed natural gas (CNG) and Liquid natural gas fuelled cars. To prepare the natural gas for use in the vehicles CNG is compressed to 2,400-3600 psi and LNG is cooled to 259 degrees F (Sinor, 1992). Currently there are more than 1 million natural gas vehicles in use world-wide. One out of every five public buses in the United States is powered by natural gas (Sinor 1992). CNG fuelling stations are available in major cities, but LNG refuelling stations are still only available in a few locations. The performance and maintenance of natural gas powered vehicles is comparable to gasoline powered vehicles, but the travel range can be less, depending on fuel storage capacity, than gasoline powered vehicles. In some areas the fuel cost for LNG and CNG can be less expensive than the gasoline equivalent, depending on local price variations, taxes and fees. In Stockholm, Sweden, methane from fermented sewage is used to drive engines, including cars. It should be observed, however, that the natural gas in this case, is renewable since it is made from a kind of biomass.

2) *Fuel Cells Powered by Hydrogen Derived from Methane*

The fuel cell is another technology that holds promise for increasing the efficiency of natural gas use in electricity production. Fuel cells are electrochemical devices that use hydrogen to generate electricity through a chemical process. A reformer can be used to extract the hydrogen from another fuel source such as natural gas or methanol (Breakthrough Technologies Institute, 2000). A fuel cell powered by hydrogen derived from natural gas can yield lower emissions per kWh than traditional natural gas power generation methods (Beals & Hutchinson, 1993). Fuel cells are being considered for electricity generation and for powering cars because they are efficient (over 40 percent of the fuel energy is converted into electricity) and relatively clean (Beals & Hutchinson, 1993). Natural gas powered fuel cells are anticipated to be a front runner in the fuel cell market due to several aspects including reasonable cost, low emissions, and minimal fuel preparation (Beals & Hutchinson, 1993).

Geography

From 1988 - 1997, the production of dry natural gas increased at an average annual rate of 1.8 percent (U.S. Department of Energy, 2000). In 1997, Russia produced the most natural gas with 20.2 trillion cubic feet, followed by the United States with 18.9 trillion cubic feet, Canada with 5.9 trillion cubic feet, the United Kingdom with 3.2

cubic feet, and the Netherlands with 3.0 trillion cubic feet. In 1997, the United States was the leading consumer of dry natural gas with 22.0 trillion cubic feet, followed by Russia with 13.4 trillion cubic feet, Germany with 3.4 trillion cubic feet, the United Kingdom with 3.2 trillion cubic feet and Canada with 3.0 trillion cubic feet. Overall, Russia and the United States account for more than 40% of the world's production and consumption of natural gas (U.S. Department of Energy, 2000).

Table 3.1 World natural gas production in 1997 (International Energy Agency, 1997) (Trillion Cubic Feet).

Region	**Consumption** (Trillion Cubic Feet)
North America	25.94
Central and South America	2.93
Western Europe	9.90
Eastern Europe & Former USSR	24.75
Middle East	6.03
Africa	3.59
Far East & Oceania	8.57
Total	81.71

Table 3.2 World natural gas consumption in 1997 (International Energy Agency, 1997).

Region	**Consumption** (Billion Cubic Feet)
North America	26,129
Central and South America	2,930
Western Europe	14,151
Eastern Europe & Former USSR	22,028
Middle East	5,660
Africa	1,844
Far East & Oceania	8,901
Total	81,643

Economics

The use of natural gas technologies that are more efficient and produce less greenhouse emissions than other fossil fuels is expected to increase due to several factors. For natural gas fuel cells, which show promise for filling electricity generation needs, recent technology advances have helped to reduce the manufacturing costs. Mass production of a fuel cell with the capacity to heat a household or small office is expected occur in the United States by 2001 (Anonymous, 1999)

The energy deregulation policies across Europe and in the United States are also helping to create environments that encourage energy efficient solutions such as NGVs, Fuel Cells, natural gas combined-cycle technologies.

Life cycle assessment

Data from several different LCA studies is used for this survey. In some cases typical, hypothetical natural gas data are used in lieu of data from a specific existing plant. In a Swiss study completed by the Swiss Federal Institute of Technology (ETHZ) and the Paul Scherrer Institute (PSI) lifecycle resource use was analysed for many different energy systems. Values were reported as UCPTE country averages using 1992 values. The UCPTE country average is meant to represent the mean situation for Belgium, Germany, France, Greece, Italy, Ex-Yugoslavia, Luxembourg, The Netherlands, Austria, Portugal, Switzerland, and Spain (Frischknecht *et al.*, 1994). This data is reported in several publications and the data is also relied on heavily in a 1994 report by Det Norske Veritas (Sandgren & Sorteberg, 1994).

The Swiss study presents values for greenhouse gas emissions for the mix of UCPTE countries and considers several factors including, leakage, Swiss and European end uses, treatment for high sulfur gas, and different production methods. Natural gas LCA data from energy chains originating in Germany, Norway, Algeria, etc, are incorporated since no gas powered plant exists in Switzerland (Dones *et al.*, 1994). Gas leakage for natural gas from Russian sources is estimated at 2% (although uncertain) and gas leakage for local distribution systems in Switzerland is estimated at 0.9%. The average leakage is estimate at 1%. For the calculations the natural gas composition is assumed to be 84% natural gas, 8% coke gas and 8% blast-furnace. After comparing the energy chain data from all of the fossil fuels the overall electricity consumption for plant operation, etc. in the natural gas chain is the lowest at approximately 1% (Dones *et al.*, 1994).

Natural gas accounts for two percent of Swedish energy. A 1996 Swedish lifecycle assessment studied a (hypothetical) natural gas fired combined cycle power plant; i.e. both the gas expansion and the heat were used to generate electricity. The net efficiency is therefore rather high, 53 percent and the power output is 465 MW. A plant lifetime of 40 years is assumed. The lifecycle analysis includes building and operating the natural gas pipelines (offshore and on land) and building, operating and dismantling the power plant. The gas source is the Norwegian part of the North Sea where oil and gas are produced together. The gas is transported by pipeline from Norway, through Denmark, to the power plant situated in the Southwest of Sweden (Brännström-Norberg & Setterwall, 1996). As a back up, the power plant is fuelled with light oil when technical disturbances occur and when the pipelines are checked (Brännström-Norberg & Setterwall, 1996).

Two hypothetical 1,000 MW natural gas power plants have been studied in Japan. The first is a single, simple turbine power plant, while the other is a combined cycle system. The net efficiencies are 37.64 and 48.25 percent, respectively. The lifetime of each plant is assumed to be 30 years (Uchiyama, 1994).

3.2 Use of resources

Non-renewables

The use of non-renewable resources in the Swedish power plant was calculated in the Swedish LCA. Only material that was used in large quantities was included. Data on the energy consumption used in this and other the life cycle analysis are usually based on the electricity mix in the countries where the electricity is consumed. The results are presented in Table 3.3 Extensive amounts of iron ore and ballast are used to build the pipelines needed for gas transportation. The reserve power of the plant is oil which accounts for the large oil consumption.

Table 3.3 The use of non-renewable resources in the Swedish power plant (Brännström-Norberg & Setterwall, 1996).

Non-renewable	Unit	Total use
Energy		
Uranium	$kg\cdot kWh^{-1}$	$4.42\cdot10^{-9}$
Coal	$kg\cdot kWh^{-1}$	$1.54\cdot10^{-4}$
Oil	$m^3\cdot kWh^{-1}$	$2.87\cdot10^{-6}$
Gas	$m^3\cdot kWh^{-1}$	$1.72\cdot10^{-1}$
Petrol	$m^3\cdot kWh^{-1}$	$5.03\cdot10^{-9}$
Diesel	$m^3\cdot kWh^{-1}$	$5.43\cdot10^{-7}$
Material		
Iron ore	$g\cdot kWh^{-1}$	$3.09\cdot10^{-1}$
Limestone + gypsum	$g\cdot kWh^{-1}$	$5.98\cdot10^{-2}$
Ballast	$g\cdot kWh^{-1}$	3.25
Copper ore	$g\cdot kWh^{-1}$	$3.73\cdot10^{-1}$
Stone wool	$g\cdot kWh^{-1}$	$1.78\cdot10^{-3}$
Titan	$g\cdot kWh^{-1}$	$2.57\cdot10^{-3}$
Vinyl chloride monomer	$g\cdot kWh^{-1}$	$2.50\cdot10^{-3}$
Bauxite	$g\cdot kWh^{-1}$	$2.26\cdot10^{-4}$
Polythene	$g\cdot kWh^{-1}$	$2.14\cdot10^{-3}$
Tri-sodium phosphate	$g\cdot kWh^{-1}$	$3.07\cdot10^{-4}$
Hydrazine	$g\cdot kWh^{-1}$	$2.46\cdot10^{-3}$
Nitric acid	$g\cdot kWh^{-1}$	$3.00\cdot10^{-3}$
Sodium hydroxide	$g\cdot kWh^{-1}$	$3.84\cdot10^{-2}$
Ammonia (25%)	$g\cdot kWh^{-1}$	$3.14\cdot10^{-1}$
Polymer	$g\cdot kWh^{-1}$	$9.22\cdot10^{-5}$
Hydrochloric acid	$g\cdot kWh^{-1}$	$7.68\cdot10^{-2}$
Iron chloride	$g\cdot kWh^{-1}$	$6.14\cdot10^{-3}$
Bentonite	$g\cdot kWh^{-1}$	$1.13\cdot10^{-1}$
Other chemicals	$g\cdot kWh^{-1}$	$4.09\cdot10^{-2}$

Table 3.4 lists the values for the main non-renewable resources used in LCA of the Japanese power plants and Table 3.5 lists the values by the Swiss study for major non-renewable resources used in the natural gas LCA, respectively.

Table 3.4 Non-renewables used in the Japanese power plant LCA (Uchiyama, 1994).

Material	**Unit**	**Total**
Steel	$g\cdot kWh^{-1}$	1.57
Stainless steel	$g\cdot kWh^{-1}$	$1.52\cdot10^{-2}$
Aluminium	$g\cdot kWh^{-1}$	$1.31\cdot10^{-2}$
Copper	$g\cdot kWh^{-1}$	$4.84\cdot10^{-4}$
Concrete	$g\cdot kWh^{-1}$	$7.04\cdot10^{-1}$

Table 3.5 Non-renewable resources used in the natural gas lifecycle for UCPTE average (Dones et al., 1994).

Material	**Unit**	**Total**
Total Materials	1000 tonnes$\cdot TWh^{-1}$	16
Concrete Gravel	1000 tonnes$\cdot TWh^{-1}$	2.8
Iron	1000 tonnes$\cdot TWh^{-1}$	2.1
Copper	$kg\cdot TWh^{-1}$	17000
Pa, Pt, Re, Ph, Ag	$kg\cdot TWh^{-1}$	20

Renewables

The overall use of renewable resources is low in the lifecycle of natural gas power generation (Table 3.6).

Table 3.6 The use of renewable resources in the Swedish power plant (Brännström-Norberg & Setterwall, 1996).

Renewable	**Unit**	**Total use**
Energy		
Hydropower	$kWh\cdot kWh^{-1}$	$2.82\cdot10^{-4}$
Wooden chip	$kg\cdot kWh^{-1}$	$2.11\cdot10^{-5}$
Material		
Wood	$G\cdot kWh^{-1}$	$4.92\cdot10^{-2}$

Land

The environmental assessment completed by Det Norske Veritas considers land use to be the most important kind of resource "consumed" by electricity generating systems (Sandgren & Sorteberg, 1994). In natural gas systems land use is partly due to pipelines and partly due to the facilities (e.g. offshore production facilities and the power plant itself).

In the Swedish lifecycle analysis, the land used for pipelines is calculated as the area multiplied by the time the area is occupied, whereas only the area is taken into account in calculating the land used for the power plant and the offshore facilities. The land use for natural gas electricity production was also calculated in a Swiss study. The total land use was estimated to be $1.0 \cdot 10^{-2}$ $m^2 \cdot year \cdot kWh^{-1}$ (Sandgren & Sorteberg, 1994).

Table 3.7 Total land use for the Swedish power plant (Brännström-Norberg & Setterwall, 1996).

Land use	Unit	Total use
Pipeline		
Agricultural land	$m^2 \cdot year \cdot kWh^{-1}$	$9.45 \cdot 10^{-5}$
Wooden land	$m^2 \cdot year \cdot kWh^{-1}$	$3.87 \cdot 10^{-5}$
Power plant	$m^2 \cdot kWh^{-1}$	$1.06 \cdot 10^{-6}$
Offshore	$m^2 \cdot kWh^{-1}$	$6.79 \cdot 10^{-5}$

In general, natural gas combined cycle technology and other cogeneration methods increase the amount of land used in comparison to a simple gas turbine since additional heat exchange and steam turbine equipment is needed. A 1993 report prepared for Ontario Hydro estimated that the land use for natural gas combined cycle is 1.4-1.6 m^2/Mwe-h (Beals & Hutchinson, 1993). The same 1993 report also estimates the land use by natural gas fuel cells to be in the range of 1.1-1.5 m^2/Mwe-h (Beals & Hutchinson, 1993).

3.3 Global environmental impact

Natural gas is the cleanest burning fossil fuel and the use of natural gas can, in effect, improve the environment when it is used instead of other fossil fuel options. The benefits of natural gas combustion over other fossil fuels include reduced CO_2 and NO_x emissions and essentially no SO_2 or particulate matter emissions (National Gas Supply Association, 1998). The Swiss study reports a value of 790×10^3 tonnes CO_2 equivalents/ TWh_{el} for the natural gas LCA global warming potential (GWP) for 100 years (Sandgren & Sorteberg, 1994).

Greenhouse effect

Emissions of greenhouse gases are substantial in the natural gas electricity generation LCA. Greenhouse gases are emitted both during combustion and fuel production. In addition, methane is released during transportation when natural gas is distributed by pipeline (Dones *et al.* 1994). As more natural gas is produced and as longer pipelines are built to transport natural gas over larger distances more greenhouse gases will be emitted unless tighter controls on leakage are implemented. However, recent evaluations indicate that emissions of natural gas during transportation may not be as high as sometimes anticipated (Lang & Crook, 1996; Dedikov *et al.*, 1999).

The amount of CO_2 and methane (g) emitted per kWh has been calculated in several studies. The emissions reported by Japanese and Swedish studies are shown in Table 3.8 and Table 3.9, respectively. The Swiss study estimated CO_2 emissions at 422 grams CO_2 equivalents per kilowatt-hour.

During oil and gas production the inputs and outputs of methane are metered. Often is the output less than the input. The deficit, referred to as “unaccounted-for-gas”, is a combination of actual losses and a net metering error. Estimations of the unaccounted-for-gas in percent of the total production for different countries have been compiled by (Eng, 1990). Estimates of leakage from facilities in the U.S.A. have been estimated at about 1.4 percent (Lang & Crook, 1996). In Russia the losses have recently been at 1-2 percent, local distribution excluded (Dedikov *et al.*, 1999). Previous estimates for the former Soviet Union have reported leakage amounting to 10-20 tonnes of methane per km of pipe (Freund *et al.*, 1998) Emissions of this magnitude are preventable if best available technologies are used when building and replacing pipelines (Freund *et al.*, 1998).

Table 3.8 The emission of greenhouse gases in carbon dioxide equivalents ($g^{x}kWh^{-1}$) from Japanese natural gas power plants (Uchiyama, 1994).

Substance	**Unit**	**Manufacturing and construction**	**Operation and maintenance**	**Total**
Conventional LNG fired power plant				
CO_2 carbon dioxide	$g\cdot kWh^{-1}$	2.02	591.70	593.72
CH_4 methane	$g\cdot kWh^{-1}$	0.11	57.64	57.75
Total	**$g\cdot kWh^{-1}$**	**2.13**	**649.34**	**651.47**
Advanced LNG combine power plant				
CO_2 carbon dioxide	$g\cdot kWh^{-1}$	1.17	461.96	463.13
CH_4 methane	$g\cdot kWh^{-1}$	0.07	44.99	45.06
Total	**$g\cdot kWh^{-1}$**	**1.24**	**506.95**	**508.19**

Table 3.9 The emission of greenhouse gases from the Swedish combined cycle power plants lifecycle (Brännström-Norberg & Setterwall, 1996).

Substance	**Unit**	**Total**
CO_2	$g\cdot kWh^{-1}$	422
CH_4	$g\cdot kWh^{-1}$	$3.28\cdot10^{-2}$
N_2O	$g\cdot kWh^{-1}$	$3.78\cdot10^{-4}$

In Table 3.8 most of the CO_2 and methane emitted from both Japanese LNG plants is derived from operation of the plant (i.e. combustion). The comparison of the conventional and advanced LNG power plants demonstrates clearly that a more efficient technology can reduce greenhouse gas emissions. The conventional LNG power plant emits approximately 28% more CO_2 and methane than the advanced combined cycle LNG plant.

A 1993 Report prepared for Ontario Hydro (Table 3.10) estimates the amount of CO2 emissions for simple cycle gas turbine technology, combined cycle natural gas technology, fuel cells powered by hydrogen derived from natural gas. These values again demonstrate that the use of more efficient technologies reduces amount fossil fuels consumed and amount of greenhouse gases emitted per unit of energy produced. In turn, if these more efficient technologies are utilised on a larger scale, especially for replacing old fossil fuel based thermal power stations, a positive effect on the overall rate of fossil fuel consumption and greenhouse gas emissions may be realised.

Table 3.10 Lifecycle carbon dioxide emissions (g/KWe-h) for three natural gas technologies (Beals & Hutchinson, 1993).

Generation Method	**Total LCA CO_2 Emissions**
Simple Cycle Natural Gas Turbine	747-866
Combined Cycle Natural Gas Turbine	524-612
Fuel Cell using hydrogen derived from natural gas	414-660

Increasing the efficiency of natural gas power plants is one way to decrease the greenhouse gas emissions. Another way to decrease emissions is to choose natural gas technology (i.e. fuels partly based on hydrogen) instead of fossil fuels with a comparative high carbon content. Many countries are making efforts to diversify their fuel use and to gradually switch to lower carbon and renewable energy options. With an increase in per capita energy demands, Egypt has chosen to supplement hydropower and oil use with natural gas. Starting in the early 1970's Egypt made a shift to natural gas. By 1990, natural gas comprised 38% of the total energy consumption in Egypt. An estimated 4 Mtonnes of CO_2 emissions have been avoided by meeting additional energy needs with natural gas instead of oil in Egypt from 1970 to 1990 (Emara & Rashad, 1994).

Using LNG Technology to Reduce Methane Emissions

Currently liquefaction and re-gasification technologies to produce and use liquid natural gas (LNG) can be prohibitively expensive to implement. In some cases, however, the uses of LNG technology may be the best way to recover sources of natural gas that currently contribute to the large pool of methane emitted to the atmosphere.

A large volume of methane is given off during the process of recovering many types of fuels. Estimates for methane emissions during oil and gas production total 47 Mt/year and this number is expected to increase with the increase with natural gas use (Freund *et al.*, 1998). Coal bed methane (CBM) is often liberated during coal mining and processing and methane emissions from combined world coal mine sources are estimated at 22 Mt/year (Freund *et al.*, 1998). These sources of natural gas are often flared (during oil production), vented (oil and gas), leaked (from old equipment and gas compressors), or pumped out (coal) especially in rural areas where pipelines and/or technologies to collect/conserve these sources of gas are not available. In this situation, gas to liquid conversion may be a viable alternative. Lower cost methods to liquefy natural gas are being developed and will be made available in the future (Sinor, 1992).

Ozone layer depletion

Since the 1980's seasonal, polar ozone layer depletion has been a concern. Anthropogenic emissions of several suspect chemicals have been targeted and the long residence time of these substances has aroused concern in the scientific community. A reduced ozone layer may contribute to a greater risk of cancer, mutations in the animal kingdom, and other environmental harm. Though the methane and NO_x are substances that can potentially degrade the stratospheric ozone layer, the specific effects and interactions attributable to these greenhouse gases emitted as part of the natural gas LCA are difficult to assess and predict. The Swiss study presents a UCPTE country average value of 25 kg CFC11 equivalents/ TWh_{el} for the natural gas LCA (Dones *et al.*, 1994). This is probably not a large concern for the natural gas lifecycle (Dones *et al.*, 1994).

3.4 Local and regional environmental impact

The Environmental impact review by Det Norske Veritas concludes that data and the analytical tools to assess local impacts is currently not available, but some general comments can be made.

On a local and regional scale natural gas power generation may influences biodiversity in several different ways:

- Acidification can destroy biotopes and cause serious harm to ecosystems.
- Endangered species may not be able to survive.
- Eutrophication *can severely* affect aquatic ecosystems
- Photochemical smog can damage plants and lead to the extinction of some species.
- Ecotoxical emissions can cause serious environmental health problems. Ecotoxic substances can accumulate in food chains, and thus especially harm predators (and human beings).

For all of these factors, coal, oil, and lignite contribute significantly more emissions over their lifecycle than natural gas while nuclear power and hydro contribute significantly less.

Acidification

Though natural gas is considered a clean fuel by many, emissions of NO_x may pose a problem to local environments. The deposition of NO_x may lower soil and water pH and therefore harm ecosystems. Local conditions (geological, biological, etc.) affect the magnitude and kind of ecosystem damage from NO_x deposition (Dones *et al.*, 1994). Sensitive ecosystems with certain kinds of susceptible vegetation may become more prone to blight and disease as a side effect of acidification (Dones *et al.*, 1994). The Swiss study reports a value of 1.4 tonnes SO_2^- equivalents/TWh_{el} (Dones *et al.*, 1994)

Eutrophication

NO_x emissions from the natural gas LCA also contribute to eutrophication. Different water reservoirs will be effected differently depending on chemical composition, location, aquatic flora and fauna, the extent of exposure to air pollution, etc. The Swiss study reports a UCPTE country average eutrophication potential for natural gas LCA at 203 tonnes PO_4^{3-} equivalents/TWh_{el} (Dones *et al.*, 1994).

Photochemical oxidant formation

Photochemical reactions between substances such NO_x, volatile hydrocarbons and other chemical pollutants can lead to the formation of photochemical oxidants. These substances can damage plants, cause respiratory problems in humans, and lead to other environmental harm. Photochemical ozone creation potential (POCP) is usually presented as grams of ethene-equivalents per kWh of produced electricity. The Swiss study reports a UCPTE country average value of 38 kg ethene-equivalents/kWh.

Ecotoxic impact

Ecosystems may suffer damage from the emission of toxic chemicals into water and soil reservoirs. The Swiss study reports a UCPTE country average value of 3.1 tonnes/ TWh_{el} for toxic substances discharged to water and a value of 45 tonnes/ TWh_{el} for toxic substances discharged to air (Dones *et al.*, 1994). This value accounts for discharges of antimony, arsenic, beryllium, lead, cadmium, chromium, cobalt, copper, mercury, silver, tin, polycyclic aromatic hydrocarbons, and tri-butyl tin.

Habitat alteration

Local climate

The advantage of using natural gas instead of other fossil fuels is that particulate matter emissions are essentially eliminated. Therefore the haze that can be associated with coal mining is not an issue for natural gas electricity generation. However, greenhouse gas emissions may still impact climate, though to a lesser extent than for other fossil fuels.

Aquatic

A 1997 Danish study examines the external costs related to different power plant lifecycles (Schleisner & Nielsen, 1997). During the natural gas lifecycle some emissions enter ocean and river reservoirs. The primary impacts to the North Sea from the natural gas fuel cycle are from offshore drilling and natural gas treatment, both of which produce some emissions. This study concludes that these emissions to the marine environment from offshore oil and gas production are negligible. Pollution from oil leakage and waste products are more of a concern.

3.5 Accidents

The data presented in Table 3.11 is from a 1994 Norske Veritas LCA report (Sandgren & Sorteberg, 1994). For natural gas the risk of immediate fatalities (those occurring from an explosion or other sudden accident) was found to be greater than the risk of fatalities caused by delayed risks (e.g. continued exposure to power plant operation over time). This is a reverse of the trend found for coal, oil, and nuclear power where the delayed risks of fatality are greater than the immediate risks. Natural gas accidents can produce highly explosive fires and this characteristic of natural gas leads to the greater risk of immediate fatalities. Table 3.11 considers the risk of accidents throughout the natural gas lifecycle from extraction and transportation to power plant operation. The data indicate that offshore natural gas production methods pose a slightly higher risk of fatalities that on-land natural gas recovery methods.

Table 3.11 Estimated Lifecycle Fatalities due to Natural Gas (fatalities/GW$_e$*year) (Sandgren & Sorteberg, 1994).*

Extraction method	**Occupational (immediate)**	**Public (immediate)**	**Public (delayed)**
Land	0.10-0.15	0.2	0.004-0.2
Offshore	0.17-1.0	0.2	0.004-0.2

3.6 Impact on biodiversity

In global terms, the main environmental effect of electricity produced by natural gas combustion is the additional contribution of anthropogenic greenhouse gases. Less greenhouse gases are emitted during the natural gas lifecycle than for any other fossil fuel used for generating electricity, but any additional greenhouse gases emitted to the atmosphere may exacerbate global warming. This can lead to rapid changes in local weather conditions and can thus have many and profound influences on biodiversity. Flora and fauna that cannot adapt or migrate successfully under changing climate conditions will not survive. Endangered species can be especially at risk since their habitats often have already been changed or significantly reduced in size.

One interesting phenomenon related to NG is the fragmentation of wildlife habitats caused by above-ground pipelines in permafrost areas. In North America, this has called for a need to construct special crossings for caribou.

3.7 Impacts on humans

Health risks

The main public health risk associated with natural gas electricity generation is from air pollution due to power plant operation (Schleisner & Nielsen, 1997). A 1997 Danish Study estimates that accidents related to road traffic during plant construction, and accidents related to plant operation are insignificant compared to the risks associated with air pollution.

Risk perception

In the psychometric paradigm study carried out by (Slovic *et al.*, in 1979) fossil electric power options rate lowest on the ‘unknown risk’ factor. With respect to the “dread” factor measured in the study, only nuclear power is perceived to be (far) worse than all other power options. Since this 1979 study, much research has been completed that may have changed the public’s perception of risk with respect to different power generation options. The following are examples of the kinds of information that have recently been made available to the public:

- Public discussions about acidification and its effects have only been initiated on a broad scale since 1980 when the first International scientific conference on acid rain took place in Norway. (The topic was introduced to the world community at the UN environmental conference in Stockholm 1972).
- Research on global warming has lead to scenarios with large potential catastrophes and has also revealed much uncertainty about the consequences.
- Much research has been done on carcinogenic substances (e.g., arising from combustion processes) in recent years.
- Newer research has shown that human health impact pathways (e.g., of photochemical smog, acidification, carcinogenics) are often not known well and can hardly be quantified.

Such ‘new’ hazards to human health are diffuse, not easily observed, involuntary, partly global, potentially catastrophic, sometimes delayed in their effects, and mostly impossible to personally avoid. These characteristics greatly influence risk perception. This would probably lead to a higher score on the ‘dread’ scale as well as on the ‘unknown risk’ factor scale if the study were repeated today. On the other hand, some very substantial improvements have taken place in the meantime, which might, in fact, counter the higher risk perceptions, somewhat including the fact that new technologies are available which can substantially reduce many emissions.

Even though scientific insight into the possible health effects of natural gas has and will increase, it is not likely that the ‘unknown risk’ factor score will decrease soon. This continuous process of uncovering new public disadvantages stemming from the use of natural gas power may lead to further increases in public's perception of 'unknown risk'. With such new insights into the possible effects of global or regional problems like global warming or acidification, the 'dread' factor is almost certainly bound to increase, as well. This development is probable in spite of recent technological developments because even with the new technologies it is not likely that sum total of world-wide carbon dioxide emissions will be cut.

Social and socio-economic impact

Resettlements

Natural gas generation requires extensive land use due to pipelines and oil/gas fields. But this land use does not usually lead to resettlement.

Culture

Replacing or retrofitting older power plants with natural gas technology will lead to retraining opportunities for employees but no real cultural changes. When natural gas is introduced into regions that have extensive power needs (e.g., LNG use in Southern China) then new jobs and training will occur. When new natural gas power plants are introduced into formerly non-industrialised rural regions this will lead to the greatest cultural changes. Building pipelines and constructing power generation facilities offers an alternative to farming and other occupations. How these changes are to be evaluated is a topic for future research.

Aesthetic impact

Visual

Natural gas pipelines have little impact on landscape in comparison to strip mines, but offshore oil/gas rigs can be considered a nuisance to coastal communities. The state of Florida has outlawed most oil and gas exploration off the Florida coast in an effort to preserve the ocean view from beachfront property. Floridians value the view more than the expected revenue that fuels the Alabama, Mississippi, and Texas economies. It is common to be able to see 20 or 30 platforms while standing on an Alabama beach and looking out at the Gulf of Mexico. Unless new platforms are built further from the coast, and unless old platforms are retired and disassembled, these ocean view distractions will continue to effect tourism. It is likely that above ground pipelines and right-of-ways as artificial corridors in the natural landscape are often regarded as intrusions on the aesthetic amenities, but few studies appear to address this aspect in general terms. In some regions where pipelines have been buried in permafrost soil, thawing and upheavals tend to broaden the right-of-ways and alter the local conditions, phenomena that are even observed on satellite images (Kayser-Threde & Wegmüller, 1997).

Acoustic

The operation of the power plants and natural gas prep plants will only cause acoustic disturbances in the immediate surroundings. Offshore oil/gas production noise is also only a localised issue.

4. NUCLEAR

4.1 Frame conditions

In 1997, nuclear power ranked fifth as a primary energy source. Nuclear power generation accounted for 6.3 percent of world primary energy production. From 1988 to 1997 the world's total output of nuclear electric power increased 26.4 %, rising from 1.8 trillion kWh to 2.3 trillion kWh (U.S. Department of Energy, 2000).

Nuclear power plays an important role in electricity production for several countries, but the use of nuclear power remains controversial. Together the United States, France, and Japan produced 58 percent of the nuclear electric power generated world-wide in 1997 (U.S. Department of Energy, 2000). Even so, few countries are expanding their nuclear energy programs. China and Japan are practically the only countries that are actively building new plants. Economic factors, citizen protests, and competing electricity options have recently cooled plans by South Korea, Taiwan, several countries in SE Asia to progress with nuclear power (Anonymous, 1998).

Environmental burdens occur in several stages of the nuclear power fuel chain. The operation of the plant however, does not give rise to any significant emissions of carbon dioxide (CO_2), acidifying compounds or other harmful substances as compared to fossil fuel burning. The spent nuclear fuel is strongly radioactive and has to be stored in a proper way for a very long time. The other troubling concern related to nuclear power is how to view the risk of a major reactor accident, which could have a variety of complex, extensive effects.

A continuous supply of uranium must be available to operate the plant. Yet the amount of uranium fuel required is relatively small compared to the amount of coal needed to fuel a coal power plant during its lifecycle for a comparable amount of produced electricity.

Technology

Nuclear energy is produced through the process of nuclear fission, where atom nuclei of uranium-235 are split apart by neutrons, and two or three new neutrons are released. The energy released in this process is used to heat water to generate steam, which is then used to drive a turbine. The released neutrons split other nuclei and a chain reaction is generated. The fuel consists of 2-4 % U-235 and 96-98% U-238. The latter isotope is normally not fissionable. When a neutron hits an atom of U-238, the neutron is absorbed and gradually plutonium-239 is formed. Plutonium is also fissionable but not in the nuclear power plants in common use. The splitting products consist of other elements, of which most are radioactive. These daughter products will continue to decay through different stages until they eventually become stable (non-radioactive) elements.

During these decay processes, energy is released in the form of ionising radiation. The released neutrons are very high in energy and are called ”fast” neutrons. Their speed is too high to split new uranium atoms. Therefore the speed of these fast neutrons must be reduced. Depending on the type of reactor this is done by using a moderator of hydrogen (water), heavy hydrogen or carbon (graphite). In order to avoid the uncontrolled growth of nuclei splitting chain reactions, the reactions are controlled by neutron absorbing materials like cadmium or boron. To cool the reactor, different mediums, such as water, gas or liquid metals, can be used. The most common cooling medium is water; about 80 % of the world's reactors are water-cooled and also water-moderated (Stevens, 1991).

Mining and milling

The most common way to extract uranium is in open mines or underground mines, but it can also be leached out of uranium-rich sandstone. After mining, the uranium ore is milled to fine sand. The uranium is leached out of the sand with an acid, often sulphuric acid. The kind of leaching medium used depends on the kind of ore, if it contains much carbonate a base is used as leaching medium. The uranium containing solution is purified from other metals with an organic liquid, oxidised and finally separated and dried. The resulting product is U_3O_8, called ”yellow cake”.

Conversion, isotope enrichment and fuel fabrication

In the conversion process the ”yellow cake” is converted into uranium hexafluoride, UF_6, through a series of physical and chemical transformations. The concentration of U-235 in the primary uranium is 0.7 %, but this is too low to be used as nuclear fuel in most types of reactors. The concentration of U-235 has to be approximately 3 % and therefore it is necessary to enrich the uranium. This can be done through different methods including gas diffusion, gas centrifuge or laser-enrichment. The uranium hexafluoride is heated to above 60°C and vaporised in as part of the enrichment process. The gas diffusion is the most common enrichment method used world-wide, but it is also the most energy intensive process (Van Engelenburg & Nieuwlaar, 1992). The laser-enrichment method is under development and a pilot plant in USA is conducting tests. The enriched uranium hexafluoride is transformed chemically to a powder of uranium dioxide, UO_2, which is compressed to cylindrical pellets and then sintered. Finally the pellets are loaded into zirconium tubes.

Production

There are several types of nuclear reactors operating in the world today. An old technique requires the use of gas (CO_2 or helium) to cool the reactor. The reactor is fuelled with the natural mixture of uranium isotopes and the chain reaction is regulated with graphite. Carbon dioxide or helium is circulated in a closed circuit through the core under high pressure. Steam is raised in a carbon dioxide/water exchanger and electricity is generated via conventional steam turbines (Dryden, 1982).

Another type of reactor is a liquid-cooled reactor. Light water (ordinary) or heavy water (water that includes deuterium oxide and has a 10% greater density than ordinary water) is often used because water is both a good moderator and a good coolant. Enriched uranium must be used in light water reactors because the hydrogen is a “parasitic” absorber of neutrons. Two examples of liquid-cooled reactors are pressurised water reactors (PWR) and boiling water reactors (BWR). A PWR operates at a high enough pressure to prevent boiling and steam is generated indirectly via a heat exchanger. In BWR boiling is permitted in the upper part of the core and steam is generated directly.

All of the types of reactors above have a moderator to slow fission neutrons down. Fast reactors do not slow the neutrons down. The temperature in such reactors becomes high and metallic fuel is therefore unsuitable. For these types of reactors uranium or plutonium oxide must be used. When water is a good moderator it cannot be used as a coolant and liquid metal coolants such as sodium are used instead. The electricity is generated through a secondary sodium coolant circuit. The main advantage of fast reactors is that they have the ability to breed fissile material from fertile material more effectively.

Reprocessing

Some countries that use nuclear power send their spent nuclear fuel to be reprocessed to re-circulated uranium. The fuel then undergoes a series of complex physical and chemical stages to separate the different elements from each other. There are only two commercial reprocessing plants in the world and they are La Hauge in the north of France and Sellafield in the United Kingdom. The out-burnt fuel contains plutonium. This can be used to produce mixed uranium/plutonium oxide (MOX) fuel rods, which partly can replace the uranium fuel in light water reactors. The MOX fuel contains typically 5 % plutonium. This is, however, probably the largest emitting step in the nuclear fuel cycle, since radioactive gases encapsulated in the out-burnt fuel can be inadvertently released.

Geography

World-wide uranium resources

Uranium is an abundant element in the earth’s crust, but mostly it is present in very small quantities that cannot be mined economically. The large recoverable resources are located in only a few places. The greatest resources are found in Australia, Canada, the USA, South Africa and Niger. Large resources are also expected to exist in the former USSR, but they are less well quantified. Uranium is also present in many rivers and in seawater. Seawater uranium may be an usable source of uranium in the future, if large-scale extraction techniques are developed (World Energy Council, 1992).

In 1997, United States produced the most nuclear electric power with 629 billion kWh followed by France with 374 billion kWh and Japan with 306 billion kWh (U.S. Department of Energy, 2000). A summary of nuclear power generation by region is listed in Table 4.1.

Table 4.1 World Net Nuclear Electric Power Generation, 1988-1997 (Billion kWh) (U.S. Department of Energy, 2000).

World Total	2,267.8
North America	717.2
Central & South America	10.5
Western Europe	840.0
Eastern Europe & Former USSR	251.1
Middle East	-
Africa	12.6
Asia & Oceania	436.4

Economics

Currently one of the most pressing economic issues surrounding nuclear power is how to properly decommission old nuclear plants. In 1998, 434 nuclear plants were in operation around the world (Anonymous, 1998). Yet, few plans exist to replace these plants when they reach the end of their lifetime. Most are scheduled to shut down before 2030 (Anonymous, 1998). Nuclear plants are expensive to build and expensive to close. If they are closed prior to the end of their lifetime due to public concerns about nuclear power, finding a clean, cheap replacement source of electricity can be difficult.

The Swedish government is interested in making a shift away from nuclear power, but their electricity alternatives are not particularly inviting. Electricity can be purchased from Danish coal fired plants to the south, but greater electricity output also would lead to additional acid rain that would effect forests in the south of Sweden. Nuclear plants in Russia and Eastern Europe could also sell electricity to Sweden, but the safety records and monitoring of the Swedish nuclear plants are more rigorous than at these alternative plants (Anonymous, 1998). Fossil fuels are more polluting to the environment and renewable energy sources can logistically only replace a small portion of the energy demand. Therefore, in this example, making, an early switch away from nuclear power requires an unattractive economic or environmental trade-off (Anonymous, 1998).

Many other countries are also wary of nuclear power. After the Chernobyl nuclear accident in the Ukraine, Italy ceased to support nuclear power and has recently used combined cycle natural gas plants to fill in some energy needs. Italian electricity demand is also, in part, satiated by energy imports from France, which are, interestingly enough, generated by nuclear power (Anonymous, 1998).

In general, once a nuclear plant is built electricity generation is fairly cheap. Therefore it makes economic sense to utilise an existing plant until the end of its lifetime as long as safety considerations are met.

Lifecycle assessment

Data from several different life cycle analyses are used in this report. A lifecycle analysis was completed for nuclear power in Sweden in 1996. The Swedish boiling water reactor power plant (BWR) *Forsmark 3* is considered. The length of the power plants' operational phase is assumed to be 40 years and the power plant can produce 1,158 MW. It is assumed that the fuel is mined in a Canadian surface-quarry and transported to a uranium plant. The product from the plant is transported in barrels, on trucks, to a converting plant 4,000 km away. The product is converted to uranium hexafluoride in two stages and the uranium is transported 600 km between these two stages (Brännström-Norberg *et al.*, 1996)

After the conversion, the uranium hexafluoride is transported to Europe for enrichment on trucks (435 km), on boat (5,500 km) and by train (805 or 150 km depending on if the material is going to France or Holland). The enrichment can be done in two ways: through gas diffusion or through gas centrifugation. The gas diffusion process is largely energy demanding. 60 percent of the uranium is supposed to be enriched by the centrifuge process and the rest by the gas diffusion process (Tunbrant *et al.*, 1996).

The fuel is transported by railway (150 or 805 km depending on whether the material comes from Holland or France), by boat (1250 or 1000 km) and on trucks (378 km). In the processing plant the uranium hexafluoride is converted to uranium dioxide and put down into long fuel pipes constructed of zirkaloy. The fuel is then transported to the nuclear power plant by trucks (157 km) (Tunbrant *et al.*, 1996).

During the operation and maintenance phase of the lifecycle, the average values of actual emissions and resource use from *Forsmark 3* are used. The rest of the products are dealt with in three different ways. Low active waste is stored in underground storage near the power plant. Medium active waste is transported to SFR, a specially constructed storage area below the sea level near Forsmark. Highly active waste is transported to CLAB (also a specially constructed, deep storage area) for a temporary storage. For the LCA it is assumed that after 40 years, the waste material is encapsulated and transported to the final underground storage destination (Tunbrant *et al.*, 1996).

As can be seen, the fuel chain from mine to final storage is very long. Therefore, there is the possibility that alternative results would surface if another fuel chain were utilised in the LCA. The emissions and resource use would clearly be altered if the waste material was handled in an another manner. The operation phase assessment, however, is applicable to other, similar nuclear power plants (Tunbrant *et al.*, 1996).

Another lifecycle analysis for a nuclear electricity generating plant was completed in Japan. Three different power plants were considered. The first plant is a boiling water reactor model plant. The power output is 1,000 MW and the net efficiency is 33.4 percent. The uranium is enriched by the gas diffusion process. The power plant is assumed to have a lifetime of 30 years. The fuel is not assumed to be recycled. This option should by the most be similar to the Swedish example (Uchiyama, 1995). The second Japanese plant is more advanced than the first one, but the power output; the lifetime and the efficiency are the same. The uranium is enriched by the centrifugal process. The fuel is reprocessed and the plutonium is recycled (Uchiyama, 1995). The third plant is a fast breeder reactor, a metal fuel/sodium coolant model plant. The lifetime is expected to be 30 years and the fuel is reprocessed on site (Uchiyama, 1995).

In a Swiss study completed by the Swiss Federal Institute of Technology (ETHZ) and the Paul Scherrer Institute (PSI) lifecycle resource use was analysed for many different energy systems. Values were reported as UCPTE country averages using 1992 values. The UCPTE country average is meant to represent the mean situation for Belgium, Germany, France, Greece, Italy, Ex-Yugoslavia, Luxembourg, The Netherlands, Austria, Portugal, Switzerland, and Spain (Dones *et al.*, 1995). This data is reported in several publications and the data is also relied on heavily in a 1994 report by Det Norske Veritas (Sandgren & Sorteberg, 1994).

Data from the Swiss study considers Swiss installations of 1,000 MW boiling water reactors and pressurised water reactors. The fuel is assumed to be recycled. Missing data were added from a literature review (Dones *et al.*, 1995).

4.2 Use of resources

Non-renewables

The use of non-renewable resources according to the Swedish study is shown in Table 4.2. These values would be significantly different if an alternate fuel chain was used in the LCA. The use of energy is based on the electricity mix in the countries where the fuel is processed. The use of chemicals is largely compared to other electricity generating options, e.g. hydropower. There is a lack of data for some of the resources and the environmental effects of resources are not followed through the entire energy chain. Only values that pertain to the entire nuclear power plant lifetime are shown in the Table 4.2.

Table 4.2 Use of non-renewable resources in the power plant Forsmark 3 in Sweden (Tunbrant et al., 1996).

Resource	Unit	Use
Energy		
Uranium	$g\cdot kWh^{-1}$	$2.37\cdot10^{-4}$
Coal	$g\cdot kWh^{-1}$	$7.63\cdot10^{-1}$
Oil	$m^3\cdot kWh^{-1}$	$3.15\cdot10^{-8}$
Gas	$m^3\cdot kWh^{-1}$	$9.96\cdot10^{-5}$
Diesel	$m^3\cdot kWh^{-1}$	$2.96\cdot10^{-7}$
Petrol	$m^3\cdot kWh^{-1}$	$5.15\cdot10^{-10}$
Material		
Uranium	$g\cdot kWh^{-1}$	$2.31\cdot10^{-2}$
Cement	$g\cdot kWh^{-1}$	$2.41\cdot10^{-1}$
Steel	$g\cdot kWh^{-1}$	$9.52\cdot10^{-2}$
Aluminium	$g\cdot kWh^{-1}$	$6.17\cdot10^{-5}$
Copper	$g\cdot kWh^{-1}$	$1.58\cdot10^{-2}$
Lead	$g\cdot kWh^{-1}$	$5.96\cdot10^{-4}$
Titan	$g\cdot kWh^{-1}$	$9.25\cdot10^{-5}$
Bentonite	$g\cdot kWh^{-1}$	$2.96\cdot10^{-1}$
Quartz sand	$g\cdot kWh^{-1}$	1.29
Glass	$g\cdot kWh^{-1}$	$3.94\cdot10^{-3}$
PVC	$g\cdot kWh^{-1}$	$3.05\cdot10^{-3}$
Stone wool	$g\cdot kWh^{-1}$	$1.41\cdot10^{-3}$
Explosive	$g\cdot kWh^{-1}$	$6.75\cdot10^{-3}$
Oil	$g\cdot kWh^{-1}$	$5.83\cdot10^{-4}$
Chemicals		
Ion changing mass	$g\cdot kWh^{-1}$	$9.52\cdot10^{-4}$
Sulphuric acid	$g\cdot kWh^{-1}$	$1.66\cdot10^{-1}$
Fluorhydrogen acid	$g\cdot kWh^{-1}$	$1.08\cdot10^{-2}$
Nitric acid	$g\cdot kWh^{-1}$	$8.61\cdot10^{-3}$
Ammonia	$g\cdot kWh^{-1}$	$1.56\cdot10^{-2}$
Sodium hydroxide	$g\cdot kWh^{-1}$	$4.41\cdot10^{-3}$
Methanol	$g\cdot kWh^{-1}$	$3.21\cdot10^{-3}$
Aluminium phosphate	$g\cdot kWh^{-1}$	$2.02\cdot10^{-3}$
Chalk	$g\cdot kWh^{-1}$	$1.00\cdot10^{-1}$
Other chemicals	$g\cdot kWh^{-1}$	$6.34\cdot10^{-3}$

Renewables

The use of renewable resources is shown in Table 4.3. The use of water is underestimated.

Table 4.3 Use of renewable resources in the Swedish nuclear powers lifecycle (Tunbrant et al., 1996).

Resource	Unit	Use
Energy		
Hydropower	$KWh^{-1} \cdot kWh^{-1}$	$3.28 \cdot 10^{-3}$
Wooden chip	$g \cdot kWh^{-1}$	$2.60 \cdot 10^{-2}$
Material		
Wood	$g \cdot kWh^{-1}$	$4.67 \cdot 10^{-2}$
Water	$m^3 \cdot kWh^{-1}$	$2.06 \cdot 10^{-5}$
Cooler-water	$m^3 \cdot kWh^{-1}$	$1.80 \cdot 10^{-1}$

Land

Depending on how the lifecycle analysis is carried out, the magnitude of land use will differ significantly. In the Swiss, ETH-study the land use was calculated by multiplying the land area by the number of years the area is occupied. The results from this study indicate that nuclear power generation gives rise to the largest land use impact of all power generation options. The value calculated for the Swiss study is 79 $km^{2\cdot}$year/TWh of electricity produced (Dones *et al.*, 1995). In the Swedish study, however, land occupation time is not factored in and, therefore, the land use impact for the nuclear power generation LCA is not greater than for other electricity generating options.

4.3 Global environmental impact

In all stages of the nuclear cycle there are emissions of airborne pollutants due to energy requirements, the transportation of materials used in the plants, and the production of these materials.

Radionuclides can be emitted in different amounts, both to air and water, during all of the processing stages in the nuclear fuel chain. The emissions produced during electricity generation are small and controlled in the developed (western) countries. One environmental concern is whether or not the activities in the nuclear power fuel chain will create an accumulation of radionuclides in the atmosphere. The effects of concentrating radionuclides are uncertain.

Greenhouse effect

The estimating of amount of greenhouse gases emitted to the atmosphere from nuclear power is difficult and relatively uncertain. In the Swedish study, only carbon dioxide is estimated (Table 4.4). The emission of carbon dioxide and methane for the Japanese power plants in carbon dioxide equivalents are shown in Table 4.5. The emissions are generally lower for nuclear power generation than for other electricity generating options.

Table 4.4 Estimated emissions of carbon dioxide from the Swedish nuclear power plants lifecycle (Tunbrant et al., 1996).

Substance	**Unit**	**Manufacturing and construction**	**Operation and maintenance**	**Dismantling**	**Total**
Carbon dioxide	g·kWh^{-1}	$2.71 \cdot 10^{-1}$	2.37	$1.76 \cdot 10^{-1}$	**2.82**

Table 4.5. Estimated emissions of greenhouse gases in the Japanese nuclear power plants lifecycle (Uchiyama, 1995).

Substance	**Unit**	**Manufacturing and construction**	**Operation and maintenance**	**Dismantling**	**Total**
BWR					
CO_2 carbon dioxide	g·kWh^{-1}	3.67	16.28	0.07	20.02
CH_4 methane	g·kWh^{-1}	0.11	0.77	-	0.88
Total	**g·kWh^{-1}**	**3.78**	**17.05**	**0.07**	**20.90**
Advanced BWR					
CO_2 carbon dioxide	g·kWh^{-1}	3.78	4.71	0.07	8.56
CH_4 methane	g·kWh^{-1}	0.15	0.22	-	0.37
Total	**g·kWh^{-1}**	**3.93**	**4.93**	**0.07**	**8.93**
Fast breeder reactor					
CO_2 carbon dioxide	g·kWh^{-1}	4.66	2.74	0.08	7.48
CH_4 methane	g·kWh^{-1}	0.18	0.15	-	0.33
Total	**g·kWh^{-1}**	**4.83**	**2.89**	**0.08**	**7.80**

Ozone layer depletion

Since the 1980's seasonal, polar ozone layer depletion has been a concern. Anthropogenic emissions of several suspect chemicals have been targeted and the long residence time of these substances has aroused concern in the scientific community. A reduced ozone layer may contribute to a greater risk of cancer, mutations in the animal kingdom, and other environmental harm. Though methane and NO_x are substances that can potentially degrade the stratospheric ozone layer, the specific effects and interactions attributable to these greenhouse gases emitted as part of the natural gas LCA are difficult to assess and predict. The Swiss study presents a UCPTE country average value of 3.2 kg CFC11 equivalents/ TWh_{el} for the natural gas LCA (Dones *et al.*, 1995). This is probably not a large concern for the nuclear power lifecycle (Dones *et al.*, 1995).

4.4 Local and regional environmental impact

The Environmental impact review by Det Norske Veritas concludes that data and the analytical tools to assess local impacts is currently not available, but some general comments can be made (Sandgren & Sorteberg, 1994).

On a local and regional scale nuclear power generation may influence biodiversity in several different ways:

- Acidification can destroy biotopes and cause serious harm to ecosystems.
- Endangered species may not be able to survive.
- Eutrophication can severely affect aquatic ecosystems
- Photochemical smog can damage plants and lead to the extinction of some species.
- Ecotoxic emissions can cause serious environmental health problems. Ecotoxic substances can accumulate in food chains, and thus especially harm predators (and human beings).

For all of these factors, coal, oil, and lignite, and natural gas contribute significantly more emissions over their lifecycle than nuclear power or hydropower.

Acidification

The Swedish lifecycle analysis quantifies the emissions of nitrogen oxides and sulphur dioxide. The estimates for sulphur dioxide and nitrogen oxides are not complete, but the overall emissions of acidifying compounds for nuclear power are low (Table 4.6).

Table 4.6 Emissions of acidifying compounds in the nuclear fuel cycle as compiled in Sweden. Operation phase includes the mining of the fuel raw material etc. (Tunbrant et al., 1996).

Substance	**Unit**	**Manufacturing and construction**	**Operation and maintenance**	**Dismantling**	**Total (SO_2-equivalents)**
NO_x	$g{\cdot}kWh^{-1}$	$8.23{\cdot}10^{-4}$	$1.33{\cdot}10^{-2}$	$2.50{\cdot}10^{-3}$	$1.17{\cdot}10^{-2}$
SO_x as SO_2	$g{\cdot}kWh^{-1}$	$5.99{\cdot}10^{-4}$	$1.21{\cdot}10^{-2}$	$1.32{\cdot}10^{-3}$	$1.29{\cdot}10^{-2}$
Total	$\mathbf{g{\cdot}kWh^{-1}}$				$\mathbf{2.46{\cdot}10^{-2}}$

Impacts from mining and milling

Waste water

The liquid effluents from mining activities and the water from the milling plants have heightened concentrations of radioactivity and need to be treated before being released to the environment. The acid solution remaining from the leaching process can either be recycled or neutralised (with calcium carbonate). The acid solution also contains dissolved radium (Uranium Institute, 1997), which can be removed relatively easily through precipitation with $BaCl_2$.

Solid waste

The solid waste from uranium mining includes waste rock and any precipitation that remain after acid leaching. Waste from the acid leaching process and precipitation from the water treatment process with the $BaCl_2$ should be deposed of properly. Sand from the milling process contains radium and has also to be properly handled. Depending on type of rocks, climate etc, there are different methods for waste disposal. The sands and the precipitates can, in some cases, be back-filled into the uranium mine (European Commission, 1995).

Impacts from conversion, isotope enrichment and fuel fabrication

During the production of nuclear fuel lots of chemicals are used. The conversion processes use hydrogen fluoride (HF) which is a potentially hazardous acid. Use of HF requires precautions both to protect workers and to prevent harmful effects to the environment. Ammonia is also used. Gaseous releases of these chemicals can also be an issue. Chemicals are handled during other stages of the nuclear power lifecycle, but the use of these chemicals does not constitute any great threat to the surrounding environment if they are handled properly.

Eutrophication

The nuclear power does not give rise to significant eutrophication effects. The emissions of nitrogen compounds and COD calculated in the Swedish study are shown in Table 4.7. COD is a measure of amount of oxygen demanding organic material. Ammonia is only quantified for the operation and maintenance phase.

Table 4.7 Emissions of eutrophication compounds in the Swedish nuclear power lifecycle (Tunbrant et al., 1996).

Substance	**Unit**	**Manufacturing and construction**	**Operation and maintenance**	**Dismantling**	**Total (O_2-decrease)**
NO_x	$g\cdot kWh^{-1}$	$8.23\cdot10^{-4}$	$1.33\cdot10^{-2}$	$2.50\cdot10^{-3}$	$1.00\cdot10^{-1}$
COD	$g\cdot kWh^{-1}$	$1.52\cdot10^{-5}$	$3.05\cdot10^{-6}$	-	$6.15\cdot10^{-5}$
Tot-N	$g\cdot kWh^{-1}$	$1.35\cdot10^{-6}$	$3.27\cdot10^{-4}$	$3.57\cdot10^{-6}$	$6.56\cdot10^{-3}$
Ammonia	$g\cdot kWh^{-1}$	-	$9.96\cdot10^{-4}$	-	$1.59\cdot10^{-2}$
Total	$\mathbf{g\cdot kWh^{-1}}$				$\mathbf{1.26\cdot10^{-1}}$

Photochemical oxidant formation

Photochemical reactions between substances such NO_x, volatile hydrocarbons and other chemical pollutants can lead to the formation of photochemical oxidants. These substances can damage plants, cause respiratory problems in humans, and lead to other environmental harm. Photochemical ozone creation potential (POCP) is usually presented as grams of ethene-equivalents per kWh of produced electricity. The Swiss study reports a UCPTE country average value of 0.71 kg ethene-equivalents/kWh (Dones *et al.*, 1995). This value is very small; photochemical oxidant formation is not a concern for nuclear power generation.

Ecotoxic impact

Radiation

As the radioactive nuclei decay radiation is emitted. The rate of decay is measured in Becquerel (Bq). The radiation ionises atoms or molecules and the energy absorbed is measured in joules per kilogram. A basic dose of radiation is measured in a unit called a Gray (Gy). Since different kinds of radiation (e.g. X-rays, neutron radiation, etc.) can effect different biological cells to various extents another until called the Sieverts (Sv) is used to take into account these levels of harm. For an LCA, the total impact of radiation depends on the number of individuals exposed and the magnitude of the doses. The collective dose is the sum of the doses of all of the exposed individuals and is measured in man-Sieverts (manSv) which estimates whole body equivalent doses (Dones *et al.*, 1995).

Impacts from mining and milling

The activity in mines is spread over a wide area and the emissions of radioactivity are therefore hard to quantify. Particles from the mill tailings can be dispersed by the wind. These particles can be a source of radiation, since they contain radium. After processing, the mill tailings are transported back to the mine and they are covered, but leakage to groundwater can occur. Radon gas is released from the ore and uranium dust is released from mining activities during the activities. When radon gas and uranium dust decay radionuclides are released.

The area surrounding a mine often has a high natural radiation background level because of the high uranium content in the rock. Mining activities do however somewhat increase these background levels.

The Canadian open-cast mine considered in the Swedish study (Key Lake) is situated in a remote area and the emissions from the mine only impact the workers. Emissions from Key Lake and average values from mines in Canada, Australia and the former Eastern Germany (UNSCEAR) are shown in Table 4.8.

Table 4.8 Emissions of radionuclides from uranium mines and plants (Tunbrant et al., 1996).

Emission	**Unit**	**Rn-222**	**Pb-210**	**Th-230**	**Ra-226**	**U-238**
To air						
Key Lake	$Bq\cdot TWh^{-1}$	-	$1.0\cdot10^{4}$	$3.5\cdot10^{3}$	$2.1\cdot10^{3}$	$4.6\cdot10^{5}$
UNSCEAR	$Bq\cdot TWh^{-1}$	$3.4\cdot10^{11}$	$2.3\cdot10^{6}$	$2.3\cdot10^{6}$	$2.3\cdot10^{6}$	$4.6\cdot10^{7}$
To water						
Key Lake	$Bq\cdot TWh^{-1}$	-	$2.6\cdot10^{5}$	$2.6\cdot10^{5}$	$7\cdot10^{5}$	$4.1\cdot10^{5}$
UNSCEAR	$Bq\cdot TWh^{-1}$	-	$1.1\cdot10^{6}$	$1.1\cdot10^{6}$	$2.2\cdot10^{6}$	$3.4\cdot10^{7}$

Impacts from conversion, isotope enrichment and fuel fabrication

Wastewater is produced in all stages of uranium refinement. Wastewater can contain a variety of different chemical compounds and radionuclides. If the water is not treated before it is discharged it can be harmful. There are, however, different ways of treating wastewater to avoid environmental damages. For example, the remaining fluoride from the conversion of UF_6 to UO_2 is precipitated as insoluble calcium fluoride. In some cases the water can also be recycled. Usually the ecotoxic emissions are low from both the conversion process and the isotope enrichment and fuel fabrication process.

Table 4.9 Emissions of radionuclides from conversion, isotope enrichment and fuel fabrication in the Swedish LCA.

Emission	Unit	Th-228	Th-230	Th-232	Th-234	U-234	U-235	U-238
Conversion								
To air								
Cameco	Bq·TWh^{-1}	-	-	-	-	-	-	$2.5\cdot10^{6}$
UNSCEAR	Bq·TWh^{-1}	$2.2\cdot10^{3}$	$3.9\cdot10^{4}$	$2.2\cdot10^{3}$	$1.3\cdot10^{7}$	$1.3\cdot10^{7}$	$6.0\cdot10^{5}$	$1.3\cdot10^{7}$
To water								
Cameco	Bq·TWh^{-1}	-	-	-	-	-	-	$1.3\cdot10^{6}$
UNSCEAR	Bq·TWh^{-1}	-	-	-	-	$9.0\cdot10^{6}$	$4.1\cdot10^{6}$	$9.0\cdot10^{6}$
Enrichment								
To air								
EURODIF	Bq·TWh^{-1}	-	-	-	-	$1.9\cdot10^{5}$	$9.7\cdot10^{3}$	$1\cdot10^{5}$
UNSCEAR	Bq·TWh^{-1}	-	-	-	-	$1.5\cdot10^{5}$	$6.8\cdot10^{3}$	$1.5\cdot10^{5}$
To water								
EURODIF	Bq·TWh^{-1}	-	-	-	-	$3.8\cdot10^{4}$	$1.9\cdot10^{3}$	$2\cdot10^{4}$
UNSCEAR	Bq·TWh^{-1}	-	-	-	-	$1.1\cdot10^{6}$	$5.8\cdot10^{4}$	$1.1\cdot10^{6}$
Fuel fabrication								
To air								
ABB	Bq·TWh^{-1}	-	-	-	-	$8.6\cdot10^{3}$	$3.8\cdot10^{2}$	$1.9\cdot10^{3}$
UNSCEAR	Bq·TWh^{-1}	-	-	-	$3.9\cdot10^{4}$	$3.9\cdot10^{4}$	$1.6\cdot10^{2}$	$3.9\cdot10^{4}$
To water								
ABB	Bq·TWh^{-1}	-	-	-	$2.5\cdot10^{5}$	$1.1\cdot10^{4}$	$5.5\cdot10^{4}$	$2.9\cdot10^{5}$
UNSCEAR	Bq·TWh^{-1}	-	-	-	$1.9\cdot10^{7}$	$1.6\cdot10^{5}$	$1.9\cdot10^{7}$	$1.9\cdot10^{7}$

Impacts from electricity production

Impacts from electricity generation are easier to measure than impacts from the overall fuel chain since the nuclear reactor is a closed system. Emissions to water are generally more critical than emissions to air in the electricity production phase because the heavier compounds that are emitted to the water have a longer lifetime. The emissions to water are due to fuel cell damage and activation of corrosion products in the reactor water.

Emissions from the power plant Forsmark 3 in 1992 are shown in Table 4.10. Only the most important nuclides are included.

Table 4.10 Emissions of nuclides to air and water from the Swedish power plant Forsmark 3 in 1992 (Tunbrant et al., 1996).

Nuclide	**Unit**	**Emission**
To air		
Xe-133	$GBq{\cdot}TWh^{-1}$	$1.2{\cdot}10^{4}$
I-131	$GBq{\cdot}TWh^{-1}$	$5.0{\cdot}10^{-2}$
Mn-54	$GBq{\cdot}TWh^{-1}$	$7.7{\cdot}10^{-4}$
Co-58	$GBq{\cdot}TWh^{-1}$	$5.0{\cdot}10^{-3}$
Co-60	$GBq{\cdot}TWh^{-1}$	$1.0{\cdot}10^{-2}$
Cs-134	$GBq{\cdot}TWh^{-1}$	$8.1{\cdot}10^{-4}$
Cs-137	$GBq{\cdot}TWh^{-1}$	$9.5{\cdot}10^{-4}$
To water		
H-3	$GBq{\cdot}TWh^{-1}$	$1{\cdot}10^{2}$
Mn-54	$GBq{\cdot}TWh^{-1}$	$2.2{\cdot}10^{-1}$
Co-58	$GBq{\cdot}TWh^{-1}$	1.1
Co-60	$GBq{\cdot}TWh^{-1}$	2.1
Zn-65	$GBq{\cdot}TWh^{-1}$	$2.6{\cdot}10^{-1}$
Ag-110m	$GBq{\cdot}TWh^{-1}$	$3.2{\cdot}10^{-2}$
Sb-124	$GBq{\cdot}TWh^{-1}$	$2.5{\cdot}10^{-1}$
Sb-125	$GBq{\cdot}TWh^{-1}$	$1.1{\cdot}10^{-1}$
Cs-134	$GBq{\cdot}TWh^{-1}$	$3.0{\cdot}10^{-1}$
Cs-137	$GBq{\cdot}TWh^{-1}$	$4.0{\cdot}10^{-1}$
I-131	$GBq{\cdot}TWh^{-1}$	$2.5{\cdot}10^{-1}$

The most obvious and controversial environmental problem arising from nuclear power generation is the spent nuclear fuel. The spent fuel consists of radioactive fission products, plutonium and actinides; elements with atomic number from 89 and upward. Some of these products have very long half-lives and have to be handled with care. The spent fuel will be radioactive for a very long time and must therefore be stored in a proper container in order to minimise harm to people and the environment. Because the decomposition of the radioactive elements within the spent fuel will continue after the fuel has been removed from the reactor, large amounts of heat will continue to be produced. Therefore, the spent fuel has to be cooled for several years after removal. Generally the spent fuel is stored in large pools of water.

There are also other types of radioactive wastes generated from the operation of a nuclear plant. These are called low and intermediate level radioactive wastes and are composed of used cleaning filters, protection equipment, used tools etc. They are less radioactive and therefore also less harmful than the spent fuel, which is considered high-level waste.

Impacts from reprocessing

- Use of chemicals
  Lots of chemicals are used in processing, such as nitric acid, caustic soda, formaldehyde and others (Tunbrant *et al.*, 1996). These have to be collected and treated.

- Waste water
  Liquid effluents containing different levels of radioactivity and waste chemicals are produced during processing. They have to be collected and chemically treated.

- Solid waste
  The solid wastes from the reprocessing include structural wastes from the fuel elements, fission products and sludge from the treatment of effluents. A method for disposing of old and worn equipment is also necessary (Tunbrant *et al.*, 1996).

Habitat alteration

Water is used in nuclear plant cooling systems. In once-through systems, large amounts of water are needed. When returning the cooling water to the source, this heated water can sometimes cause thermal pollution, which can have adverse effects on the aquatic ecosystem (Langford, 1990). In evaporative cooling systems, the water use is greatly reduced since the cooling water is recycled.

Accidents

One area of great concern is the risk of reactor accidents in a nuclear power plant, especially since accidents with severe effects have already occurred. It is hard to compare the risks for accidents between different parts of the world, since the types of reactors used and the control and safety systems differ. At least in the western World, the reactors are equipped with safety systems and there are proven systems used to supply the reactor with cooling water. These systems use electricity and are equipped with diesel-powered back-up generators. Overall, the risk of a nuclear power accident is very small.

4.6 Impact on biodiversity

Impacts on flora and fauna are mainly caused by the presence of the mine. However, other stages in the nuclear power lifecycle can lead to more or less serious, direct or indirect effects on the living organisms and ecosystems. Indirect effects can be the effects caused by emissions of different pollutants and can vary between different ecological areas.

After an accident, such as the Chernobyl catastrophe, the radiation can cause biological mutations and major disruptions to sensitive populations and biotopes.

Health risks

In all stages of the nuclear fuel chain, radioactive elements can be emitted, and it is the radiation from these substances that pose the greatest risk to human health. Different occupational risks are related to the different stages of the fuel chain, where especially mining activities can cause health problems and accidents.

The Swiss study presents LCA data for human fatalities related to nuclear power (Dohes et.al., 1995). The data presented in Table 4.11 considers the risk of accidents throughout the nuclear power plant lifecycle from uranium mining and transportation to power plant operation. The data indicate that uranium mining poses a greater risk to human life than operation of the power plant. "Immediate" risk indicates that the accident caused a sudden fatality and "delayed" risk indicates that a long term exposure or activity related to nuclear power eventually lead to death.

Table 4.11 Estimated Lifecycle Fatalities due to Nuclear Power (fatalities/GW$_e$year) (Dones et al., 1995).

	Occupational immediate (mining)	**Occupational delayed (mining)**	**Public Immediate (transport)**	**Public (delayed) Power plant**
	fatalities/GW$_e$year	fatalities/GW$_e$year	fatalities/GW$_e$year	fatalities/GW$_e$year
Underground Mining	0.09-0.5	0.13-0.37	0.001-0.01	0.005-0.2
Surface Mining	0.07-0.4	0.07-0.33		

Risk perception

Risks to public health can be psychological, mainly in the form of stress, due to the perception of risks from nuclear electricity production. Radiation exposure cannot be seen or heard and this kind of health threat is more disturbing to people than more familiar pollution impacts.

Major nuclear accidents have made the public wary of nuclear energy. The Three Mile Island accident of 1979 indicated and the Chernobyl disaster in 1986 explicitly showed that even though a major accident is very unlikely to happen, when safety controls are not in place nuclear power plants have the potential to cause enormous damage on a world-wide scale.

Even if the actual risks associated with nuclear power are very small, especially in western countries, the public perception of risk is often very large. Though nuclear power has many advantages including a firm supply of power, cost effective electricity generation, and low emission production, the risk of a major catastrophe, and the lack of long term storage disposal sites, make the public burden to large for many societies to accept.

Social and socio-economic impact

The costs of repairing local regions after a major disaster are huge and the damage affects several generations.

Aesthetic impact

The most obvious visual impact is from uranium mines. In addition, tall cooling towers often stand out a major architectural feature, especially in small communities.

5. BIOMASS

5.1 Frame conditions

Biomass and biofuels (derived from biomass) are considered renewable energy sources and renewables account for approximately 13 percent of the total world energy supply (Hall & House, 1994). Biomass energy is also considered a firm supply of energy since biomass fuelled plants can operate year-round.

In industrialised countries, biomass is considered an alternative; renewable energy source with little associated environmental harm. Industrialised countries are generally trying to encourage the use of such renewable energy sources, while developing countries are trying to reduce the use of certain biomass fuels. The reason for these different approaches is that developing countries often use different raw biomass materials. Traditional biomass is the main energy source for about half of the world's population (Pimentel *et al.*, 1994), but these traditional biomass sources are often not part of sustainable energy schemes and can produce more significant environmental burdens when used for energy. Biomass use can be divided into two categories (International Energy Agency, 1998):

1. *Traditional biomass*

- Fuel wood and charcoal for domestic use
- Straw (including rice husks)
- Other vegetation residues
- Animal wastes

2. *Modern biomass*

- Wood residues (for industrial use)
- Biogas
- Urban wastes
- Biofuels (including energy crops, crops grown for the production of ethanol, biogas production)

This report is mostly concerned with modern biomass use. Wood residues include waste wood from forests, the wood products industry, and agriculture. During logging and wood processing (for lumber and other use) a significant portion of each tree is discarded as waste material. Plantations are also used to generate biomass for energy production.

One of the main reasons for using biomass fuel is that when biomass in converted to energy there is virtually no net production of CO_2. The trees and plants absorb carbon dioxide through photosynthesis as they grow and then CO_2 is released back to the atmosphere when biomass is converted into energy. When biomass is used as an alternative to another energy option (such as coal) the result is a decrease in the amount of CO_2 emitted to the atmosphere. Over the course of the biomass power generation life cycle the only net emissions of CO_2 are due to construction of the power plant, the use of fossil fuels for transportation of the biomass to the plant, and the manufacturing of nitrogen fertilisers, if extra nutrients are used for growing the biomass (Brännström-Norberg *et al.*, 1994). The other environmental impacts largely depend on the type of biomass and the specific kind of energy generation technique used.

Technology

Many countries are investigating the use of biomass plants as an alternative to fossil fuel burning. In the United States biomass test plots and facilities are gradually being built as support for the use of renewable energy increases, e.g. a biomass demonstration facility is currently being constructed in Burlington, Vermont.

Fuel plantations

Instead of utilising forestry and agricultural waste products for biomass fuels, energy crops can be grown on plantations for use as biomass fuels. Woody species are chosen for their fast growth and compatibility with local climate. For example, Poplar grows well in cool areas with high rainfall. Some common energy crops are (Golob & Brus, 1993):

- Fast growing hardwood trees (willow, Poplar, Eucalyptus, etc.).
- Fast growing herbaceous plants.
- Annual and perennial grasses (fibre Sorghum, switchgrass, Cynara, etc.).

For an example of energy crop management consider willow. Willow is a fast growing hardwood tree that can be densely planted (10,000 plants/ha) and allowed to grow for one year. After one year the trees are cut to increase the number of shoots. Then the plantations are harvested every 2-6 years for a period of 20-30 years. This is a short rotation crop (SRC) plantation management method. The trees are harvested in the wintertime when the crops are dormant.

Agricultural and forestry waste

Agricultural and forestry waste contains many different types of biomass, such as animal slurries, straw and forest residues. To use forest residues (i.e. the vegetation left after logging) the material must first be harvested. This can be achieved as part of an overall forest management practice. The residues can be converted to small wood chips in the forest or whole trees, except the stumps, can be harvested and the waste portions can be reserved for energy generation.

The emphasis in this report is on using fast growing hardwood trees and forest residues for biomass energy generation. Many different species can be used depending on availability, climate, and geographical conditions.

Transports, handling and storage

The energy content of the biomass fuel is fairly low and the transport costs are high. Therefore, biomass is normally used locally for energy generation. The fuel is transported by trucks directly to the plant or to a storage place near the plant. If the distance is long, the fuel can be converted to material with higher energy content, e.g. pellets, before transportation.

Combustion

The efficiency of the plant and the environmental emissions produced vary depending on the technique used to generate electricity from the biomass. The traditional combustion techniques are similar to those used to burn coal (see Chapter 2). When biomass is burned in a boiler, steam is produced which drives the turbines to produce energy. The efficiency of this kind of traditional boiler is normally under 20 percent, but state of the art technology today can yield up to 42 percent net efficiency. Circulating Fluidised Bed (CFB) systems are becoming more common and integrated gasification combined cycle (IGCC) systems are an emerging technology. New techniques, such as hot gas clean-up methods that remove additional particulate and gaseous emissions (SO_x, NO_x, etc.) are also being developed for biomass energy generation.

BIGCC or IGCC

Gasification technology commonly used in coal fuelled power plants has been adapted for use with biomass. Integrated gasification combined cycle (IGCC) is a new, effective technique for biomass electricity production. Gasification adds air to the biomass feedstock at high temperatures to produce a gas fuel that can be fed into turbines to generate electricity. IGCC technology is twice as efficient than traditional biomass combustion boilers and allows a biomass power plant to generate both heat and electricity (U.S. Department of Energy, 1997).

A 1997 US Department Energy Biomass LCA reports that the efficiency of a 113MW hypothetical biomass integrated gasification combined cycle (BIGCC) plant is 37.2%. The efficiency of biomass energy over the biomass lifecycle is estimated at 34.9 % where 77% of the energy consumed by the system is due to production of the biomass fuel (Mann & Spath, 1997).

Geography

The resources of biomass in the world are very large. The use of wood fuels in electric power plants has recently increased in both developing and industrialised countries (Golob & Brus, 1993). The resources must be properly managed; however, to be considered as renewable resources. The biomass energy use in some selected countries is shown in Table 5.1.

Table 5.1 Biomass energy uses in selected countries in 1987 (Flavin & Lenssen, 1994).

Country	**Biomass use (Petajoules)**	**Share of total energy consumption**
United Kingdom	46	<1
United States	3,482	4
Denmark	84	9
Thailand	206	20
Brazil	1,604	25
China	9,287	28
Costa Rica	31	32
Zimbabwe	143	40
India	8,543	56
Indonesia	2,655	65
Tanzania	925	97

Economics

Even though there are vast biomass resources in the world, converting these potential energy sources to saleable energy can be an economic challenge. The locations for biomass power plants have to be chosen carefully, and the power plants have to be of an appropriate size. If the plants are too big then the costs of transporting the raw material to the plants will be high. On the other hand, if they are too small, the costs to operate the plants will be too high.

An advantage of using biomass to generate energy is that the process is fairly labour intensive, and therefore a biomass energy plant can offer new jobs. Also, due to high transportation costs, it makes economic sense to build biomass plants near sources of fuel. Therefore, in the future biomass plants may be planned for rural areas where forestry products and agricultural wastes are more readily available, hence bringing a needed boost rural economies. Converting waste biomass from logging to energy can also improve the bottom line for forestry operations and therefore help provide for sustainable forestry management practices.

Several kinds of raw biomass materials can be used for energy generation. Waste materials can be salvaged or special plantations can be planned to grow crops exclusively for biomass energy. Before choosing a biomass source several factors have to be considered including climate, regional land use laws, environmental impacts, storage, land quality and the cost of not using the land for alternative use.

Even if a source of biomass is available, choosing to use biomass for energy generation may not be the best decision. There is competing use for different kinds of biomass. Biomass can be composted, used to make other products, and/or recycled in addition to being converted to energy. These other uses may, in some cases, prove to be better economical and social alternatives.

Life-cycle assessment

A few studies are available that complete an LCA for biomass energy systems. LCA studies from Spain, Canada, and Sweden are considered in this report.

A Spanish LCA study examines the use of short rotation energy crops to produce biomass electricity on a large scale in a temperate climate. In the study 28 ideal sites were selected for 1 GW plants. Poplar, eucalyptus and acacia were selected for the plantations. Most of the sites (22) were assumed to use Fluidised Bed Combustion (CFB, 25% efficiency) and the rest were assumed to use Biomass Integrated Gasification Combined Cycle (BIGCC, 40% efficiency). The cost of electricity and delivered fuel was calculated. The results show that ideally the CFB sites can produce electricity at an average cost of 10.1 cents/kWh. It is likely that the cost will be reduced if the BIGCC technology is used. The study concludes that biomass energy can reasonably supply up to 5-10 percent (2.3-5 GW) of Spain’s present energy need (Centro de Investigaciones Energeticas, 1997).

A life-cycle assessment from Sweden considers the use of the fast growing hardwood tree Salix and forest residues from pine and spruce as biomass fuels. This LCA documents the environmental effects caused by the use of biomass for electricity production. In this study, a CFB-pan (Circulating Fluidised Bed) and an IGCC-pan (Integrated Gasification Combined Cycle) is used to combust biomass. The power plants are located in the central parts of Sweden and the distance from the energy crop plantations to the power plants is short. The power plants have two purposes: 1) to produce electricity and 2) to produce heat. The size of the CFB-plant is 9 MW and the size of the IGCC-plant is 59 MW (includes electricity production only). The efficiency for electricity production is 27.1 % for the CFB-plant and 42.0 % for the IGCC-plant. (Brännström-Norberg & Dethlefsen, 1998)

For the Swedish LCA the power plants life is assumed to be 40 years. The lifecycle is divided into a manufacturing and construction phase, an operation and maintenance phase, and a dismantling phase. The operation phase includes the management and transportation of the fuel. The emissions and use of resources are reported here only for the sum of the three phases, except for the emissions of greenhouse gases (Brännström-Norberg & Dethlefsen, 1998).

Since the plants are combined systems, the emissions are divided between heat production and electricity production. 25 percent of the total energy gained from the CFB-plant is electricity and, therefore, 25 percent of the total emissions are allocated to electricity production. For the IGCC plant, 49.6 percent of the total emissions are allocated to electricity production. Metals may be recycled many times, and therefore it is necessary to set a recycling boundary condition to analyse metals use. In this study, 50 percent of the metals are assumed to be recycled. The use of electricity is based on an average of Swedish electricity consumption (Brännström-Norberg & Dethlefsen 1998).

The use of forest plantation crops for electricity production was studied in Eastern Ontario, Canada. Emissions were calculated using a full lifecycle method. (Beals &

Hutchinson, 1993) In Canada, three forest plantation species and schemes are used: 1) short rotation Poplar, 2) mini rotation Poplar, and 3) mini rotation willow. The short rotation period is 10-40 years, while the mini rotation period is 1-10 years. Emissions are estimated assuming a conventional steam cycle biomass power plant with electrostatic precipitators, 25 percent efficiency, an 85 percent annual capacity factor and a 30-year life span. The biomass is fed into the boiler as wood chips (Beals & Hutchinson, 1993).

5.2 Use of resources

Non-renewables

In the biomass energy generation life-cycle, the use of non-renewable energy sources is relatively small. Most of the non-renewable use is due to biomass harvesting, the transportation of biomass to the power plant, power plant building and manufacturing, and power plant decommissioning. Table 5.2 and 5.3 show the consumption of non-renewable energy and materials for the Swedish IGCC and CFB plants, respectively.

Table 5.2 Non-renewable resources used in the biomass IGCC plant lifecycle in Sweden (Brännström-Norberg & Dethlefsen, 1998). IGCC is a combined cycle power plant and 49.6 percent of the produced energy is electricity. The emissions listed in the table are adjusted accordingly.

Non-renewable	Unit	Salix	Forest residue
Energy			
Uranium	$\mathrm{kg\cdot kWh^{-1}}$	$6.41\cdot10^{-9}$	$4.48\cdot10^{-9}$
Coal	$\mathrm{kg\cdot kWh^{-1}}$	$1.54\cdot10^{-2}$	$1.44\cdot10^{-2}$
Oil	$\mathrm{m^3\cdot kWh^{-1}}$	$4.21\cdot10^{-8}$	$1.91\cdot10^{-8}$
Gas	$\mathrm{m^3\cdot kWh^{-1}}$	$3.86\cdot10^{-3}$	$9.07\cdot10^{-6}$
Diesel	$\mathrm{m^3\cdot kWh^{-1}}$	$3.32\cdot10^{-6}$	$4.65\cdot10^{-6}$
Material			
Iron ore	$\mathrm{g\cdot kWh^{-1}}$	$4.29\cdot10^{-1}$	$4.29\cdot10^{-1}$
Limestone + gypsum	$\mathrm{g\cdot kWh^{-1}}$	$1.37\cdot10^{-1}$	$1.37\cdot10^{-1}$
Ballast	$\mathrm{g\cdot kWh^{-1}}$	1.08	1.08
Copper ore	$\mathrm{g\cdot kWh^{-1}}$	$1.67\cdot10^{-1}$	$1.67\cdot10^{-1}$
Bauxite	$\mathrm{g\cdot kWh^{-1}}$	$4.51\cdot10^{-4}$	$4.51\cdot10^{-4}$
Titan dioxide	$\mathrm{g\cdot kWh^{-1}}$	$1.48\cdot10^{-3}$	$1.48\cdot10^{-3}$
Stone wool	$\mathrm{g\cdot kWh^{-1}}$	$2.25\cdot10^{-2}$	$2.25\cdot10^{-2}$
Clay	$\mathrm{g\cdot kWh^{-1}}$	$3.54\cdot10^{-2}$	$3.54\cdot10^{-2}$
Tri-sodium phosphate	$\mathrm{g\cdot kWh^{-1}}$	$6.69\cdot10^{-4}$	$6.69\cdot10^{-4}$
Hydrazine	$\mathrm{g\cdot kWh^{-1}}$	$1.18\cdot10^{-3}$	$1.18\cdot10^{-3}$
Dolomite	$\mathrm{g\cdot kWh^{-1}}$	$4.54\cdot10^{-3}$	$4.54\cdot10^{-3}$
Ammonia	$\mathrm{g\cdot kWh^{-1}}$	$1.19\cdot10^{-3}$	$1.19\cdot10^{-3}$
Hydrochloric acid	$\mathrm{g\cdot kWh^{-1}}$	$8.41\cdot10^{-2}$	$8.41\cdot10^{-2}$
Sodium hydroxide	$\mathrm{g\cdot kWh^{-1}}$	$8.41\cdot10^{-2}$	$8.41\cdot10^{-2}$
Vinyl chloride monomer	$\mathrm{g\cdot kWh^{-1}}$	$1.71\cdot10^{-3}$	$1.71\cdot10^{-3}$

Table 5.3 Non-renewable resources used in the biomass CFB plant lifecycle in Sweden (Brännström-Norberg & Dethlefsen, 1998). CFB is a combined cycle power plant and 25 percent of the produced energy is electricity. The emissions listed in the table are adjusted accordingly.

Non-renewable	**Unit**	**Salix**	**Forest residue**
Energy			
Uranium	$kg\cdot kWh^{-1}$	$2.76\cdot10^{-9}$	$1.25\cdot10^{-9}$
Coal	$kg\cdot kWh^{-1}$	$1.88\cdot10^{-4}$	$1.76\cdot10^{-4}$
Oil	$m^3\cdot kWh^{-1}$	$3.00\cdot10^{-8}$	$1.48\cdot10^{-8}$
Gas	$m^3\cdot kWh^{-1}$	$2.24\cdot10^{-3}$	$1.39\cdot10^{-5}$
Diesel	$m^3\cdot kWh^{-1}$	$2.14\cdot10^{-6}$	$3.58\cdot10^{-6}$
Material			
Iron ore	$g\cdot kWh^{-1}$	$3.15\cdot10^{-1}$	$3.15\cdot10^{-1}$
Limestone + gypsum	$g\cdot kWh^{-1}$	$1.87\cdot10^{-1}$	$1.87\cdot10^{-1}$
Ballast	$g\cdot kWh^{-1}$	1.48	1.48
Copper ore	$g\cdot kWh^{-1}$	$2.82\cdot10^{-1}$	$2.82\cdot10^{-1}$
Stone wool	$g\cdot kWh^{-1}$	$1.00\cdot10^{-2}$	$1.00\cdot10^{-2}$
Clay	$g\cdot kWh^{-1}$	$2.17\cdot10^{-2}$	$2.17\cdot10^{-2}$
Cyclohexyl amine	$g\cdot kWh^{-1}$	$3.79\cdot10^{-4}$	$3.79\cdot10^{-4}$
Hydrazine	$g\cdot kWh^{-1}$	$1.89\cdot10^{-3}$	$1.89\cdot10^{-3}$
Ammonia	$g\cdot kWh^{-1}$	$1.04\cdot10^{-3}$	$5.73\cdot10^{-3}$
Sodium chloride	$g\cdot kWh^{-1}$	$6.31\cdot10^{-3}$	$6.31\cdot10^{-3}$
Vinyl chloride monomer	$g\cdot kWh^{-1}$	$3.54\cdot10^{-3}$	$3.54\cdot10^{-3}$

Renewables

Since biomass is the fuel source, biomass is obviously the primary renewable resource used during the biomass energy generation lifecycle. Other renewable energy sources and renewable materials are, however, used during the manufacturing, operating and dismantling phases. An example is the use of wood in the manufacturing phase of the power plant. Some energy use is also required in all phases. Table 5.4 and 5.5 show the use of renewables in the Swedish IGCC and CFB power plants, respectively.

Table 5.4 Renewable resources used during the biomass IGCC plant in Sweden (Brännström-Norberg & Dethlefsen, 1998). IGCC is a combined cycle power plant and 49.6 percent of the produced energy is electricity. The emissions listed in the table are adjusted accordingly.

Renewable	**Unit**	**Salix**	**Forest residue**
Energy			
Hydropower	kWh·kWh^{-1}	$2.49 \cdot 10^{-4}$	$2.40 \cdot 10^{-4}$
Wooden chip	kg·kWh^{-1}	$3.48 \cdot 10^{-5}$	$3.48 \cdot 10^{-5}$
Wooden fuel	kg·kWh^{-1}	-	$5.12 \cdot 10^{-1}$
Salix	kg·kWh^{-1}	$5.35 \cdot 10^{-1}$	-
Material			
Wood	g·kWh^{-1}	$1.00 \cdot 10^{-1}$	$1.00 \cdot 10^{-1}$

Table 5.5 Renewable resources used during the biomass CFB plant in Sweden (Brännström-Norberg & Dethlefsen, 1998). The CFB is a combined cycle power plant and 25 percent of the produced energy is electricity. The emissions listed in the table are adjusted accordingly.

Renewable	**Unit**	**Salix**	**Forest residue**
Energy			
Hydropower	kWh·kWh^{-1}	$7.59 \cdot 10^{-5}$	$6.82 \cdot 10^{-5}$
Wooden chip	kg·kWh^{-1}	$3.13 \cdot 10^{-5}$	$3.13 \cdot 10^{-5}$
Wooden fuel	kg·kWh^{-1}	-	$3.98 \cdot 10^{-1}$
Salix	kg·kWh^{-1}	$4.17 \cdot 10^{-1}$	-
Material			
Wood	g·kWh^{-1}	$1.21 \cdot 10^{-1}$	$1.21 \cdot 10^{-1}$

Land

Nutrient depletion

When agricultural and forestry wastes are used for energy generation the loss of soil nutrients can be a concern. In the Swedish LCA study ashes from the power plant are returned to the forest floor in order to maintain the mineral balance of the soil. Ash is also returned to the Salix plantations in order to maintain a productive soil base (Brännström-Norberg & Dethlefsen, 1998).

Land Use Conflicts

The land use required by biomass energy generation life-cycles can be extensive and controversial. In some areas land designated for fuel crops may be needed for other social uses. For example, the land may be prime farmland or suitable for housing. The main land use in the biofuel chain is for plantations, but land is also required for the power plant. Although the power plant only requires a small portion of the total biomass land use, the environmental impacts connected with this land are the largest. The Spanish LCA demonstrates that to produce 2 percent of the nation's electrical capacity roughly 1 percent of the total land area would be required (Centro de Investigaciones Energeticas, 1997).

Table 5.6 Land use for the biomass IGCC plant in Sweden (Brännström-Norberg & Dethlefsen, 1998). IGCC is a combined cycle power plant and 49.6 percent of the produced energy is electricity. The emissions listed in the table are adjusted accordingly.

Land	**Unit**	**Salix**	**Forest residue**
Arable land	$m^2 \cdot kWh^{-1}$	$2.23 \cdot 10^{-1}$	-
Forest land	$m^2 \cdot kWh^{-1}$	-	$8.53 \cdot 10^{-2}$
Industrial land	$m^2 \cdot kWh^{-1}$	$4.80 \cdot 10^{-6}$	$4.80 \cdot 10^{-6}$

Table 5.7 Land use for the biomass CFB plant in Sweden (Brännström-Norberg & Dethlefsen, 1998). The CFB is a combined cycle power plant and 25 percent of the produced energy is electricity. The emissions listed in the table are adjusted accordingly.

Land	**Unit**	**Salix**	**Forest residue**
Arable land	$m^2 \cdot kWh^{-1}$	$1.74 \cdot 10^{-1}$	-
Forest land	$m^2 \cdot kWh^{-1}$	-	$6.64 \cdot 10^{-2}$
Industrial land	$m^2 \cdot kWh^{-1}$	$6.30 \cdot 10^{-7}$	$6.30 \cdot 10^{-7}$

5.3 Global environmental impact

Greenhouse effect

In all stages of the biomass fuel cycle there are emissions of airborne pollutants due to the use of energy, transportation of material used in the plants and production of these materials, collection of biomass, transportation of the biomass fuel, etc.

Compared to coal and oil, biomass use gives rise to much less atmospheric CO_2 in the long term. Since CO_2 was originally sequestered from the atmosphere during photosynthesis while the plants were growing, the net emissions of CO_2 are virtually zero. The overall CO_2 emissions depend mainly on how the biomass is transported to the power plant. In the Swedish study the original absorption of CO_2 by the biomass is not considered and this is why the CO_2 emissions are rather large (Lundborg, 1994). 424 $g \cdot kWh^{-1}$ of the emission from the IGCC-plant and 330 $g \cdot kWh^{-1}$ of the emission from the CFB-plant are due to the fuel combustion. However, it must be remembered that the biomass originally adsorbed this amount of CO_2 from the atmosphere (Brännström-Norberg & Dethlefsen, 1998). Therefore, no net emissions of CO_2 result from the combustion of the biomass.

Table 5.8 The emission of carbon dioxide from the Swedish power plants (Brännström-Norberg & Dethlefsen, 1998). Emissions from biomass combustion are included in this table. The power plants are combined cycle plants that produce both heat and electricity. The emissions listed in the table are adjusted accordingly.

Emission	**Unit**	**Salix**	**Forest residue**
CO_2 IGCC	g·kWh^{-1}	440	437
CO_2 CFB	g·kWh^{-1}	341	340
N_2O IGCC	g·kWh^{-1}	-	-
N_2O CFB	g·kWh^{-1}	$1.64\cdot10^{-2}$	$1.64\cdot10^{-2}$

The study from Canada considers three different cases. The first case is a worst case scenario in which it is assumed that forests are clear-cut and no new trees are planted. The second case considers conventional forestry practices and assumes that the carbon originally sequestered by the plants equals the carbon released upon biomass combustion. In the third case it is assumed that energy crops are planted on agricultural land. The soil storage of carbon gives a net absorption of carbon dioxide from the atmosphere. This alternative is the most optimistic and it is likely that the emissions are actually larger in practice (Table 5.9).

Table 5.9 Emissions of carbon dioxide from selected forest culture scenarios in Canada (Beals & Hutchinson, 1993).

Technology	**Unit**	**Extraction**	**Construction**	**Operation**	**Total**
Clear-cut with no re-growth.	g·kWh^{-1}	28	2.6	1334	1365
Conventional re-growth	g·kWh^{-1}	-1306	2.6	1334	31
Short rotation on agricultural land	g·kWh^{-1}	-1444	2.6	1334	-107

Ozone layer depletion

Anthropogenic emissions of several suspect chemicals may reduce the Earth's ozone layer and contribute to a greater risk of cancer, mutations in the animal kingdom, and other environmental harm. The specific effects and interactions attributable to the low amounts of gases emitted as part of the biomass Life-cycle are difficult to assess and predict. The overall emissions of substances harmful to the ozone layer from biomass combustion are low. Specific data is not readily available.

5.4 Local and regional environmental impact

On a local and regional scale biomass power generation may influence biodiversity in several different ways:

- Acidification can destroy biotopes and cause serious harm to ecosystems.
- Endangered species may not be able to survive.
- Eutrophication can severely affect aquatic ecosystems
- Photochemical smog can damage plants and lead to the extinction of some species.
- Ecotoxical emissions can cause serious environmental health problems. Ecotoxic substances can accumulate in food chains, and thus especially harm predators (and human beings).

Acidification

Plant growth contributes, naturally, a net release of acid to the soil. When the plants die and the organic material decays equivalent amounts of alkaline substances are returned to the soil. Hence, in natural forests the chemical conditions are maintained at some equilibrium. Thus, removal of organic matter from forests and agricultural soil, for example in the form of biomass residues, also brings about net losses of substances with capacity to buffer acidification. Therefore, biomass extraction without compensation measures, such as bringing back the ash, adds to acidification. The acidification problem varies depending on the size and location of biomass plantations. In places with acid rain and high deposition of sulphur and nitrogen compounds the acidification can be extensive. With a high deposition rate the soil may not be able to neutralise the sulphur and nitrogen compounds. Emissions of sulphur and nitrogen compounds from biomass combustion, in the absence of chemical treatments of the flue gas, may be of regional interest, since the emissions can cause acidification in areas far from the power plant. Biomass contains less sulphur than coal and oil, and emission of sulfur dioxide per unit electricity is thus comparatively low, whereas the amounts of nitrogen oxides are approximately the same (Table 5.10 and 5.11). In modern biomass-fuelled power plants, ammonia is added to the flue gas. This leads to emissions of elementary nitrogen instead of acidifying and fertilising nitrogen oxides.

Table 5.10 Emissions of acidification compounds from a biomass IGCC plant in Sweden (Brännström-Norberg & Dethlefsen, 1998). IGCC is a combined cycle power plant and 49.6 percent of the produced energy is electricity. The emissions listed in the table are adjusted accordingly.

Emission	**Unit**	**Salix**	**Forest residue**
NO_x	$g \cdot kWh^{-1}$	$3.73 \cdot 10^{-1}$	$4.12 \cdot 10^{-1}$
SO_2	$g \cdot kWh^{-1}$	$1.81 \cdot 10^{-1}$	$1.83 \cdot 10^{-1}$
NH_3	$g \cdot kWh^{-1}$	$3.54 \cdot 10^{-2}$	$3.26 \cdot 10^{-2}$

Table 5.11 Emissions of acidification compounds from a biomass CFB plant in Sweden (Brännström-Norberg & Dethlefsen, 1998). The CFB is a

combined cycle power plant and 49.6 percent of the produced energy is electricity. The emissions listed in the table are adjusted accordingly.

Emission	**Unit**	**Salix**	**Forest residue**
NO_x	$g\cdot kWh^{-1}$	$2.91\cdot 10^{-1}$	$3.35\cdot 10^{-1}$
SO_2	$g\cdot kWh^{-1}$	$4.12\cdot 10^{-2}$	$4.28\cdot 10^{-2}$

Acidification of soil occurs on normal agriculture land as part of biomass cycle (harvesting), deposition of acid compounds, and the introduction of acid fertilisers. A similar amount of acidification occurs on hardwood energy crop plantations. One way to combat soil acidification is to return the power plant ash to the plantations. The ashes contain minerals such as potassium, calcium and manganese that the trees originally adsorbed from the soil, but nitrogen is not present in the ash. By returning the residual ash to the land the overall load of nitrogen in the soil will be decreased and the soil minerals will be replenished, as well (Lundborg, 1997). If ash return is not feasible then additions of lime can be used to reduce soil acidification.

Eutrophication

Eutrophication occurs when oxygen levels in water systems decrease and algal growth increases due, in part, to excess nitrogen. Different water reservoirs will be effected differently depending on chemical composition, location, aquatic flora and fauna, the extent of exposure to air pollution, etc.

Fertilisers are often used to optimise the energy crop harvests. Less fertiliser is used for biomass energy crops than for traditional agriculture management. The contribution of biomass fertilisers to global eutrophication is related to the type and amount of fertiliser applied.

The leaching of soil nutrients is generally higher in autumn and winter, and since hardwood energy crop plantations are grown throughout the year, the leaching of nutrients is less severe than for normal agricultural plantations. Also, biomass energy crops have the ability to take up large quantities of nutrients, which leaves fewer nutrients in the soil to be leached. The extent of nutrient leaching also depends on climate and soil type.

As was indicated above, in areas where significant a amount nitrogen deposition is adversely effecting forest health, the removal of forest residues can actually counteract nitrogen leakage (Lundborg, 1997). Most of the nitrogen in the biomass leaves the combustion plant as nitrogen gas, the most abundant gas in the atmosphere, while only 5-10 percent of the nitrogen from biomass combustion is returned to the atmosphere as NO_x. Therefore, removal of forest residues lowers the nitrogen load in forest soils since nitrogen is not returned to the atmosphere after biomass combustion in a form that can be redeposit as NO_x.

However, the 5-10 percent of the combusted biomass nitrogen that is remitted as nitrogen oxides, and ammonia, gives rise to global eutrophication.

Table 5.12 Emissions of eutrophication compounds from the IGCC plant in Sweden (Brännström-Norberg & Dethlefsen, 1998).

Emission	Unit	Salix	Forest residue
To air			
NO_x	$g \cdot kWh^{-1}$	$3.73 \cdot 10^{-1}$	$4.12 \cdot 10^{-1}$
NH_3	$g \cdot kWh^{-1}$	$3.54 \cdot 10^{-2}$	$3.26 \cdot 10^{-2}$
To water			
Tot-N	$g \cdot kWh^{-1}$	$2.00 \cdot 10^{-2}$	$2.00 \cdot 10^{-2}$
Tot-P	$g \cdot kWh^{-1}$	$5.00 \cdot 10^{-5}$	$5.00 \cdot 10^{-5}$

Table 5.13 Emissions of eutrophication compounds from the CFB plant in Sweden (Brännström-Norberg & Dethlefsen, 1998).

Emission	Unit	Salix	Forest residue
To air			
NO_x	$g \cdot kWh^{-1}$	$2.91 \cdot 10^{-1}$	$3.35 \cdot 10^{-1}$
To water			
Tot-N	$g \cdot kWh^{-1}$	$1.64 \cdot 10^{-2}$	$1.64 \cdot 10^{-2}$
Tot-P	$g \cdot kWh^{-1}$	$3.10 \cdot 10^{-5}$	$3.10 \cdot 10^{-5}$

Photochemical oxidant formation

As in all types of combustion, photochemical oxidants are formed when biomass is burned. This is due to incomplete combustion of the biomass fuel, which leads to emissions of volatile organic compounds (VOC). These compounds react with nitrogen oxides under the influence of sunlight. The problem is larger in the summertime (Naturvårdsverket, 1990).

The complete combustion is essential for lowering the emissions of VOC. For example, the emission of carbon monoxide varies between $3.6 \cdot 10^{-2}$ and 17 g per kWh depending on the completeness of the combustion (Naturvårdsverket, 1990). The emissions of carbon monoxide from the Swedish power plant examples are shown in Table 5.14. In modern power plants the VOC emissions are low and installing purification filters can help reduce the emissions further. Overall, the formation of photochemical oxidants is not an important issue in the biomass fuels lifecycle.

Table 5.14 Emissions of CO from the power plants (Brännström-Norberg & Dethlefsen, 1998). The power plants produce both heat and electricity. The emissions in the table are therefor allocated accordingly.

Emission	Unit	Salix	Forest residue
CO IGCC	$g \cdot kWh^{-1}$	$9.82 \cdot 10^{-2}$	$1.06 \cdot 10^{-1}$
CO CFB	$g \cdot kWh^{-1}$	$2.03 \cdot 10^{-1}$	$2.14 \cdot 10^{-1}$

Ecotoxic impact

Use of chemicals

Weeds, insects, and other pests have to be well controlled during the early stages of establishing plantation crops. For this herbicides and pesticides are usually used. Fertilisers may also be applied. These added chemicals contain different substances, which can potentially affect the soil quality, reach groundwater and enter surface water reservoirs through surface runoff. The extent of the effects is related to the amounts and types of chemicals used to maximise the energy crop yields.

The life-cycle emissions of heavy metals from biomass energy generation are difficult to quantify. The amount of emissions depends on the heavy metal content in the biomass fuel and on the power plant design. Specific numbers are not available, but the emission of heavy metals from biomass combustion is significantly less than for coal combustion.

Solid waste

Compared to coal, the ash content of biomass is much lower and is generally free of the toxic metals and trace elements present in coal ash. On the other hand, the ash is rich in phosphates, carbonates and alkali salts, which are easily leached. This is an advantage if the ash is going to be applied to improve soil quality. Nevertheless, if the ashes are going to be returned to the biomass plantations, they should first be treated to decrease the dissolution rate and to reduce the leaching of potentially toxic trace metals.

Habitat alteration

The habitat alteration due to the biomass life cycle can be large if land is used for plantations. Habitat alteration can be of particular concern if spruce and pine forests are planted because these trees deplete soil nutrients and leave the soil less suitable for agricultural uses.

Local climate

If an area traditionally planted with agricultural crops is planted with hardwood energy crops instead, the resulting altered wind velocities near the ground and altered pattern of evapotranspiration will cause minor change of the local climate.

Geophysical changes

The main geophysical effect from biofuel crops is erosion prevention. In some countries where the soils have become degraded over time, planting energy crops can be useful since they will help stabilise the soil (Kort *et al.*, 1998). Energy crop plantations reduce water erosion by improving water infiltration and reduce wind erosion by improving soil organic matter, soil structure and which therefore reduces soil erosion (Kort *et al.*, 1998). However, if the energy crop plantations replace a sensitive natural ecosystem, then the overall impact could be negative. In addition, if forest residues are used as a fuel source, then surface runoff can increase and exacerbate soil erosion when the residues are collected (Kort *et al.*, 1998).

Aquatic Impacts

The leaching of nutrients from the cultivation of biomass fuels would theoretically be less than the leaching from traditional farming, since the energy crops keep the soil covered during the whole year (Kort *et al.*, 1998). According to the Swedish study, the cultivation of Salix and other species also consumes large amounts of water. The greatest risk for leaching is during crop harvests and when stumps are removed to clear the land for a new plantation.

5.5 Accidents

The risk of major accidents is not high during the biomass fuel lifecycle. When biomass fuel is stored there is a risk of fire. Occupational injuries can occur from accidents related to biomass harvesting and transportation. When energy crops are used as biomass fuel about $2 \cdot 10^{-5}$ accidents per TWh occur due to sawing and harvesting, while $4 \cdot 10^{-5}$ accidents per TWh occur due to transportation (Stjernquist, 1986). 0.3 accidents and $4 \cdot 10^{-3}$ deaths per TWh are attributable to biomass fuel combustion (Stjernquist, 1986).

5.6 Impact on biodiversity

Energy plantations

How the cultivation of energy crops will affect the indigenous flora and fauna depends on the previous land use, the nature of the crop and the size and design of the plantation. If energy forests are planted on land that was previously open farmland, then the biodiversity will probably increase (Christian *et al.*, 1998). However, some species of birds and other animals will flourish whereas other may be negatively impacted by the land use change. If energy crop plantations replace natural ecosystems the overall impacts will be negative (Christian *et al.*, 1998).

Recent studies of birds and small mammals inhabiting plantations in North America show that both birds and small mammals extensively use the plantations. Several bird species particularly like to inhabit the edges of forests and, if only the edges are considered, bird density is actually larger there than inside forests or in plantations. The numbers of forest-associated bird species are fewer in plantations than in forests. Yet, bird communities that frequent plantations are more varied than bird communities that inhabit agricultural lands. The composition of mammal communities are similar for energy crop plantations and for agricultural land, yet rabbits, hares and tree squirrels make very little use of biofuel plantations in the wintertime (Christian *et al.*, 1998).

Forestry waste

The most significant impact on plant and animal habitats is from logging trees, but there are also effects caused by the removal of forest residues for biomass energy generation (Brännström-Norberg & Dethlefsen, 1998). When the residue is collected, animal shelters and substrates for decomposing micro-organisms are removed. However, when forest waste products are removed this can clear spaces for the reestablishment of some plant species that may have been adversely effected by the presence of forest residues. But some species thrive with the presence of decaying vegetation and when the residues are removed, protection against temperature extremes decreases (e.g. some types of flora and do not thrive in direct sunlight). Therefore, leaving 10-30 percent of the residues and old trees in a forest that has been logged may be the best ecological compromise (Lundborg, 1994).

5.7 Impact on humans

Health risks

The magnitude of emissions from combustion of compounds harmful to human health depends on the power plants size, how the power plants are designed, and the presence of filter systems in the plant. Locally, the height of the power plants chimneys is also an important factor. Large power plants give rise to less concentration of harmful compounds than small ones. This is due to the fact that taller chimneys allow the toxic compounds to be diluted more before they are deposited on the ground (Rosen-Lidholm *et al.*, 1992).

Working environment

When biomass fuel is stored, micro-organisms continue to grow in the biomass. The activity of the micro-organisms depends on the storage volume, where a large storage volume will have a lower overall activity. The activity also depends on the amount and kind of nutrients present, moisture content, particle size, storage temperature, etc. The presence of the micro-organisms will give rise to dust. Mold spores are the most dangerous micro-organism since they can cause allergic reactions. Chronic bronchitis can develop when workers are exposed to these micro-organisms for long periods of time (Rosen-Lidholm *et al.*, 1992). The risk of dust can be controlled by limiting the storage time and by handling the fuel in contained area (Brännström-Norberg & Dethlefsen, 1998).

The power plant ash also gives off dust and has to be handled and stored carefully. If the ashes are wetted then dusting can be reduced, but the ash particles can be particularly problematic since they are very small and can stay in the air for several hours. Workers who come in contact with the ash should take precautions and wear protective equipment (Rosen-Lidholm *et al.*, 1992).

6. HYDROPOWER

6.1 Frame conditions

The kinetic energy from running or falling water has been used to generate power for hundreds of years. For electricity generation, waterpower has been used since the late 19th century. Today, hydropower is a well-proven and mature technology that is used all around the world. In 1999, hydropower generation ranked sixth as a primary energy source (Consult IEA for updated energy statistics at http://www.iea.org/statist) accounting for 2.3 % of the total supply. Primary energy is defined as the heat content of the fuel. In condensing power plants (almost all nuclear belong to this type) most of the generated heat is disseminated to the atmosphere. On average, only about 1/3 of the heat content is converted to electricity in such power plants. In terms of electricity production, bearing the distinction between primary energy and beneficial output in mind, hydro is the second most important source and accounted for 17.5 % of the world total generation.

There are two main types of hydropower plants, run-of-river and reservoir power plants. Run-of-river plants make use of the natural flow of water in streams and rivers. Since the natural discharge varies with the season for most parts of the world it is only feasible to use a fraction (usually less than the annual average flow) to run the turbines. In this respect, run-of-river hydroelectricity has similarities with wind power, with the important distinction that the former kind of power plant is usually accessible for power generation at all times and can satisfy both peaking power as well as base load demands. Wind power plants are used more or less exclusively for base load. The level of service is consequently higher for run-of-river hydro plants than for power plants that use wind to run the generators.

The seasonal runoff pattern and the differential need for electricity make facilities that have the capacity to store water feasible structures in hydroelectric systems. Reservoir power plants make a more efficient use of the annual runoff compared to run-of-river plants and their level of service makes them outstanding in their capacity to supply power during times of peak electricity demand. The reservoir provides energy storage in the form of a large body of water that withhold and accumulate water in periods when the demand is low and can supply more than average natural amounts of water to the turbines when the electricity demand is high. This capacity results in greater electricity production flexibility in systems with a large share of hydro.

Hydropower is a clean energy source in that it does not directly generate pollutants from fuel combustion. There are, however, other environmental burdens associated with hydropower, which primarily cause local environment impacts. These effects are site-specific and differ based on the type and size of plants, the local climate, site characteristics, vegetation, etc. Large dams are not built in conjunction with run-of-river plants so the effects from this kind of power generation are often less than the environmental impacts from large reservoir hydropower projects.

Even if there are no direct emissions of pollutants during the operation of hydropower plants, construction activities, and the production and transportation of building materials still give rise to emissions. The type of power plant and the size of the dam for reservoir plants are factors that influence the amount of emissions. In reservoir systems, the emissions also depend on the type of dam and what material the dam is made of, e.g., the emissions of CO_2 will be greater from concrete dams than from dams made of earth and rock fills.

Technology

River flow and hydraulic head are the two main factors that dictate the hydropower electricity generation potential. Run-of-river hydro plants make use of direct river water flow and generally only have small storage capacities. Pumped storage plants (included as reservoir plants for this analysis) raise water from low sites for storage in a basin at a higher altitude. In this way, electricity can be produced when the demand is greatest by using the increased head and extra electricity generated during non-peak times that has been used to pump the water back up to the storage basin. Pumped storage plants are particularly common in regions where large thermal power plants satisfy base load demands. Reservoir power plants use dams to create reservoirs for water storage and to increase the hydraulic head. Reservoirs can be used to store water for long period of time to account for seasonal variations in electricity demand. Due to this kind of water regulation, the water level can fluctuate extensively in the reservoir throughout the year. There will also be water level fluctuations in the river due to short-term (daily and weekly) water regulation. Some projects divert water to the power station through long canals or tunnels, and this will usually reduce the water flow in the section of the river directly downstream from a dam.

The dams for reservoir hydropower plants are generally made out of concrete or rock and earth fill material. The latter is less expensive and most of the world's large dams are made of vast earth and rock embankments. Concrete is used to make straight or arched dams. The arch dams require less material to yield the same strength. Gravity dams, that withhold the water mainly by their weight, also contain large amounts of concrete.

Geography

In regions with high annual precipitation, cool climates that reduce evaporative losses and make it possible to store water naturally in the form of snow, hydroelectricity is a particularly attractive and sufficient stand-alone option for water use. Such conditions are particularly common in Northern latitudes (northern part of North America, Scandinavia and Russia), in very Southern latitudes (Tasmania, Chile, Argentina), and in high mountain ridges like the Alps, Himalayas and the Andes. In other parts of the world, and particularly where there is a shortage of water, it is often feasible to combine hydroelectricity with storage of water for irrigation etc.

In Sweden there are about one thousand hydropower plants and hydropower accounts for about 50 percent of the total electricity production. In Norway almost all electricity is generated by hydropower. The climate and topography in these regions makes it possible to make use of over 50 percent of the precipitation for electricity production.

In areas with large, dry savannahs evaporation reduce the accessible runoff so that not more than about 10 percent of the annual rainfall can be used for electricity generation.

In 1997, the five largest producers of hydropower in the world were the United States, Canada, Brazil, China, and Russia. These top five countries together produced 51 percent of the global hydroelectricity. Canada produced the most with 346 billion kWh followed by the United States with 319 billion kWh, Brazil with 293 billion kWh, China with 204 billion kWh and Russia with 161 billion kWh (International Energy Agency, 2002). Hydropower electricity generation summaries for 1999 are listed by region in Table 6.1.

Table 6.1 World Net Hydroelectric Power Generation, 1999 (Billion Kilowatt-hours)(International Energy Agency, 2002).

World Total	*2,659*
North America	*697*
Central & South America	*521*
Western Europe	*532*
Eastern Europe & Former USSR	*268*
Middle East	*16*
Africa	*72*
Asia & Oceania	*553*

Economics

A well-planned hydropower generation plant can produce cheap electricity. The plant lifetimes are often long (at least 50 years), and with upgrades they can last many additional years. The life span of dams lasts even longer, and there is generally no technical reasons for their future removal. The cost of hydropower electricity per kilowatt-hour is therefore lower than for many other energy sources.

The generation of hydroelectric power increased at an average annual rate of 2.1 percent (by 430 billion kWh) between 1988 and 1997 (U.S. Department of Energy, 2000).

The economics of small and large dams vary greatly. Large dams are often expensive, lengthy projects financed by several groups of international investors while small dam building can be a more localised project.

Lifecycle assessment

Several LCAs on hydroelectric systems have been made in recent years. The Swiss Federal Institute of Technology (ETH) has compiled LCA inventory results representing the UCPTE average hydropower share: 52.1% run-of-river and 47.9% reservoir power plants. Pumped storage plants were included as part of the reservoir hydropower plant total. The individual investigated countries were Austria, Switzerland, France, Italy and Germany. For electricity use in construction and materials production, the local power mix was considered (Gantner & Hofstetter, 1996). Future, projected emissions from wastes etc. were calculated for an unlimited time horizon. Most hydropower plants analysed were built between 1945 and 1970. However, modern hydropower technology does not differ considerably from those used in the past. Nor has the efficiency of hydropower plants changed over the years because the technique was mature already when the first hydroelectric power plants were installed. Technical improvements have added or might increase efficiency by a few percent at most and the total efficiency is usually as high as 95%, which makes hydropower outstanding in this respect.

Infrastructure requirements for the entire initial, main processes in the fuel cycle were included (building supplies, etc.). Secondary infrastructures (e.g. construction of a factory to build components for a power plant) were not considered. At the other boundary, electricity distribution was not considered, but waste disposal sites and their emissions were included as often as possible.

Another lifecycle assessment completed in Sweden included three power plants and one major man-made reservoir. This LCA represent a true cradle-to-grave approach in that accounts of energy and material used for construction, operation and maintenance started already in the mines for several of the resources used. The future dismantling following expected life-spans of 60 years for the power plant and 100 years for the dam was also included (Brännström-Norberg *et al.*, 1995).

Other LCAs of hydropower derive from Norway (Sandgren & Sorteberg, 1994) and Japan (Uchiyama, 1995).

None of these studies includes detailed accounts of the altered flow of elements following the formation of artificial bodies of water and changed flow regimes downstream of the dams. Such data are available from other studies that have addressed this issue more explicitly but are omitted here.

6.2 Use of resources

Non-renewables

Table 6.2 gives a detailed account of the use of non-renewable resources as presented in the UCPTE study (Gantner & Hofstetter, 1996). Resources contributing less than 0.1% of the total relative use were omitted. The implication of "non-renewable" is that the use of such resources is not unlimited. It may already compete with other uses or do so in the future. The use of these resources may also imply that they are permanently withdrawn from current or future use, hence reducing availability and perhaps ultimately causing a shortage. This so-called Static Reserve Life is related to the estimated size of the global reserve and the current or predicted use. It is expressed as the time lapse before exhaustion (Lindfors, *et al.* 1995). It should be observed that some non-renewables to a large extent are gathered and reused or re-processed following dismantling. Thus, the Swedish LCA anticipates that 70% of the copper is recovered after dismantling (Table 6.3).

Table 6.2 The use of non-renewable resources for an average hydropower lifecycle in UCPTE-countries (Gantner & Hofstetter, 1996).

Resource	**Unit**	**Use**	**Static reserve life (years)**
Lead (Pb)	g·kWh^{-1}	$6.84\cdot10^{-5}$	20
Chromium (Cr)	g·kWh^{-1}	$2.83\cdot10^{-3}$	105
Iron (Fe)	g·kWh^{-1}	$6.44\cdot10^{-1}$	119
Copper (Cu)	g·kWh^{-1}	$2.08\cdot10^{-4}$	36
Manganese (Mn)	g·kWh^{-1}	$2.78\cdot10^{-3}$	95
Nickel (Ni)	g·kWh^{-1}	$4.93\cdot10^{-4}$	55
Silver (Ag)	g·kWh^{-1}	$8.46\cdot10^{-7}$	1
Tin (Sn)	g·kWh^{-1}	$4.72\cdot10^{-7}$	28
Oil gas	g·kWh^{-1}	$1.53\cdot10^{-2}$	40
Methane	g·kWh^{-1}	$8.06\cdot10^{-3}$	60
Brown coal	g·kWh^{-1}	$2.35\cdot10^{-1}$	390
Hard coal	g·kWh^{-1}	1.06	390
Natural gas	g·kWh^{-1}	$4.57\cdot10^{-2}$	60
Oil	g·kWh^{-1}	$2.69\cdot10^{-1}$	40

In the Swedish lifecycle analysis, the use of resources has been divided into a building and manufacturing phase (Table 6.3) and an operation and maintenance phase (Table 6.4). The use of non-renewable resources in the latter phase is low, as can be seen in Table 6.4.

Table 6.3 The use of non-renewable resources in Sweden during manufacturing and construction of the power plants. (Brännström-Norberg et al., 1995).

Resource	**Unit**	**Use in Seitevare**	**Use in Harsprånget**	**Use in Boden**
Iron ore	g·kWh^{-1}	$5.6\cdot10^{-2}$	$1.9\cdot10^{-1}$	$1.6\cdot10^{-1}$
Limestone + gypsum	g·kWh^{-1}	$1.7\cdot10^{-1}$	$3.6\cdot10^{-1}$	$5.7\cdot10^{-1}$
Ballast	g·kWh^{-1}	1.00	0.92	3.38
Copper ore	g·kWh^{-1}	$3\cdot10^{-2}$	$9\cdot10^{-2}$	$4\cdot10^{-2}$
Lead ore	g·kWh^{-1}	$1\cdot10^{-3}$	$1\cdot10^{-3}$	$3\cdot10^{-3}$
Plastics	g·kWh^{-1}	$3\cdot10^{-4}$	$4\cdot10^{-4}$	$4\cdot10^{-4}$
Nitric acid	g·kWh^{-1}	$3.7\cdot10^{-2}$	$1.2\cdot10^{-2}$	$6\cdot10^{-3}$
Ammonia	g·kWh^{-1}	$1\cdot10^{-2}$	$3\cdot10^{-3}$	$2\cdot10^{-3}$
Bauxite	g·kWh^{-1}	$2\cdot10^{-5}$	$6\cdot10^{-5}$	$9\cdot10^{-5}$
Sulphuric acid	g·kWh^{-1}	$5\cdot10^{-5}$	$6\cdot10^{-5}$	$8\cdot10^{-3}$

Table 6.4 The use of non-renewable resources in Sweden during operation and maintenance of the plants (Brännström-Norberg et al., 1995).

Resource	**Unit**	**Use in Seitevare**	**Use in Harsprånget**	**Use in Boden**
Iron ore	g·kWh^{-1}	$2\cdot10^{-2}$	$6\cdot10^{-2}$	$3\cdot10^{-2}$
Copper ore	g·kWh^{-1}	$1\cdot10^{-2}$	$4\cdot10^{-2}$	$1\cdot10^{-2}$
Lead ore	g·kWh^{-1}	$1\cdot10^{-2}$	$1\cdot10^{-2}$	$1\cdot10^{-2}$
Sulphuric acid	g·kWh^{-1}	$3\cdot10^{-4}$	$3\cdot10^{-4}$	$5\cdot10^{-4}$

In the Japanese study the dam is made of concrete. The non-renewable resource use is therefore different from situations where rock- or earth-filled dams are used, such as in Sweden.

Table 6.5 The use of non-renewable resources in Japanese hydropower (Uchiyama, 1995).

Resource	**Unit**	**Manufacturing and construction**	**Operation and maintenance**	**Total**
Steel	g·kWh^{-1}	$9.04\cdot10^{-1}$	$5.83\cdot10^{-2}$	$9.62\cdot10^{-1}$
Stainless steel	g·kWh^{-1}	$2.23\cdot10^{-3}$	$6.70\cdot10^{-4}$	$2.90\cdot10^{-3}$
Aluminium	g·kWh^{-1}	$8.73\cdot10^{-4}$	$2.63\cdot10^{-4}$	$1.14\cdot10^{-3}$
Copper	g·kWh^{-1}	$1.64\cdot10^{-2}$	$4.93\cdot10^{-3}$	$2.13\cdot10^{-2}$
Cement	g·kWh^{-1}	6.70	0	6.70
Alloy	g·kWh^{-1}	$3.98\cdot10^{-3}$	$1.20\cdot10^{-3}$	$5.18\cdot10^{-3}$
Silicon	g·kWh^{-1}	$2.86\cdot10^{-2}$	$8.59\cdot10^{-3}$	$3.72\cdot10^{-2}$
Forged	g·kWh^{-1}	$1.20\cdot10^{-2}$	$3.59\cdot10^{-3}$	$1.55\cdot10^{-2}$
Cast iron	g·kWh^{-1}	$1.61\cdot10^{-2}$	$3.79\cdot10^{-3}$	$1.99\cdot10^{-2}$
Lead	g·kWh^{-1}	$1.19\cdot10^{-3}$	$3.56\cdot10^{-4}$	$1.54\cdot10^{-3}$
Brass	g·kWh^{-1}	$1.02\cdot10^{-4}$	$2.54\cdot10^{-5}$	$1.27\cdot10^{-4}$
Zinc oxide	g·kWh^{-1}	$2.12\cdot10^{-4}$	$6.78\cdot10^{-5}$	$2.80\cdot10^{-4}$
Vinyl chloride	g·kWh^{-1}	$3.39\cdot10^{-3}$	$1.02\cdot10^{-3}$	$4.41\cdot10^{-3}$
Polyethylene	g·kWh^{-1}	$3.13\cdot10^{-3}$	$9.41\cdot10^{-4}$	$4.07\cdot10^{-3}$
Epoxy resin	g·kWh^{-1}	$4.24\cdot10^{-5}$	$1.70\cdot10^{-5}$	$5.93\cdot10^{-5}$
Insulation	g·kWh^{-1}	$1.84\cdot10^{-3}$	$5.51\cdot10^{-4}$	$2.39\cdot10^{-3}$
SF6 gas	g·kWh^{-1}	$5.09\cdot10^{-5}$	$1.70\cdot10^{-5}$	$6.78\cdot10^{-5}$
Insulator	g·kWh^{-1}	$1.92\cdot10^{-3}$	$5.76\cdot10^{-4}$	$2.50\cdot10^{-3}$
Kraft paper	g·kWh^{-1}	$1.61\cdot10^{-4}$	$5.09\cdot10^{-5}$	$2.12\cdot10^{-4}$
Press board	g·kWh^{-1}	$8.48\cdot10^{-4}$	$2.54\cdot10^{-4}$	$1.10\cdot10^{-3}$
Paint	g·kWh^{-1}	$7.63\cdot10^{-5}$	$2.54\cdot10^{-5}$	$1.02\cdot10^{-4}$
Insulation oil	g·kWh^{-1}	$6.75\cdot10^{-3}$	$2.03\cdot10^{-3}$	$8.77\cdot10^{-3}$

Renewables

Hydropower is a renewable energy technology that efficiently transforms the potential energy of water to electric energy. A potential energy of 1,28 kWh from the water is needed to generate 1 kWh of electricity, according to the ETH-study. The transformation factor is thus 78%. On average, 23.7 tonnes of water is required to generate this amount of energy with hydropower turbines according to this study. However, it should be remembered that the specific water use in this context is highly variable between different geographical settings, depending mainly on the available head. Minor amounts of water are also used in some other related processes in the hydropower lifecycle. These uses amount to $42.1 g \cdot kWh^{-1}$. Wood is another renewable resource used in the hydropower LCA. A total of $1.06 \cdot 10^4 g \cdot kWh^{-1}$ is used (Frischknecht & Müller-Lemans, 1996). Table 6.6 lists the maximum and minimum usage of renewable resources among the different countries examined The amount of water passed through the turbines per kWh is inversely proportional to the available head, i.e. the potential energy of the water. In Italy, for example, hydropower plants are usually reservoir plants with large head, while the many run-of-river plants in Germany only have small amounts of potential energy available. Therefore the German plants require more water to produce the same amount of electricity.

Table 6.6 Maximum and Minimum uses of renewable resources for UCPTE countries (Frischknecht & Müller-Lemans, 1996).

Resource	**Unit**	**Minimal use**	**Country**	**Maximal use**	**Country**
Potential energy water	$kWh \cdot kWh^{-1}$	1.23	Germany	1.30	Italy
Turbine water	$g \cdot kWh^{-1}$	$1.58 \cdot 10^7$	Italy	$4.00 \cdot 10^7$	Germany
Other water use	$g \cdot kWh^{-1}$	27.9	Switzerland	44.6	Italy
Wood	$g \cdot kWh^{-1}$	$9.29 \cdot 10^{-3}$	Germany	$1.12 \cdot 10^{-2}$	Italy

A small amount of energy is used in addition to water and wood in the hydropower lifecycle. The use of renewable energy and use of wood for the building and manufacturing phase in the Swedish LCA are shown in the table below.

Table 6.7 Use of renewable resources for construction in Swedish hydropower (Brännström-Norberg et al., 1995).

Resource	**Unit**	**Use Seitevare**	**Use Harsprånget**	**Use Boden**
Energy				
Hydropower	$kWh \cdot kWh^{-1}$	$0.58 \cdot 10^{-4}$	$1.13 \cdot 10^{-4}$	$1.60 \cdot 10^{-4}$
Wooden chips	$kg \cdot kWh^{-1}$	$9.83 \cdot 10^{-4}$	$3.70 \cdot 10^{-3}$	$2.27 \cdot 10^{-3}$
Material				
Wood	$m^3 \cdot kWh^{-1}$	0.51	1.28	1.98

Land

Land is actually not consumed but alterations following hydropower development may be comprehensive and long-lasting. Land reclaimed for buildings, access roads and dams are inaccessible for alternative use as long as the hydropower installations are in place. Other areas, such as draw-down zones, become depleted of their flora and fauna. Together, such areas represent net habitat losses since very few animals and plants can make use of this artificial and heavily disturbed land. However, it should be noted that water-level fluctuations in reservoirs and regulated rivers have very different outcomes in terms of the impact on biota depending on climate, soil conditions and human use. There is clearly a need of differentiating impacts on land-use.

The ETH study attempts this for the UCPTE countries. Four different quality classes of land were defined in that study:

- class I: natural (human influence since industrial revolution not larger than the influence exerted by other species)
- class II: modified (human influence larger than other species' influence, but mostly uncultivated, e.g. natural forest)
- class III: cultivated (human influence larger than other species' influence, mostly cultivated, e.g. agriculture, forestry)
- class IV: built up (dominated by buildings, roads, dams, mines etc.)

Using these categories also assessed changes in land use. For example, building a road into agricultural land would change the land class from III to VI. Land change is given in m^2a, considering average time of use and time needed to re-cultivate the land. It was assumed that class IV land takes 5 years to be re-cultivated to class III land, class III land requires 50 years to be re-cultivated to class II, and class II requires 100'000 years to turn into class I land again. The realism of these time-spans can of course be questioned.

Hydropower makes an extensive direct use of land. In the referred study it was assumed that class I land is not affected by hydropower development in the UCPTE region. The following Table 6.8 shows the specific land use shifts that were calculated:

Table 6.8 Land use changes in the UCPTE region (Frischknecht & Müller-Lemans, 1996).

Land use type	Unit	Area
River bed area II-III	$m^2a \cdot kWh^{-1}$	$1.99 \cdot 10^{-5}$
River bed area II-IV	$m^2a \cdot kWh^{-1}$	$2.05 \cdot 10^{-6}$
River bed area III-IV	$m^2a \cdot kWh^{-1}$	0.00
Land area II-III	$m^2a \cdot kWh^{-1}$	$4.68 \cdot 10^{-3}$
Land area II-IV	$m^2a \cdot kWh^{-1}$	$9.79 \cdot 10^{-5}$
Land area III-IV	$m^2a \cdot kWh^{-1}$	$1.50 \cdot 10^{-5}$
Land area IV-IV	$m^2a \cdot kWh^{-1}$	$1.12 \cdot 10^{-7}$
Total	$\mathbf{m^2a \cdot kWh^{-1}}$	$\mathbf{4.82 \cdot 10^{-3}}$

According to this study the main land use change brought about by hydropower development is from class II to class III. Building the dam and filling the reservoir induce a shift of this type. The formation of reservoirs accounts for the majority of class II-III land use change. The UCPTE average land acquisition is $4.82 \cdot 10^{-3}$ $m^2a \cdot kWh^{-1}$. In the different countries studied, land use varies surprisingly little according to the ETH study.

- minimum: $4.75 \cdot 10^{-3}$ $m^2a \cdot kWh^{-1}$ (Germany)
- maximum: $4.86 \cdot 10^{-3}$ $m^2a \cdot kWh^{-1}$ (Italy)

In the Swedish study, land acquisition is expressed as the area flooded per unit electricity produced (Table 6.9).

Table 6.9 Loss of land due to flooding in Sweden (Brännström-Norberg et al., 1995).

Land type	Unit	Reservoir area
Agricultural		
Arable land	$m^2 \cdot kWh^{-1}$	$5 \cdot 10^{-7}$
Meadowland	$m^2 \cdot kWh^{-1}$	$7 \cdot 10^{-6}$
Old haymaking land	$m^2 \cdot kWh^{-1}$	$5 \cdot 10^{-5}$
Ground-plot land	$m^2 \cdot kWh^{-1}$	$3 \cdot 10^{-6}$
Forested		
Productive woodland	$m^2 \cdot kWh^{-1}$	$10 \cdot 10^{-4}$
Non-productive woodland	$m^2 \cdot kWh^{-1}$	$3 \cdot 10^{-4}$
Woodland to buildings and roads.	$m^2 \cdot kWh^{-1}$	$1 \cdot 10^{-4}$

6.3 Global environmental impact

Greenhouse effect

Greenhouse gas emissions attributable to hydropower plants are widely debated in the world today. Even though hydropower is considered to be a renewable source of electricity, some emissions of greenhouse gases normally do occur, at least during construction. Emissions are very low for run-of-river power plants, while there are divergent opinions and observations about the magnitude of the emissions from reservoir power plants. Different studies have suggested very different amounts of emissions; according to recent reports the emissions range between 4 and 410 g CO_2 per kWh (Gagnon & Van de Vate, 1997).

Emissions from the manufacturing and construction phase are low. The gases are mainly emitted during manufacturing of the cement and during transportation of building material to the power plant. Therefore, emissions are lower for earth and rock-filled dams than for those made of concrete. Run-of-river plants generally have lower emissions than reservoir power plants since run-of-river plants do not use large quantities of building materials. Life cycle analyses done in Sweden and Japan have estimated the emissions from reservoir power plants, but these analyses do not include estimates of emissions caused by inundation. The difference between rock-filled dams as exemplified by the Swedish LCA study (Table 6.10) and dams made of cement as revealed from the Japanese LCA (Table 6.11) is obvious.

Table 6.10 Emissions of carbon dioxide from three Swedish hydropower plants (Brännström-Norberg et al., 1995).

Substance	**Unit**	**Manufacturing and construction**	**Operation and maintenance**	**Total**
Seitevare	g·kWh^{-1}	$4.74\cdot10^{-1}$	$1.02\cdot10^{-1}$	$5.76\cdot10^{-1}$
Harsprånget	g·kWh^{-1}	$6.89\cdot10^{-1}$	$0.56\cdot10^{-1}$	$7.45\cdot10^{-1}$
Boden	g·kWh^{-1}	$7.24\cdot10^{-1}$	$0.63\cdot10^{-1}$	$7.87\cdot10^{-1}$

Table 6.11 Emissions of greenhouse gases expressed as carbon dioxide equivalents from Japanese hydroelectric power plants (Uchiyama, 1995).

Substance	**Unit**	**Manufacturing and construction**	**Operation and maintenance**	**Total**
CO_2 carbon dioxide	g·kWh^{-1}	17.0	0.26	17.2
CH_4 methane	g·kWh^{-1}	0.40	0	0.40
Total	**g·kWh^{-1}**	**17.4**	**0.26**	**17.6**

Yet another study was made in Norway and the emissions were very low according to that study, i.e. 0.2 g·kWh^{-1} CO_2-equivalent emissions due to manufacturing and construction and 1.25 g·kWh^{-1} for operation and maintenance (Sandgren & Sorteberg, 1994).

Most environments contain a pool of dead organic matter, reflecting a time lag between the production and decomposition processes and/or an imbalance between the rate of primary production and respiration, respectively. This imbalance is small in most tropical and arctic environments, but tends to increase in temperate ones, being particularly large where extremely wet or extremely dry, and cold conditions prevail (Goudriaan, 1994). Hence, there is a net retention of carbon in the natural environment.

The transformation of terrestrial environments into freshwater ones, following the construction and use of dams, alters the ratio between production and respiration. Recent observations demonstrate that lakes usually act as sources of carbon dioxide emitted to the atmosphere (Cole *et al.*, 1994). When anaerobic conditions arise, a common situation in stratified and eutrophic lakes and reservoirs, decomposition of organic matter will result in methane formation. Methane has a greenhouse gas potential (GHG_{100}) that is 21 times that of CO_2. Measurements and model calculations of methane emissions from some boreal and tropical reservoirs have led to the conclusion that hydropower sometimes causes an atmospheric load of greenhouse gases that is comparable or even exceeds that from fossil-fuelled power plants (Rosenberg *et al.*, 1995; Galy-Lacaux *et al.*, 1999).

A critical review of the studies underlying this conclusion reveals that factors used to transform the greenhouse gas potential of methane to carbon dioxide have been incorrect (Gagnon & Chamberland, 1993). Moreover, no account has been given to how much gas the flooded land would have emitted in the absence of the reservoir. It should also be noted that man-made lakes in arid regions on average contain more carbon than their terrestrial surroundings, so that hydropower in such areas actually contribute to a net sequestration of carbon and hence to negative emissions of greenhouse gas. Lake Nasser, a man-made reservoir providing water to the Aswan High Dam, is one such example. Theoretical considerations as well as measurements of dissolved carbon-dioxide and transport of organic carbon in the Nile before and after impoundment invariably point to a net sequestration of carbon of at least 1 g per kWh when related to the anticipated electricity production over 100 years (Axelsson, 1999).

Table 6.12 shows the greenhouse gas emissions in CO_2-equivalents in the UCPTE region. CH_4 and N_2O emissions were omitted in the ETH study, because reservoirs of UCPTE power plants are mostly located at high altitudes, where the amount of biomass is naturally low. Hence, comparatively low amounts of organic matter are available for decomposition following reservoir flooding. Low temperature also increases the amount of dissolved oxygen and reduces the rate and extension of anaerobic processes that give rise to methane. The estimated CH_4 emission for Swiss hydroelectric reservoirs is $1.44 \cdot 10^{-2}$ g·kWh^{-1} (Table 6.12). Substances causing greenhouse gas emissions of less than 0.1% of the total, expressed as CO_2-equivalents, were omitted in the table below.

Table 6.12 Emissions of greenhouse gases in the UCPTE region (Frischknecht & Müller-Lemans, 1996). m = emissions from transport (mobile); p = process specific emissions, often diffuse, e.g., leakage, evaporation etc.; s = stationary emissions, e.g., from combustion, flue gases.

Substance	**Unit**	**Emission**	**GWP 100 years g CO_2-equivalents/g)**	**CO_2-equivalents**
CF_4 p	$g{\cdot}kWh^{-1}$	$8.82{\cdot}10^{-7}$	6500	$5.72{\cdot}10^{-3}$
CH_4 methane p	$g{\cdot}kWh^{-1}$	$8.53{\cdot}10^{-3}$	21	$1.79{\cdot}10^{-1}$
CH_4 methane s	$g{\cdot}kWh^{-1}$	$1.44{\cdot}10^{-2}$	21	$3.02{\cdot}10^{-1}$
CO carbon monoxide p	$g{\cdot}kWh^{-1}$	$8.28{\cdot}10^{-3}$	3	$2.48{\cdot}10^{-2}$
CO carbon monoxide s	$g{\cdot}kWh^{-1}$	$1.23{\cdot}10^{-2}$	3	$3.71{\cdot}10^{-2}$
CO_2 carbon dioxide m	$g{\cdot}kWh^{-1}$	$1.07{\cdot}10^{-1}$	1	$1.07{\cdot}10^{-1}$
CO_2 carbon dioxide p	$g{\cdot}kWh^{-1}$	1.26	1	1.26
CO_2 carbon dioxide s	$g{\cdot}kWh^{-1}$	2.39	1	2.39
N_2O p	$g{\cdot}kWh^{-1}$	$2.79{\cdot}10^{-5}$	310	$8.64{\cdot}10^{-3}$
N_2O s	$g{\cdot}kWh^{-1}$	$2.13{\cdot}10^{-5}$	310	$6.62{\cdot}10^{-3}$
Total	**$g{\cdot}kWh^{-1}$**			**4.03**

The total amount of CO_2-equivalents emitted during a 100 years perspective is thus 3.71 $g{\cdot}kWh^{-1}$ for the UCPTE average. Using other time-horizons alters this figure only marginally. The difference is mainly due to the differential contribution of methane as observed in the previous Table (cf. IPCC, 1996). However, the emissions are very low compared to emissions from other energy sources.

- 20 year GWP: 5.11 $g{\cdot}kWh^{-1}$
- 500 year GWP: 4.00 $g{\cdot}kWh^{-1}$

The range of CO_2-equivalent emission from the UCPTE countries is:

- minimum: 3.96 $g{\cdot}kWh^{-1}$ (Switzerland)
- maximum: 4.43 $g{\cdot}kWh^{-1}$ (Italy)

It is important to note that these values are only valid for UCPTE conditions, i.e. the UCPTE hydropower mix (52.1% run-of-river to 47.9% reservoir), and reservoirs in mostly high altitudes with low temperatures, with scarce vegetation, and with a low surface to volume ratio. In other geographical settings, e.g., in tropical forests, where considerable amounts of biomass may be flooded, hydropower reservoirs may give rise to far greater amount of greenhouse gases, although it is highly unlikely that they ever reach levels comparable to fossil-fuelled power plants, as is sometimes alleged (McCully, 1996).

Ozone layer depletion

Table 6.13 lists the ozone layer depletion potentials (ODP) resulting from hydropower in the UCPTE region. Substances contributing less than 0.1% of the total ozone depletion potential (ODP) were omitted.

Table 6.13 Emissions of ozone depleting substances from the UCPTE region (Frischknecht & Müller-Lemans, 1996). p = process specific emissions, often diffuse, e.g., leakage, evaporation etc.

Substance	**Unit**	**Emission**	**Best estimate ODP factor (g CFC-11 equiv./g)**	**CFC-11 equiv.**
H 1301 halon	$g \cdot kWh^{-1}$	$1.04 \cdot 10^{-7}$	16	$1.67 \cdot 10^{-6}$
R11 FCKW	$g \cdot kWh^{-1}$	$5.11 \cdot 10^{-9}$	1	$5.11 \cdot 10^{-9}$
R114 FCKW	$g \cdot kWh^{-1}$	$1.35 \cdot 10^{-7}$	0.8	$1.08 \cdot 10^{-7}$
Tetrachlormethane	$g \cdot kWh^{-1}$	$4.93 \cdot 10^{-9}$	1.08	$5.33 \cdot 10^{-9}$
Total	$\mathbf{g \cdot kWh^{-1}}$			$\mathbf{1.79 \cdot 10^{-6}}$

The total ODP from hydropower in CFC-11-equivalents is $1.79 \cdot 10^{-6}$ $g \cdot kWh^{-1}$ in the UCPTE region. Halon is by far the main contributor.

The following values show the range of ODP for the UCPTE countries. For all observed UCPTE countries the emissions vary only slightly:

- minimum: $1.65 \cdot 10^{-6}$ $g \cdot kWh^{-1}$ (Switzerland)
- maximum: $1.85 \cdot 10^{-6}$ $g \cdot kWh^{-1}$ (Germany)

6.4 Local and regional environmental impact

Acidification

Several chemical compounds emitted to the atmosphere when later deposited deplete the capacity of soil and water to withstand acidification. A list of those substances and their acidification potential (AP) is given in Table 6.14 together with average emissions as revealed from the hydropower LCA for the UCTPE countries. Emissions contributing less than 0.1% of the total AP were omitted.

Table 6.14 Emissions of acidifying substances from hydropower in UCPTE countries (Frischknecht & Müller-Lemans, 1996). m = emissions from transport (mobile); p = process specific emissions, often diffuse, e.g., leakage, evaporation etc.; s = stationary emissions, e.g., from combustion, flue gases; f = to freshwater.

Substance	**Unit**	**Emission**	**Max. factor (g SO_2-equivalents/g)**	**Max. AP (SO_2-equivalents)**
HCl p	$g{\cdot}kWh^{-1}$	$2.46{\cdot}10^{-5}$	0.88	$2.16{\cdot}10^{-5}$
HCl s	$g{\cdot}kWh^{-1}$	$1.56{\cdot}10^{-4}$	0.88	$1.38{\cdot}10^{-4}$
NH_3 p	$g{\cdot}kWh^{-1}$	$1.88{\cdot}10^{-5}$	1.88	$3.53{\cdot}10^{-5}$
NO_x as NO_2 m	$g{\cdot}kWh^{-1}$	$1.36{\cdot}10^{-3}$	0.7	$9.54{\cdot}10^{-4}$
NO_x as NO_2 p	$g{\cdot}kWh^{-1}$	$3.85{\cdot}10^{-4}$	0.7	$2.70{\cdot}10^{-4}$
NO_x as NO_2 s	$g{\cdot}kWh^{-1}$	$9.76{\cdot}10^{-3}$	0.7	$6.84{\cdot}10^{-3}$
SO_x as SO_2 m	$g{\cdot}kWh^{-1}$	$1.22{\cdot}10^{-3}$	1	$1.22{\cdot}10^{-3}$
SO_x as SO_2 p	$g{\cdot}kWh^{-1}$	$3.48{\cdot}10^{-3}$	1	$3.48{\cdot}10^{-3}$
SO_x as SO_2 s	$g{\cdot}kWh^{-1}$	$5.62{\cdot}10^{-3}$	1	$5.62{\cdot}10^{-3}$
Ammonium as N f	$g{\cdot}kWh^{-1}$	$3.38{\cdot}10^{-5}$	1.88	$6.37{\cdot}10^{-5}$
Total	$\mathbf{g{\cdot}kWh^{-1}}$			$\mathbf{1.86{\cdot}10^{-2}}$

The maximum acidification potential of hydropower in SO_2-equivalents is thus $1.82{\cdot}10^{-2}$ $g{\cdot}kWh^{-1}$. SO_X and NO_X emissions, mainly stemming from construction and materials production, are the main contributors. Depending on the type of soil or ecosystem affected, the actual acidification potential will vary between the maximum and the minimum potential, which is $1.05{\cdot}10^{-2}$ $g{\cdot}kWh^{-1}$. In the observed countries, the following extremes in AP can be noted:

- minimum: $1.59{\cdot}10^{-2}$ $g{\cdot}kWh^{-1}$ (Switzerland)
- maximum: $1.90{\cdot}10^{-2}$ $g{\cdot}kWh^{-1}$ (Italy)

Table 6.15 Emissions of acidification compounds from hydropower in Sweden (Brännström-Norberg et al., 1995).

Substance	Unit	Emission Building	Emission Operation	Emission Total	Total (SO_2-equivalents)
Seitevare					
NO_x	$g \cdot kWh^{-1}$	$7.53 \cdot 10^{-3}$	$5.98 \cdot 10^{-4}$	$8.13 \cdot 10^{-3}$	$5.69 \cdot 10^{-3}$
SO_x as SO_2	$g \cdot kWh^{-1}$	$1.02 \cdot 10^{-3}$	$0.57 \cdot 10^{-4}$	$1.08 \cdot 10^{-3}$	$1.08 \cdot 10^{-3}$
Total	**$g \cdot kWh^{-1}$**				**$6.77 \cdot 10^{-3}$**
Harsprånget					
NO_x	$g \cdot kWh^{-1}$	$5.12 \cdot 10^{-3}$	$1.33 \cdot 10^{-4}$	$5.25 \cdot 10^{-3}$	$3.68 \cdot 10^{-3}$
SO_x as SO_2	$g \cdot kWh^{-1}$	$1.53 \cdot 10^{-3}$	$1.32 \cdot 10^{-4}$	$1.66 \cdot 10^{-3}$	$1.66 \cdot 10^{-3}$
Total	**$g \cdot kWh^{-1}$**				**$5.34 \cdot 10^{-3}$**
Boden					
NO_x	$g \cdot kWh^{-1}$	$4.79 \cdot 10^{-3}$	$2.94 \cdot 10^{-4}$	$5.08 \cdot 10^{-3}$	$3.56 \cdot 10^{-3}$
SO_x as SO_2	$g \cdot kWh^{-1}$	$1.63 \cdot 10^{-3}$	$0.90 \cdot 10^{-4}$	$1.72 \cdot 10^{-3}$	$1.72 \cdot 10^{-3}$
Total	**$g \cdot kWh^{-1}$**				**$5.28 \cdot 10^{-3}$**

The Swedish LCA arrives at emission of acidifying substances that is one order of magnitude lower compared to the Swiss study. This is because a higher amount of fossil fuel is used during construction and manufacturing in the UCPTE setting.

Table 6.16 Emissions of acidification substances from hydropower in Norway (Sandgren & Sorteberg, 1994)

Substance	Unit	Emission Building	Emission Operation	Emission Total	Total (SO_2-equivalents)
NO_x	$g \cdot kWh^{-1}$	$2 \cdot 10^{-3}$	$1 \cdot 10^{-5}$	$2 \cdot 10^{-3}$	$1.4 \cdot 10^{-3}$
SO_x	$g \cdot kWh^{-1}$	$2.5 \cdot 10^{-3}$	$2 \cdot 10^{-6}$	$2.5 \cdot 10^{-3}$	$2.5 \cdot 10^{-3}$
Total	**$g \cdot kWh^{-1}$**				**$3.9 \cdot 10^{-3}$**

Eutrophication

As with acidification it is possible to calculate the strength by which different emissions might add to eutrophication. Table 6.17 gives the maximum eutrophication potentials (EP) for chemical compounds quantified in the UCPTE hydropower LCA. Again, emissions contributing less than 0.1% of the total EP were omitted. The reason why EP is expressed as amount of oxygen per unit weight is that the most severe effect of eutrophication is its depletion of dissolved oxygen in the aquatic environment.

Table 6.17 Emissions of eutrophication substances from hydropower in UCPTE countries (Frischknecht & Müller-Lemans, 1996). m = emissions from transport (mobile); p = process specific emissions, often diffuse, e.g., leakage, evaporation etc.; s = stationary emissions, e.g., from combustion, flue gases; f = to freshwater; sw = to the sea.

Substance	**Unit**	**Emission**	**Max. eutrophication factor (g O_2 /g)**	**Max. EP in O_2 decrease**
NH_3 p	$g\cdot kWh^{-1}$	$1.88\cdot10^{-5}$	16	$3.01\cdot10^{-4}$
NOx as NO_2 m	$g\cdot kWh^{-1}$	$1.36\cdot10^{-3}$	6	$8.17\cdot10^{-3}$
NOx as NO_2 p	$g\cdot kWh^{-1}$	$3.85\cdot10^{-4}$	6	$2.31\cdot10^{-3}$
NOx as NO_2 s	$g\cdot kWh^{-1}$	$9.76\cdot10^{-3}$	6	$5.87\cdot10^{-2}$
Ammonium as N f	$g\cdot kWh^{-1}$	$3.38\cdot10^{-5}$	16	$5.40\cdot10^{-4}$
Ammonium as N sw	$g\cdot kWh^{-1}$	$6.19\cdot10^{-6}$	16	$9.90\cdot10^{-5}$
COD f	$g\cdot kWh^{-1}$	$8.50\cdot10^{-5}$	1	$8.50\cdot10^{-5}$
Nitrates f	$g\cdot kWh^{-1}$	$2.46\cdot10^{-5}$	4.4	$1.08\cdot10^{-4}$
Phosphates f	$g\cdot kWh^{-1}$	$1.04\cdot10^{-4}$	46	$4.79\cdot10^{-3}$
Nitrogen total f	$g\cdot kWh^{-1}$	$1.71\cdot10^{-5}$	20	$3.41\cdot10^{-4}$
Nitrogen total sw	$g\cdot kWh^{-1}$	$8.24\cdot10^{-6}$	20	$1.65\cdot10^{-4}$
Total	**$g\cdot kWh^{-1}$**			**$7.56\cdot10^{-2}$**

The maximum eutrophication potential of the hydropower lifecycle is thus $7{,}56\cdot10^{-2}$ g O_2-decrease per kWh of produced electricity. The main contributions are from NO_X emissions caused by construction and materials production. The actual eutrophication potential depends greatly on the kind of ecosystem that is influenced, i.e., whether the affected ecosystem is Phosphorus-limited or Nitrogen-limited:

- potential for P-limited ecosystems: $4.93\cdot10^{-3}$ $g\cdot kWh^{-1}$
- potential for N-limited ecosystems: $7.09\cdot10^{-2}$ $g\cdot kWh^{-1}$

The range of eutrophication potential varies only slightly for the investigated UCPTE countries:

- minimum: $7.06\cdot10^{-2}$ $g\cdot kWh^{-1}$ (Switzerland)
- maximum: $7.81\cdot10^{-2}$ $g\cdot kWh^{-1}$ (Germany)

Table 6.18 Emissions of eutrophication substances from three hydropower stations in Sweden (Brännström-Norberg et al., 1995).

Substance	**Unit**	**Emission Building**	**Emission Operation**	**Emission Total**	**Max. EP in O_2 decrease**
Seitevare:					
NO_x	$g \cdot kWh^{-1}$	$7.53 \cdot 10^{-3}$	$5.98 \cdot 10^{-4}$	$8.13 \cdot 10^{-3}$	$4.88 \cdot 10^{-2}$
COD	$g \cdot kWh^{-1}$	$7.28 \cdot 10^{-6}$	$1.54 \cdot 10^{-6}$	$8.82 \cdot 10^{-6}$	$8.82 \cdot 10^{-6}$
Nitrogen total	$g \cdot kWh^{-1}$	$1.10 \cdot 10^{-6}$	$0.15 \cdot 10^{-6}$	$1.25 \cdot 10^{-6}$	$2.50 \cdot 10^{-5}$
Total	$\mathbf{g \cdot kWh^{-1}}$				$\mathbf{4.88 \cdot 10^{-2}}$
Harspranget:					
NO_x	$g \cdot kWh^{-1}$	$5.12 \cdot 10^{-3}$	$1.33 \cdot 10^{-4}$	$5.25 \cdot 10^{-3}$	$3.15 \cdot 10^{-2}$
COD	$g \cdot kWh^{-1}$	$2.22 \cdot 10^{-5}$	$4.12 \cdot 10^{-6}$	$2.63 \cdot 10^{-5}$	$2.63 \cdot 10^{-5}$
Nitrogen total	$g \cdot kWh^{-1}$	$2.25 \cdot 10^{-6}$	$0.40 \cdot 10^{-6}$	$2.65 \cdot 10^{-6}$	$5.30 \cdot 10^{-5}$
Total	$\mathbf{g \cdot kWh^{-1}}$				$\mathbf{3.15 \cdot 10^{-2}}$
Boden:					
NO_x	$g \cdot kWh^{-1}$	$4.79 \cdot 10^{-3}$	$2.94 \cdot 10^{-4}$	$5.08 \cdot 10^{-3}$	$3.05 \cdot 10^{-2}$
COD	$g \cdot kWh^{-1}$	$1.91 \cdot 10^{-5}$	$2.56 \cdot 10^{-6}$	$2.17 \cdot 10^{-5}$	$2.17 \cdot 10^{-5}$
Nitrogen total	$g \cdot kWh^{-1}$	$1.89 \cdot 10^{-6}$	$0.25 \cdot 10^{-6}$	$2.14 \cdot 10^{-6}$	$4.28 \cdot 10^{-5}$
Total	$\mathbf{g \cdot kWh^{-1}}$				$\mathbf{3.05 \cdot 10^{-2}}$

Photochemical oxidant formation

Photochemical ozone creation potentials (POCP) are calculated in Table 6.19. Substances contributing less than 0.1% of the total POCP were omitted.

Table 6.19 Emissions of POH substances from hydropower in UCPTE countries (Frischknecht & Müller-Lemans, 1996). m = emissions from transport (mobile); p = process specific emissions, often diffuse, e.g., leakage, evaporation etc.; s = stationary emissions, e.g., from combustion, flue gases; sw = to the sea.

Substance	**Unit**	**Emission**	**POCP factor (g ethene-equiv./g)**	**POCP in ethene-equiv.**
alkanes p	$g\cdot kWh^{-1}$	$5.44\cdot10^{-6}$	0.398	$2.16\cdot10^{-6}$
butane p	$g\cdot kWh^{-1}$	$2.15\cdot10^{-5}$	0.363	$7.81\cdot10^{-6}$
CH_4 methane p	$g\cdot kWh^{-1}$	$8.53\cdot10^{-3}$	0.007	$5.98\cdot10^{-5}$
CO carbon monoxide m	$g\cdot kWh^{-1}$	$2.55\cdot10^{-4}$	0.036	$9.18\cdot10^{-6}$
CO carbon monoxide p	$g\cdot kWh^{-1}$	$8.28\cdot10^{-3}$	0.036	$2.98\cdot10^{-4}$
CO carbon monoxide s	$g\cdot kWh^{-1}$	$1.23\cdot10^{-2}$	0.036	$4.43\cdot10^{-4}$
ethene p	$g\cdot kWh^{-1}$	$1.95\cdot10^{-5}$	1	$1.95\cdot10^{-5}$
ethene s	$g\cdot kWh^{-1}$	$8.71\cdot10^{-6}$	1	$8.71\cdot10^{-6}$
heptane p	$g\cdot kWh^{-1}$	$4.97\cdot10^{-6}$	0.529	$2.63\cdot10^{-6}$
Hexachlorbenzol HCB s	$g\cdot kWh^{-1}$	$9.07\cdot10^{-13}$	0.021	$1.90\cdot10^{-14}$
hexane p	$g\cdot kWh^{-1}$	$1.04\cdot10^{-5}$	0.421	$4.39\cdot10^{-6}$
NMVOC m	$g\cdot kWh^{-1}$	$1.02\cdot10^{-4}$	0.416	$4.25\cdot10^{-5}$
NMVOC p	$g\cdot kWh^{-1}$	$2.34\cdot10^{-3}$	0.416	$9.72\cdot10^{-4}$
NMVOC s	$g\cdot kWh^{-1}$	$7.92\cdot10^{-4}$	0.416	$3.29\cdot10^{-4}$
pentane p	$g\cdot kWh^{-1}$	$2.63\cdot10^{-5}$	0.352	$9.25\cdot10^{-6}$
propane p	$g\cdot kWh^{-1}$	$2.31\cdot10^{-5}$	0.42	$9.72\cdot10^{-6}$
xyloles p	$g\cdot kWh^{-1}$	$3.20\cdot10^{-6}$	0.849	$2.72\cdot10^{-6}$
xyloles s	$g\cdot kWh^{-1}$	$4.39\cdot10^{-6}$	0.849	$3.74\cdot10^{-6}$
Aromatic CHs total sw	$g\cdot kWh^{-1}$	$7.27\cdot10^{-6}$	0.761	$5.54\cdot10^{-6}$
Total	$\mathbf{g\cdot kWh^{-1}}$			$\mathbf{2.25\cdot10^{-3}}$

The UCPTE average best estimate of POCP for the hydropower life cycle is $2.25\cdot10^{-3}$ g ethene-equivalents per kWh of produced electricity. Non-methane volatile organic compounds (NMVOC) and carbon monoxide emissions are the main contributors.

Among the investigated countries, the range of values for POCP were:

- minimum: $2.15\cdot10^{-3}$ $g\cdot kWh^{-1}$ (Switzerland)
- maximum: $2.30\cdot10^{-3}$ $g\cdot kWh^{-1}$ (Germany)

The availability of NO_X is a key factor in photochemical ozone formation.

In the Swedish LCA, the emission of carbon monoxide was calculated. The magnitude of these emissions was similar to those calculated in the ETH-study. These CO values are listed in Table 6.20.

Table 6.20 Emissions of carbon monoxide from the Swedish power plants (Brännström-Norberg et al., 1995).

Site	**Unit**	**Emission Building**	**Emission Operation**	**Emission Total**
Seitevare	$g \cdot kWh^{-1}$	$2.90 \cdot 10^{-3}$	$6.34 \cdot 10^{-3}$	$9.24 \cdot 10^{-3}$
Harsprånget	$g \cdot kWh^{-1}$	$2.82 \cdot 10^{-3}$	$0.72 \cdot 10^{-4}$	$2.89 \cdot 10^{-3}$
Boden	$g \cdot kWh^{-1}$	$3.52 \cdot 10^{-3}$	$2.05 \cdot 10^{-3}$	$5.57 \cdot 10^{-3}$

Ecotoxic impact

Water and soil contamination potentials are calculated in Table 6.21. Substances contributing less than 0.5% of the total contamination of both soil and water were omitted.

Table 6.21 Emissions of ecotoxic substances from hydropower in UCPTE countries (Frischknecht & Müller-Lemans, 1996). m = emissions from transport (mobile); p = process specific emissions, often diffuse, e.g., leakage, evaporation etc.; s = stationary emissions, e.g., from combustion, flue gases; f = to freshwater; sw = to the sea.

Substance	**Emission ($g\cdot kWh^{-1}$)**	**ECA (m^3 water/mg)**	**ECT (kg soil/mg)**	**Max. water contaminated ($m^3\cdot kWh^{-1}$)**	**Max. soil contaminated ($kg\cdot kWh^{-1}$)**
Aromatics s	$2.23\cdot10^{-7}$	$5.00\cdot10^{-1}$	10.0	$1.12\cdot10^{-4}$	$2.23\cdot10^{-3}$
BaP benzo(a)pyrene s	$6.05\cdot10^{-8}$	40.0		$2.42\cdot10^{-3}$	
Cd cadmium p	$1.98\cdot10^{-7}$	200	13.0	$3.96\cdot10^{-4}$	$2.57\cdot10^{-3}$
Cd cadmium s	$4.32\cdot10^{-8}$	200	13.0	$8.64\cdot10^{-3}$	$5.62\cdot10^{-4}$
Cu copper m	$1.23\cdot10^{-6}$	2.00	$7.70\cdot10^{-1}$	$2.46\cdot10^{-3}$	$9.47\cdot10^{-4}$
Cu copper s	$1.36\cdot10^{-6}$	2.00	$7.70\cdot10^{-1}$	$2.72\cdot10^{-3}$	$1.05\cdot10^{-3}$
Hg mercury p	$3.29\cdot10^{-8}$	500	29.0	$1.65\cdot10^{-2}$	$9.54\cdot10^{-4}$
Hg mercury s	$1.11\cdot10^{-7}$	500	29.0	$5.58\cdot10^{-2}$	$3.23\cdot10^{-3}$
Ni nickel p	$4.32\cdot10^{-6}$	$3.30\cdot10^{-1}$	1.70	$1.43\cdot10^{-3}$	$7.34\cdot10^{-3}$
Ni nickel s	$1.05\cdot10^{-6}$	$3.30\cdot10^{-1}$	1.70	$3.48\cdot10^{-4}$	$1.79\cdot10^{-3}$
PAH polycyclic aromatic HC s	$2.96\cdot10^{-7}$	60.0	1.00	$1.77\cdot10^{-2}$	$2.96\cdot10^{-4}$
Pb lead m	$1.98\cdot10^{-6}$	2.00	$4.30\cdot10^{-1}$	$3.96\cdot10^{-3}$	$8.53\cdot10^{-4}$
Pb lead s	$1.72\cdot10^{-6}$	2.00	$4.30\cdot10^{-1}$	$3.45\cdot10^{-3}$	$7.42\cdot10^{-4}$
Toluol p	$3.08\cdot10^{-6}$		$6.30\cdot10^{-1}$		$1.94\cdot10^{-3}$
Zn zinc m	$1.80\cdot10^{-6}$	$3.80\cdot10^{-1}$	2.60	$6.84\cdot10^{-4}$	$4.68\cdot10^{-3}$
Zn zinc p	$1.09\cdot10^{-5}$	$3.80\cdot10^{-1}$	2.60	$4.14\cdot10^{-3}$	$2.84\cdot10^{-2}$
Zn zinc s	$5.47\cdot10^{-6}$	$3.80\cdot10^{-1}$	2.60	$2.08\cdot10^{-3}$	$1.42\cdot10^{-2}$
Aromatic CHs total f	$9.68\cdot10^{-7}$	$5.00\cdot10^{-1}$	10.0	$4.86\cdot10^{-4}$	$9.68\cdot10^{-3}$
Aromatic CHs total sw	$7.27\cdot10^{-6}$	$5.00\cdot10^{-1}$	10.0	$3.64\cdot10^{-3}$	$7.27\cdot10^{-2}$
Fats and oils total sw	$2.46\cdot10^{-4}$	$5.00\cdot10^{-2}$		$1.23\cdot10^{-2}$	
Ion arsenic f	$3.45\cdot10^{-6}$	$2.00\cdot10^{-1}$	3.60	$6.91\cdot10^{-4}$	$1.24\cdot10^{-2}$
Ion lead f	$2.06\cdot10^{-5}$	2.00	$4.30\cdot10^{-1}$	$4.10\cdot10^{-2}$	$8.86\cdot10^{-3}$
Ion cadmium f	$1.81\cdot10^{-7}$	200	13.0	$3.64\cdot10^{-2}$	$2.35\cdot10^{-3}$
Ion chromium-III f	$1.86\cdot10^{-5}$	1.00	$4.20\cdot10^{-1}$	$1.86\cdot10^{-2}$	$7.81\cdot10^{-3}$
Ion copper f	$8.82\cdot10^{-6}$	2.00	$7.70\cdot10^{-1}$	$1.76\cdot10^{-2}$	$6.80\cdot10^{-3}$
Ion nickel f	$9.32\cdot10^{-6}$	$3.30\cdot10^{-1}$	1.70	$3.08\cdot10^{-3}$	$1.58\cdot10^{-2}$
Ion mercury f	$3.15\cdot10^{-8}$	500	29.0	$1.57\cdot10^{-2}$	$9.11\cdot10^{-4}$
Ion zinc f	$2.34\cdot10^{-5}$	$3.80\cdot10^{-1}$	2.60	$8.89\cdot10^{-3}$	$6.08\cdot10^{-2}$
PAH polycycl. Aromatic HC f	$7.24\cdot10^{-8}$	60.0	1.00	$4.36\cdot10^{-3}$	$7.24\cdot10^{-5}$
PAH polycycl. Aromatic HC sw	$1.54\cdot10^{-7}$	60.0	1.00	$9.25\cdot10^{-3}$	$1.54\cdot10^{-4}$
Phenols f	$3.71\cdot10^{-6}$	5.90	5.30	$2.19\cdot10^{-2}$	$1.97\cdot10^{-2}$
Phenols sw	$1.38\cdot10^{-6}$	5.90	5.30	$8.10\cdot10^{-3}$	$7.27\cdot10^{-3}$
Total				$\mathbf{3.71\cdot10^{-1}}$	$\mathbf{3.03\cdot10^{-1}}$

Total maximum potential contamination arising from the production of 1 kWh of electricity is $3.71 \cdot 10^{-1}$ m^3 water and $3.03 \cdot 10^{-1}$ kg soil. As noted in Table 6.21, many substances were evaluated differently. The highest amounts of ecotoxically potent substances released into the environment during the hydropower lifecycle are cadmium, mercury, nickel and lead for water and zinc and aromatic hydrocarbons for soil.

The values vary only slightly between the investigated countries:

- minimum, water: $3.43 \cdot 10^{-1}$ m^3 (Germany)
- maximum, water: $3.85 \cdot 10^{-1}$ m^3 (Italy)
- minimum, soil: $2.88 \cdot 10^{-1}$ kg (Switzerland)
- maximum, soil: $3.11 \cdot 10^{-1}$ kg (Italy)

The Swiss study also provides data on emissions of radionuclides. These emissions derive from the generation of electricity for construction and manufacturing. This electricity is largely produced in coal fired power plants. However, these compilations have not been included in this report since they require further elaboration.

Habitat alteration

Local climate

Man-made lakes will give rise to increased local humidity around reservoirs where water evaporation increases. In tropical regions, large reservoirs may decrease the cloud cover. In temperate regions, when the temperature approach the freezing point, fog will form over the reservoir water and along the shore (Moreira & Poole, 1993).

Geophysical

If there are rapid water level fluctuations and altered water tables, erosion along the river shores downstream from a hydropower plant will increase. Fluvio-morphological processes like delta formation can be affected. Upstream of dams, the sedimentation of suspended solids generally increases, since the water flow is reduced. This can cause a reservoir to “silt up” if adequate mitigation measures have not been taken. The phenomenon is particularly strong for rivers with a high sediment flow.

Large dams may adversely influence geologic stability and induce seismic activity. This has been observed at some of the largest reservoirs around the world. It is very difficult to predict such effects (Vladut, 1993) but by careful design and selection of building material of dams, possible damages can be mastered. In areas of low tectonic activity, the risk of triggering changes in the bedrock from large reservoirs is minimal, whereas the frequency of seismic events may increase in areas with natural seismic activity (Vladut, 1993). While the influence of reservoirs on seismic activity attracts vigilant scientific interest among dam engineers, there is also much speculation about this phenomenon among NGOs (McCully, 1996). Frequently, the term “earthquake” is used to characterise increased seismic activity caused by reservoirs. This use of the world is unfortunate, since it implies a contention that reservoirs actually have the capacity to induce earthquakes, which they have not. Earthquakes are caused fundamentally by the friction of tectonic plates as they move against each other. Over geologic time scales, this movement – and earthquakes - will occur, whether there are dams or not. If reservoirs can influence the time table and magnitude of earthquakes is still a controversial issue. The most renowned catastrophe where a reservoir has been blamed to influence what happened occurred at the Koyna dam in India. In 1967 an earthquake reaching a magnitude of 6,3 on the Richter scale devastated an entire village, killing approximately 180 people. The largest European dam accident, the flooding of the Vaiont dam in Italy 1962 where 2600 people were killed, is also sometimes suggested to have been initially triggered by dam-induced seismic activities.

Aquatic

When a river is harnessed for hydroelectric purposes, the natural flow conditions are changed. At the location of a dam, waterfalls and rapids often disappear and downstream from the dam the timetable of fluctuations in water flow is altered. The natural flooding of a river over its banks also ceases. In many regions this flooding is important because it provides nutrients to the aquatic biota and create sheltered habitats on the floodplains. River regulation can also effect groundwater conditions, leading to impaired water quality. A reduced water flow, following diversion, can cause secondary damages in urban watersheds where pollutants entering the river from other sources (e.g. sewage outfall, etc) are no longer diluted as they once were. However, in a life cycle perspective, such damages should be allocated to the pollution source and not to hydropower generation.

Also, reservoirs affect water quality in a variety of ways. The residence time and turnover of substances change when a river is harnessed by hydropower facilities. The transportation of nutrients is affected and nuisance algae can proliferate in reservoirs where nutrients are retained. The oxygen level of reservoir water can then become depleted due to the decomposition of these algae.

The aeration levels in the water may also be affected when water flow is regulated. In deep reservoirs anoxic conditions might sometimes arise. Thermal stratification occurs where warm water accumulates on top of the colder bottom layer. In sub-tropical and tropical areas the stratification often becomes permanent leading to oxygen deficiency below the thermocline. Thermal stratification is especially problematic in regions with small seasonal changes in air temperature. The water intake to the turbines is often located in the deep part of the reservoir. There, combinations of settling organic particles and a low content of oxygen may lead to unhealthy conditions for aquatic life. The deterioration of the water quality below dams may affect living organisms over long distances.

An additional problem with anoxic reservoir bottom layers is that reducing conditions will prevail. This means that available sulphur compounds will be transformed to hydrogen sulphide (H_2S), which is toxic to living organisms and corrosive to steel. Phosphates, which have been trapped in the bottom sediments, may be released under anaerobic conditions and available as a nutrient for plants and therefore stimulate the growth of organisms in the reservoir. The decomposition of these organisms will deplete the oxygen levels even further. Anaerobic conditions can also lead to the release of naturally occurring toxic trace metals, like mercury as mentioned above.

In small-scale projects, the impoundment areas are generally shallow and/or the through-flow is fairly rapid. Therefore, small hydropower systems often do not have problems with deoxygenated, cold bottom waters, releases of phosphates and heavy metals, and methane formation.

The above list of environmental changes following dam construction could be much longer and most of the alterations observed cause a depletion of biodiversity. However, since such aspects are treated elsewhere, the intention here has been to just illustrate the complex nature of habitat alterations induced by river regulation. One should also bear in mind that not every negative impact observed globally occur at the same time or in one single project. Therefore, it is impossible to treat issues related to biodiversity in general terms. A large amount of research is also needed before biodiversity aspects can form part of LCAs.

6.5 Accidents

The main severe accident risk of hydropower is the risk of dam failure (Table 6.22). The two main reasons for dam failure are overtopping (responsible for about 40% of all failures) and foundation problems (around 30%). The average world-wide risk of any dam failing is approximately 1/10,000 per year. World-wide, the collapse of dams has caused more immediate casualties than any other power generation options (McCully, 1996). Long term economic losses from such disasters can also be severe (Roberts & Ball, 1996).

Statistics show that the frequency of dam failure is dependent on geographical location and the type and age of a dam. The frequency for failure is higher for fill dams as compared to concrete dams. The majority of failures occur during the first five years of operation (European Commission, 1995). In general, a dam can be built to withstand earthquakes.

Table 6.22 Severe dam break accidents that have been recorded world-wide. (A) Data from (Roberts & Ball, 1996). (B) (Hirschberg & Spiekerman, 1996), and (C) (McCully, 1996).

Period, study	**number of events**	**fatalities/ event**	**total imme-diate fatalities**	**total late fatalities**	**energy produced GWa**	**fatalities/ GWa**
1969-1986 (A)	8	11-2500	3839		2700	1.41
1969-1992 (B)		5-				0.9
1969-1995 (C)	19	14-230,000	88,444	145,000	4900	48

Figures on the total number of fatalities/GWa attributable to hydropower accidents are very controversial. Bearing in mind that many dams are used for flood control, providing access to agricultural land that otherwise would have been regularly flooded, and that reservoirs frequently satisfy multipurpose needs, the allocation of fatalities specifically to hydropower is an intricate task. Thus, the 1975 Henan catastrophe in China that was kept secret by the Chinese government until recently is now sometimes used when evaluating accidental risks related to hydropower. However, historical evidence demonstrates that the causes of this catastrophe were political rather than technical. The knowledge and technical skill in China at the time would have been sufficient for preventing the catastrophe if it had not been for the political short-sightedness. As a consequence of the Banqiao reservoir overtopping, approximately thirty more dams collapsed. It is estimated that the immediate flood killed 85’000 people, and 145’000 people died due to epidemics and famine, which struck the area following the flood (Si 1998). This catastrophe was not considered in the first two studies listed in the table above because this information was not available at the time. The Henan catastrophe is considered in the last calculation (McCully, 1996). This catastrophe also highlights the role a single incident can play in risk statistics calculations, and thus the problematic nature of basing estimates of accident risks on statistics.

It should be borne in mind though that the number of casualties from the natural flooding of free-flowing rivers is considerably higher than are those killed by the collapse of dams. For example, the recent heavy rain and resulting extreme flooding of the Tachira River in Venezuela in December 1999 killed more than 20,000 people according to recent news from Agence France-Presse (AFP). As already mentioned, many dams have actually been constructed to gain access to agricultural land, the reclamation of which lead to settlement where the natural flood frequency previously effectively hindered such establishment. This fact was drastically experienced during the Mississippi River flood in 1973 and to a lesser extent in 1993 (Belt, 1975) and (Philippi, 1996).

While the Henan catastrophe took place in the Yellow River, there had been several severe natural floods in other Chinese rivers, among them the Yangtze, where several 100,000 people died during the previous century (Table 6.23).

Table 6.23 Natural flood disasters in the Yangtze River in the 20th century (Jones and Freeman, 2000).

Year	No. of lives lost	Property damage
1911	"Hundreds of thousands"	
1931	145,000	Inundated an area the size of New York State. Submerged more than 3 million hectares of farm land and destroyed 108 million houses.
1935	142,000	
1954	30,000	Inundated 48 million hectares of farm land and affected 18 million people. An additional 18.88 million people suffered from flood damage. Operation of Beijing-Guangzou railway was suspended for more than 100 days
1996	no info	
1998	3,656	Affected the lives of 290 million people. 5 million houses destroyed. 21.8 million hectares of farmland submerged. Total economic cost was $ 30 billion.

6.6 Impact on biodiversity

The term "biological diversity" or "biodiversity" is an umbrella term used to describe the number of species, their genetic variation and the variety of combinations of species and their habitats in different parts of the world. In other words, biodiversity refers to all the facets of the living Planet Earth. Impacts on biodiversity usually take the form of an altered set-up of species and a reduction in species richness. The reason for these almost universal expressions of disturbance on the natural environment is that the biological variation has taken millions of years to evolve, while man-made interference with these processes is a quite recent phenomenon. It will therefore probably take the natural processes a very long time to fill the man-made habitats with new and better-adapted species than those that have vanished. Changes in biodiversity are mainly mediated by habitat alterations. Several mechanisms related to hydropower development account for such changes.

Global

As a global average, no significant impacts on biodiversity from hydropower are to be expected, since hydropower has no relevant global environmental impacts. The slight emission of greenhouse gases is by far exceeded by other power options and can on average be considered negligible. For individual hydropower projects, however, especially those located in tropical regions, global impact should nevertheless be considered especially with respect to carbon balance.

Local and regional

Flora and fauna in rivers utilised for hydropower are affected due to the alteration of several factors such as:

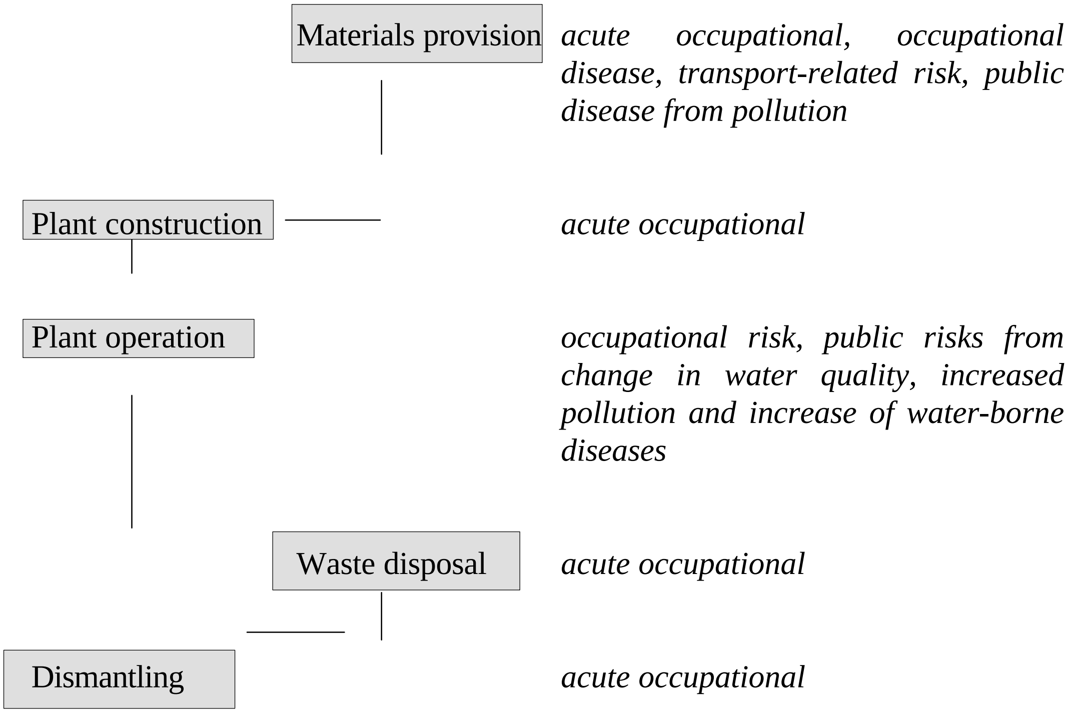
- extension and frequency of flooding
- drought conditions below diversion points
- stresses from rapid changes in water level
- water quality changes
- change in groundwater conditions

The composition of species can be altered due to hydropower. Organisms may disappear or be replaced by others, due to the changed conditions. The water level in reservoirs can vary several meters as opposed to perhaps only one meter at most during natural conditions. These fluctuations will lead to an almost barren shore where the plant cover between the upper and lower water levels has been almost totally lost. Along the shores of the downstream river the short-term regulations will cause similar effects. Organisms living in the riparian zone are an important source of food for fish in the river but also make important contributions as food to terrestrial animals. Due to the water regulation this food source will decrease and the organisms living in the open water mass, i.e. plankton, will be more important for food. However, the more stable conditions resulting from hydropower utilisation can in some cases also cause an increase in the growth of certain species. Hydropower facilities disrupt the natural waterways. This will have effects on migrating animals, such as anadromous or catadromous fish. Such obstructions can to some extent be circumvented by the construction of fish way passes, such as different kind of ladders. All too often, however, such measures appear to be inefficient, inappropriate, or prohibitively expensive.

6.7 Impact on humans

Health risks

Each stage of the hydropower life cycle has associated health concerns, as is shown in the following scheme (major accidents excluded):



Tables 6.23 and 6.24 show the results of two German studies on public and occupational risks of hydropower. The first study deals with reservoir hydropower (Thöhne & Kallenbach, 1988), while the second one considers risk of all forms of hydropower (Fritzsche, 1989).

Table 6.23 Occupational and public health risks from all stages of the hydropower life cycle (Thöhne & Kallenbach, 1988).

Acute occupational fatalities per GWa	0.15 - 0.26
Occupational disease and injuries in missed days of work per GWa	630 - 1110
Public fatalities per GWa	0.01
Public diseases and injuries in cases per GWa	0.61

Table 6.24 Occupational and public mortality risks from all stages of the hydropower life cycle (Fritzsche, 1989)

Acute occupational risk per GWa	*0.2 – 2.7*
Late occupational risk (disease) per GWa	-
Acute public risk per GWa	-
Late public risk (disease) per GWa	-

A British study calculated health risks from tidal hydropower plants. It is reasonable to assume that these risks should be comparable to those of other hydropower plants, as they share about the same characteristics (e.g., both being renewable, lacking emissions from operation, main risks prevailing under construction, similar kinds of constructions, etc.). The study estimates the acute occupational risks at 0.1 – 0.2 fatalities per GWa due to plant construction. All other risks are well below 0.1 fatalities per GWa (Roberts & Ball, 1996).

Hydropower can give rise to some indirect health impacts, which are not included in the above studies. Unfortunately, comprehensive data is not available but the following observations can be made:

- The reduced flow and stagnation of water by constructing dams can lead to changes in the prevalence of populations of disease vectors. In warm countries there can be an increase in mosquitoes that can spread malaria. Yet, other harmful organisms loose their breeding habitats in some areas, since water level fluctuations make it hard for them to breed in the reservoir area (e.g., those causing onchocerciasis). Less flooding of downstream areas can also make it easier to control such organisms in riparian wetlands (Ziyun, 1994).
- Groundwater conditions may be affected by hydropower, which can have effects on the water quality in wells.
- Reducing the water flow can also limit dilution of other pollutants that may be emitted into the river by other activities.

Unfortunately, no studies that try to calculate health risks from habitat alteration, societal changes or urban development seem to exist.

Social and socio-economic impact

Updated information regarding this aspect is provided by the World Commission on Dams (2000), so only brief characteristics of the most important elements are presented here. While multi-purpose projects often bring immediate and obvious benefits to the local society, the beneficiaries from hydroelectric development to those communities that face the environmental burdens are often questioned. The reason for this is that the intrusion on other land use from the harnessing of a river is often inevitable and readily seen, whereas the economic gain is not. In general, hydroelectric projects are more economically profitable than any other option for electricity generation.

Inundated land

The construction of dams and reservoirs means that land is flooded. There can be a loss of productive agricultural or forested land, loss of pastures or the inundation can affect cultural heritages. A survey of 180 projects in the World Bank database (Goodland, 1995) reveals no significant relationship between size (in terms of capacity) and the size of the inundated land for the entire set of dams. However, when projects from geographically limited areas are singled out, such couplings can be discerned.

Resettlement

The inundation of land can enforce the resettlement of affected people. This aspect definitely constitutes one of the gravest socio-economic drawbacks of river regulation. Again, the seriousness varies enormously between projects and it is impossible to find typical situations and meaningless to calculate average conditions.

Fishing restraints

Hydropower development may also influence fish populations or traditional means of practising fishery. Sometimes, people may loose an important source of food or income. On the other hand, large man-made lakes often sustain high and reliable stocks of commercially interesting fish encouraging the development of artisan fishery (Costa-Pierce 1997). River regulation can thus have a differential outcome on fish as well as fishers' communities.

Culture

A major construction project such as a hydropower project will inevitably bring economic and social changes to the project area. It may stimulate economic growth, the building of roads, schools, hospitals, cultural, and recreational facilities, and it may also have negative impacts on the lifestyles of some people. If the local inhabitants are indigenous people, the social and cultural aspects of the project have to be managed with particular sensitivity in order to avoid negative effects on their lifestyle and culture.

A second cultural issue is the inundation of sites of archaeological interest. Difficult decisions have to be made if archaeological sites are in the project area. In some cases such sites have been inundated, in other cases construction has been delayed while they are explored, sometimes they have been moved, and sometimes the project has been permanently stopped.

Aesthetic impact

Visual

Large reservoir hydropower schemes may have a significant effect on the visual amenity of a region. Areas of natural beauty, such as waterfalls, may disappear. Drawdown zones of reservoirs in especially temperate regions are barren. However, after some time many artificial lakes, or reservoirs, are often indistinguishable from natural lakes, and they may be enjoyed for recreational and aesthetic reasons just as natural lakes are. In arid areas, they may make the desert bloom. Downstream from a dam, a river, which had previously been a dry gravel corridor for several months of the year, may be turned into one, which has a continuous flow of water. The opposite may also occur, depending on the operation of the reservoir. Many dams have become tourist attractions which draw thousands of visitors per year (Razvan, 1992).

Acoustic

Hydropower plants do not produce much noise during operation although construction will of course give rise to some. Rather, the “silenced rivers” have become an allegorical clash in the Big Dam debate.

7. WIND

7.1 Frame conditions

The use of wind as a power source is not a new concept. For example, windmills were used early on in the Netherlands's history for pumping water. Wind power has a high potential for electricity generation and it is a widely available energy resource. The geographic distribution of areas with average wind speeds exceeding 8 m/s (roughly corresponding to a capacity of 600 W/m^2 at 50 m above ground) is mainly along the coasts and on mountain ridges and largely coincides with areas with high runoff. There are, however, several factors that limit wind power generation. For example, wind power requires the use of large amounts of land and land use conflicts can arise. A disadvantage with wind power is that a reserve power option is needed to regulate the wind energy's low-productive periods. Yet, wind power remains an intriguing power generation option in certain setting because it is essentially a clean energy source.

Green house gas emissions generated from wind power are mainly derived from the manufacturing and construction of the power plants. The magnitudes of the environmental impacts per kWh are hence dependent on the energy production of the wind power plant. The power output of wind power plants is a function of the wind speed cubed and therefore it is important to install them at particularly windy locations (Beals & Hutchinson, 1993).

When deciding where to place a wind power generating station the prevailing wind direction and the roughness of the terrain must be considered. High above ground level the wind is hardly influenced by the surface of the Earth, but near the surface frictional forces are encountered from the terrain. Existing obstacles, such as forests and cities that may divert or change wind patters near the machines must also be identified. The total amount of wind available for operating the windmills is a combination of global and local winds. Therefore, sea breeze, land breeze and valley winds must all be considered.

Offshore wind power plants have several advantages over wind power plants on land. First of all, the roughness of water is far less than the roughness of land. With the roughness factor reduced, offshore plants generally can produce more electricity than wind power plant on land. In addition, the wind on sea is less turbulent than on land and the wind power machines are therefore exposed to less wear and tear. Hence, offshore plants have longer lifetime than onshore plants.

Technology

Wind turbines harness the kinetic energy in wind to turn a rotor that drives a generator. Modern wind turbines are primarily horizontal-axis machines with three blades. Two-bladed machines are also in use. The use of a machine with two blades saves the cost of manufacturing the third blade, but the rotational speed must be higher for the same energy output, which increases the noise. Most of the machines are of the upwind type; i.e. the rotor is facing the wind. The main disadvantage of this system is that a yaw mechanism is needed.

A downwind machine has the rotor on the lee side of the tower and the yaw mechanism is not necessary. The rotor can therefore be made lighter and, as a consequence, more flexible. Despite this advantage, downwind machines are not commonly used. One reason is that the tower disrupts the wind flow and the potential power production is therefore reduced to some extent. The downwind machine also generates more disturbing noise.

Wind turbines are made of commonly used materials, such as steel and concrete, and contain standard electrical and mechanical components. The rotor blades are often made of glass fibre reinforced plastics. Metallic materials are unsuitable because of the repeated bending in the rotor blades, which leads to metal fatigue. The main producers of grid-connected wind turbines are the USA, Denmark, Germany, the Netherlands, Belgium, Italy, United Kingdom and Japan (World Energy Council, 1994).

The net efficiency of modern windmills ranges from 27 to 36 percent and they are available to generate electricity 95 percent of the time. Windmills do not operate at very low or very high wind speeds (World Energy Council, 1994).

Geography

During the last few decades, the interest for using wind for electricity generation has increased considerably. New developments in wind turbine technology have occurred and the cost of setting up a wind power station has decreased. The utilisation of wind power has, as a result, increased lately. The countries with the most installed wind power units are North America, Germany, Denmark and India. Much of the recent growth has been in Europe, which now has the world's greatest energy capacity. Yet, in fast developing countries of the East, like India and China, wind energy has increased in importance as an energy source, as well (Mays, 1996).

Table 7.1 Worldwide wind energy capacity in 1997. 7700 MW in total installed capacity is equivalent with 19 TWh per year (Danish Wind Turbine Manufacturers Association, 1999).

Country	Installed effect (MW)
Germany	2874
USA	2141
Denmark	1420
India	992
Spain	880
Netherlands	379
UK	338
China	200
Sweden	176
Italy	64
Other	689
Total	**10153**

Economics

One advantage of wind power is that the fuel is free. The dominating costs are capital costs, i.e. costs for installing the power plants. Wind power plants require installations of foundation (normally concrete), roads, transformers, cables and telephone connections for the remote controls. The costs vary with soil conditions, distances to ordinary road and distances to ordinary power lines. In fact, 75 to 90 percent of the total cost of a wind power plant is the capital cost (British Wind Energy Association, 2000). The rest of the cost is due to operation and maintenance of the wind power plant.

Wind power generation is on its way to becoming economically comparable to traditional power generation options, but wind power has not yet succeeded commercially. In general wind power generation still depends on energy subsidies. Wind turbines in California, USA, produce electricity at a cost of six to nine cents per kWh (Sterrett, 1995). Higher wind speeds lower the costs. A Danish study has shown that if the wind speed increases from five to ten m/s at hub height (the centre of the rotating turbine, i.e. the axis on which the wings are attached) the cost comes down from eight to two cents per kWh (Krohn, 1998).

Lifecycle analysis

Several lifecycle analyses have been completed for wind power generation operations over the last few years. In this report, data from several countries are considered.

A lifecycle analysis from Canada showed that the environmental emissions from wind power were almost negligible. Land use and emissions of carbon dioxide, sulphur oxides, nitrogen oxide and particles were considered (Beals & Hutchinson, 1993).

A Japanese report studied the emissions and the material requirements for the lifecycle of a three-blade propeller type wind power plant during a lifetime of 30 years. The size of the plant was 0.3 MW (Uchiyama, 1995).

In Sweden, a hypothetical windmill with an output of 500 kW was studied. The lifetime was assumed to be 25 years. The lifecycle inventory included building, operating, maintaining and dismantling the power plant and handling, recycling and transporting waste products (Dethlefsen & Tunbrant, 1996). It is difficult to estimate the amount of energy that a windmill will generate per year (i.e. how windy it will be over the course of one year). Therefore, for the Swedish lifecycle analysis two scenarios are considered. In one extreme, it is assumed that the windmill will operate for 1,500 hours and in the other extreme it is assumed that the windmill will operate for 2,500 hours. In this report, only values related to the longer operational time will be used.

Another lifecycle analysis for wind power was completed in Germany. Three types of windmills with outputs of 100, 500, and 1,000 MW were considered. The system efficiencies were within the range of 19 and 33 percent. The total number of operating hours, 1,400-3,170 per year, is based on wind converter simulations on wind velocities at several locations in Germany (Wiese & Kaltschmitt, 1996). Energy consumption, intrusions on alternative land use, and emissions due to the disposal at the completion of the wind power system lifetime are not calculated in the German study.

7.2 Use of resources

Non-renewables

The use of non-renewable resources in the wind power generating cycle is generally low. The specific consumption of steel is, however, high compared to other renewables. This is mainly due to the manufacturing of the tower that is needed to elevate the turbine above the ground. It is likely that the tower or its steel content will have a longer lifetime than the rest of the plant. Since the use of non-renewables is connected to the construction phase the specific consumption of such resources are strongly linked to the total operating time of the windmills. In the Swedish study a lifetime of 25 years and 2,500 operating hours per year are assumed. The use of non-renewables is shown in Table 7.2. Raw materials consumed during the manufacturing of glass and plastics are not included in the totals. The use of energy is based on the electricity mix of the countries where the different parts of the windmills are manufactured.

Table 7.2 The total use of non-renewable resources in the lifecycle of a Swedish wind power plant (Dethlefsen & Tunbrant, 1996).

Resource	Unit	Use
Energy		
Uranium	$g \cdot kWh^{-1}$	$3.45 \cdot 10^{-6}$
Coal	$g \cdot kWh^{-1}$	$5.36 \cdot 10^{-1}$
Oil	$m^3 \cdot kWh^{-1}$	$1.06 \cdot 10^{-7}$
Gas	$m^3 \cdot kWh^{-1}$	$2.33 \cdot 10^{-5}$
Diesel	$m^3 \cdot kWh^{-1}$	$7.26 \cdot 10^{-8}$
Material		
Limestone	$g \cdot kWh^{-1}$	$1.06 \cdot 10^{-1}$
Gravel	$g \cdot kWh^{-1}$	$8.81 \cdot 10^{-1}$
Iron ore	$g \cdot kWh^{-1}$	1.05
Copper ore	$g \cdot kWh^{-1}$	$1.45 \cdot 10^{-2}$
Vinyl chloride monomer	$g \cdot kWh^{-1}$	$1.67 \cdot 10^{-3}$
Fibre-glass	$g \cdot kWh^{-1}$	$1.13 \cdot 10^{-1}$
Lubricating oil	$g \cdot kWh^{-1}$	$2.31 \cdot 10^{-3}$

The non-renewable resource use calculated in the German lifecycle analysis for units operating under different wind velocity conditions are shown in Table 7.3. The wind velocity is apparently important for lifecycle analysis calculations. The time the windmills are in operation is also important. The results from Japan showed indicate high levels of consumption compared to the estimates given in the German study for non-renewable resources (Table 7.4).

Table 7.3 The use of resources in German wind power plants lifecycle at different annual mean wind velocities (Wiese & Kaltschmitt, 1996).

Resource	Unit	4.5 m/s	5.5 m/s	6.5 m/s
Steel	$g \cdot kWh^{-1}$	2.74-3.71	1.88-2.36	1.45-1.89
Copper	$mg \cdot kWh^{-1}$	90-140	60-90	50-70
Cement	$g \cdot kWh^{-1}$	1.61-3.46	1.10-2.20	0.85-1.76
Plastics	$mg \cdot kWh^{-1}$	340-610	230-390	180-310

Table 7.4 The use of resources in Japanese wind power model plants (Uchiyama, 1995).

Material	**Unit**	**Manufacturing and construction**	**Operation and maintenance**	**Total**
Steel	$g \cdot kWh^{-1}$	4.84	1.77	6.61
Stainless steel	$g \cdot kWh^{-1}$	$5.64 \cdot 10^{-3}$	$3.52 \cdot 10^{-3}$	$9.16 \cdot 10^{-3}$
Aluminium	$g \cdot kWh^{-1}$	$1.55 \cdot 10^{-2}$	$9.16 \cdot 10^{-3}$	$2.47 \cdot 10^{-2}$
Copper	$g \cdot kWh^{-1}$	$5.43 \cdot 10^{-2}$	$3.24 \cdot 10^{-2}$	$8.67 \cdot 10^{-2}$
Cement	$g \cdot kWh^{-1}$	3.92		3.92
Alloy	$g \cdot kWh^{-1}$	$3.85 \cdot 10^{-1}$	$2.30 \cdot 10^{-1}$	$6.15 \cdot 10^{-1}$
Silicon	$g \cdot kWh^{-1}$	$4.09 \cdot 10^{-2}$	$2.47 \cdot 10^{-2}$	$6.55 \cdot 10^{-2}$
Forged	$g \cdot kWh^{-1}$	$5.14 \cdot 10^{-2}$	$3.10 \cdot 10^{-2}$	$8.25 \cdot 10^{-2}$
Cast iron	$g \cdot kWh^{-1}$	$7.61 \cdot 10^{-2}$	$4.58 \cdot 10^{-2}$	$1.22 \cdot 10^{-1}$
Carbon	$g \cdot kWh^{-1}$	$3.24 \cdot 10^{-2}$	$1.90 \cdot 10^{-2}$	$5.14 \cdot 10^{-2}$
Vinyl chloride	$g \cdot kWh^{-1}$	$6.34 \cdot 10^{-3}$	$3.52 \cdot 10^{-3}$	$9.87 \cdot 10^{-3}$
Polyethylene	$g \cdot kWh^{-1}$	$9.87 \cdot 10^{-3}$	$5.64 \cdot 10^{-3}$	$1.55 \cdot 10^{-2}$
Epoxy resin	$g \cdot kWh^{-1}$	$7.96 \cdot 10^{-2}$	$4.79 \cdot 10^{-2}$	$1.28 \cdot 10^{-1}$
Insulation	$g \cdot kWh^{-1}$	$4.86 \cdot 10^{-2}$	$2.89 \cdot 10^{-2}$	$7.75 \cdot 10^{-2}$
Insulation oil	$g \cdot kWh^{-1}$	$3.31 \cdot 10^{-2}$	$1.97 \cdot 10^{-2}$	$5.29 \cdot 10^{-2}$
Lubricant oil	$g \cdot kWh^{-1}$	$8.46 \cdot 10^{-3}$	$4.93 \cdot 10^{-3}$	$1.34 \cdot 10^{-2}$
Glass fibre	$g \cdot kWh^{-1}$	$1.59 \cdot 10^{-1}$	$9.51 \cdot 10^{-2}$	$2.54 \cdot 10^{-1}$

Renewables

The use of renewable materials is very low for wind power generation. The use of renewable energy calculated in the Swedish study is shown in Table 7.5.

Table 7.5 The total use of non-renewable resources in the lifecycle of a Swedish windmill (Dethlefsen & Tunbrant, 1996).

Resource	**Unit**	**Use**
Energy		
Hydropower	$kWh \cdot kWh^{-1}$	$1.78 \cdot 10^{-4}$
Wind power	$kWh \cdot kWh^{-1}$	$5.27 \cdot 10^{-6}$
Wooden chips	$g \cdot kWh^{-1}$	$8.24 \cdot 10^{-3}$

Land

The land actually occupied by a single wind turbine is relatively small, about 40 m^2 (Bates *et al.*, 1996; European Commission, 1995). A wind farm, however, needs a much larger area because the plants are separated by 5-10 turbine diameters in order to reduce interference (wind shading) effects between units (Bates *et al.* 1996). The Swedish study estimates the land use at $9.05 \cdot 10^{-3}$ m^2 per kWh of electricity, if a protection zone of 300 metres around the windmill is assumed (Dethlefsen &

Tunbrant, 1996). The use of land for production processes, etc. is not included. The result from Canada indicates that $0.75 \cdot 10^{-3}$ - $8.2 \cdot 10^{-3}$ m^2 of land per produced kWh are used (Beals & Hutchinson, 1993).

7.3 Global environmental impact

Greenhouse effect

The emission of greenhouse gases from wind power generation is very low and is due to manufacturing of cement, steel and other building materials. Windmills in Canada are estimated to emit 7.4 grams of carbon dioxide per kWh of produced electricity (Beals & Hutchinson, 1993). The emission of carbon dioxide from wind power in Sweden is estimated to be 1.90 grams per kWh (Dethlefsen & Tunbrant, 1996). Data are limited, however, and the total amount of emissions could be higher. The reported value for greenhouse gas emissions in the Japanese study is considerably higher than in the Canadian and Swedish ones (Table 7.6). The German analysis calculated the carbon dioxide emissions to be 19-34 grams per kWh, 13-22 $g \cdot kWh^{-1}$ and 10-17 $g \cdot kWh^{-1}$ for average wind velocities of 4.5 $m \cdot s^{-1}$, 5.5 $m \cdot s^{-1}$ and 6.5 $m \cdot s^{-1}$, respectively (Wiese & Kaltschmitt, 1996).

Table 7.6 Emissions of greenhouse gases in carbon dioxide equivalents from a wind power plant in Japan (Uchiyama, 1995).

Emission	Unit	Manufacturing and construction	Operation and maintenance	Total
CO_2	$g\ (CO_2) \cdot kWh^{-1}$	24.7	8.84	33.5
CH_4	$g\ (CO_2) \cdot kWh^{-1}$	0.95	0.40	1.35
Total	$\mathbf{g\ (CO_2) \cdot kWh^{-1}}$	**25.6**	**9.24**	**34.9**

Ozone layer depletion

There is no information available that allows estimates of emissions that have the capacity to influence the stratospheric ozone layer.

7.4 Local and regional environmental impact

Some environmental burdens from the emission of pollutants do occur during the production of the turbines since, for example, this process has significant energy requirements. During the operation of wind turbines no emissions are released except during the production and transportation of materials needed for maintenance of the power plant.

Acidification

In the Swedish study, emissions of nitrogen oxides and sulphur dioxide are estimated (Table 7.7). The emissions of NO_x and SO_2 are considered to be negligible according to the lifecycle analysis from Canada. Conditions in Germany gave rise to emissions of $1.0 \cdot 10^{-2}$ to $3.2 \cdot 10^{-2}$ grams of sulphur dioxide and $1.4 \cdot 10^{-2}$ to $4.3 \cdot 10^{-2}$ grams of nitrogen oxides per kWh, depending on wind velocities and the number of operating hours (Wiese & Kaltschmitt, 1996).

Table 7.7 Emissions of acidification compounds in Sweden (Dethlefsen & Tunbrant, 1996).

Emission	Unit	Manufacturing and construction	Operation and maintenance	Total
NO_x	$g \cdot kWh^{-1}$	$5.29 \cdot 10^{-3}$	$8.32 \cdot 10^{-5}$	$5.30 \cdot 10^{-3}$
SO_2	$g \cdot kWh^{-1}$	$4.98 \cdot 10^{-3}$	$9.14 \cdot 10^{-5}$	$5.08 \cdot 10^{-3}$

Eutrophication

Emissions of nutrients (that cause eutrophication) are low in the wind power lifecycle. The Swedish study includes estimates for three compounds, but only two of them, NO_x and total nitrogen, are significant. The third impact indicator is COD (Chemical Oxygen Demand). COD only leads to eutrophication through a secondary process that decreases the oxygen level in water. Nitrogen oxides increase eutrophication both in terrestrial and aquatic systems.

Table 7.8 Emissions of eutrophication compounds in Sweden (Dethlefsen & Tunbrant, 1996).

Emission	Unit	Total
COD	$g \cdot kWh^{-1}$	$1.19 \cdot 10^{-4}$
NO_x	$g \cdot kWh^{-1}$	$5.30 \cdot 10^{-3}$
Total nitrogen	$g \cdot kWh^{-1}$	$1.12 \cdot 10^{-5}$

Photochemical oxidant formation

Data related to the effect of wind power generation on photochemical oxidant formation is not as yet available.

Ecotoxic impact

Wind power generates very limited ecotoxic effects. Specific data for this kind of impact was not available.

Habitat alteration

Windmills are either put on land that is already lacking forest vegetation or are located at sea. The only obvious loss of land is related to the area occupied by foundations, access roads, and perhaps cable ditches and transmission right-of-ways. The intrusion on alternative land use, including habitats for plants and animals, is consequently low.

7.5 Accidents

Rotor failure can occur during the operation of wind turbines in that blade fragments or all of a rotor can become detached. The risk of being hit by such objects is negligible at a distance greater than 700 m (Stjernquist, 1986; Bates *et al.*, 1996). In addition, the probability of a blade fragment reaching very far from the unit in the case of such a rotor accident is very unlikely. Under normal operating conditions a thrown blade fragment would not even reach 350 m (Bates *et al.*, 1996). To reduce the risk for such accidents, wind turbines should not be located close to populated areas.

In cold climates, there is a risk of ice forming on the turbine blades and ice fragments can be thrown off during operation of the machine. The distances that ice from the blades can be thrown is about 200 m (Bossanyi & Morgan, 1996). A risk assessment has shown that the risk of being hit by detached ice from a turbine in a climate with moderate icing is very small at distances greater than 250 m and can be compared to the risk of being struck by lightning. The risk is relatively independent of turbine size and configuration (Bossanyi & Morgan, 1996).

7.6 Impact on biodiversity

Effects on birds

Wind power may affect birds in mainly two ways; the birds may collide with the turbine and its rotating blades, or the behavioural patterns of birds may be disrupted by the presence of the windmills in migratory areas. The risk of collisions is the most obvious problem and studies to date have focused on this issue (Clausager & Nöhr, 1996). In good visibility conditions, studies show that there is little reason to expect collisions for resident bird species. In poorer visibility conditions (in bad weather and at night), the bird density around typical wind farm locations is expected to be low and therefore the probability of collisions will also be low. For migratory species, the problem could be greater due to unfamiliarity with the turbines. Yet, it is supposed that most birds fly well over the heights of even the largest turbines (European Commission, 1995; Bates *et al.*, 1996).

At most sites, existing studies and accounts do not show any evidence of significant impacts to birds, especially at smaller wind farms. In a study of a 7.5 MWe wind farm in the Netherlands a row of 25 turbines with an output of 300 kWe was studied. It was concluded that the number of birds killed per kilometre at the wind farm was up to ten times less than the number of birds killed per kilometre high of voltage transmission line, and comparable with that of one kilometre of motorway (Clausager & Nöhr, 1996).

There are, however, examples of wind farms that have had unexpectedly large impacts on birds. These are the Tarifa wind farms in southern Spain and the Altamonte and Solano wind farms in California. The Tarifa farms have been especially inappropriately located on the hills above the Strait of Gibraltar, which is one of Western Europe's main bird migration route to Africa (Cereols *et al.*, 1996). The bird density in the region is therefore very high during certain times of the year. The Altamonte Pass put up the largest wind turbine farm in the world with over 7000 wind turbines on hills and an open grassland (Orloff & Flannery, 1992). Both the Altamonte Pass and the Solano County are important foraging habitats for at least 13 species of resident and migrating hawks, eagles and vultures. According to their relative abundance, golden eagles, red-tailed hawks and American kestrels were killed more frequently than would be expected. Turkey vultures and common ravens were on the other hand killed less often than their relative abundance would suggest. It is supposed that the birds' different hunting behaviours account for these differences. Golden eagles, red-tailed hawks and kestrels hunt mostly by swooping on their prey, which may make them less aware of the turbine blades or cause them to misjudge distances (Orloff & Flannery, 1992).

The above mentioned accounts clearly show that it is necessary to complete environmental assessments before building a wind farm, especially in ecologically sensitive areas and in areas designated for their ornithological value.

To date most environmental studies for wind farms have been carried out in coastal areas. The impacts on birds from offshore wind turbines have to be analysed further before intensive development in offshore marine waters (Clausager & Nöhr, 1996). Other winged species, such as bats and insects may also be affected by wind turbines, but currently only data on birds are available (European Commission, 1995; Bates *et al.*, 1996).

Flora and fauna

Wind power is one of the energy systems that produces the least amount of damage to ecosystems (Llamas, 1995). The land occupied by the plant is relatively small, so the largest potential effect on ecosystems is from construction activity (European Commission, 1995).

There has been discussion about the possible disruption of local microclimates by wind turbines. Yet, there is little evidence of any modification of wind speed near the ground, which probably indicates that the evapotranspiration from the soil below will not be altered. It has also been reported that there is no change in air temperature or carbon dioxide concentration (!) near wind power units (Sörensen, 1996).

7.7 Impact on humans

Health risks

Noise

The dominant source of noise from wind power plants is the operation of the turbines. The turbines emit two major types of noise; aerodynamic noise, from the blades as they pass through the air, and mechanical noise, from the gearbox, generator and auxiliary motors. The total noise is due to the sum of aerodynamic and mechanical noise. Most complaints about wind turbines seem to relate to mechanically generated noise, in particular where the noise has a strong tonal component. In these cases, the noise problems often result from defects in components or imperfect construction, and can to some extent be abated by retrofit measures (Bates *et al.,* 1996). For turbines with a rotor diameter up to 20 m, analyses show that the mechanical noise dominates, whereas the aerodynamic noise dominates for machines with larger rotor diameters.

The noise levels are dependent on wind speed. The noise increases with wind speed, but at increasing wind speeds, the background noise will also increase and is then expected to mask the turbine noise. At 10 m/s and an aggregate of 2 MW, the noise level will be about 65 dB(A). At a distance of 300 m the background noise will dominate at 8 m/s. Therefore, it maybe that the greatest noise impacts occur in light winds. Yet on hilly sites and for variable speed machines, which are characterised by a steeper increase in noise emission with wind speed, this is not the case. For turbines situated on top of hills, the dwellings on the lee side will have reduced background noise levels and will therefore experience greater noise impact (Bates *et al.,* 1996). For modern wind turbines, the noise levels are seldom greater than 50 dB(A) at distances greater than 400 meters (Marbek Resource Consultants Ltd. & Saskatchewan Energy Conservation Development Authority, 1996).

Further, the significance of noise impacts from wind turbines depends on individual tolerance of noise. Some people are more sensitive to noise than others.

The impacts of noise from turbines can be reduced provided that:

- The turbines are located in a sufficient distance from houses
- The turbines are located on appropriate sites
- Best technology available is used

Light flicker

The wind turbines can produce a ”shadow flicker” as sunlight passes through the rotating blades. This effect can induce attacks in epilepsy sufferers. Such impacts have only a short duration each day and are very localised. They should be minimal at distances greater than 300 m (Bates *et al.,* 1996). The shadows from a wind turbine can, however, be annoying if they, for example, reach residential houses or working sites.

Social and socio-economic impact

Electromagnetic signals are scattered by the rotating blades of the wind turbines and can cause interference in communication systems. Electromagnetic signals can also be reflected from the turbine blades. Only where the interfering signal is comparable in amplitude with unscattered radio signals and where the receiving antennae is not strongly directional, strong interference is possible. The area affected covers a region (behind the turbine from the transmitter) typically 1-2 km long and a few hundreds of metres wide (Bates *et al.,* 1996). In many countries a range of advisory criteria have been developed by responsible agencies in aviation and telecommunications and if the recommended procedures are followed, interference problems can mostly be avoided at the planning stage. For domestic receivers of television signals, the effects are very localised and the effects are therefore limited. A range of technical measures including signal amplifiers, active deflectors, relay transmitters and cable television can rectify the problems.

Aesthetic impact

Among the environmental impacts wind energy gives rise to, visual intrusion is probably the most controversial. The effects are site specific and depends mainly on:

- Landscape type
- Valuation of the landscape
- The physical size and colour of the turbines
- Numbers and design of the turbines, and of the wind-farm
- The distance from the turbines to the receptor
- Weather conditions and local topography
- The population density within the zone of visual influence
- Number of visitors to the area
- The attitude of the observer

The visual effects of a wind farm are generally restricted to within 6 km. Between 6-12 km the towers are indistinct and the rotor movements will only be visible in good weather conditions. Above 12 km the effects are negligible. Beyond 20 km the turbines are not be visible to the human eye (European Commission, 1995). Local landforms, vegetation and buildings will also affect the real visibility of the plants.

8. LIFE CYCLE ANALYSIS OF DIFFERENT ELECTRIC POWER GENERATION SOURCES IN JAPAN

8.1 Land use of energy sources

The amount and type of land used for energy production effects both economics and ecosystems. Before the electricity reaches the consumers, much land is utilised directly and indirectly for power generation. This includes the land area required to house the power plant, the land used for fuel supply, etc. In addition, considering the social effects that can be caused by accidents, the area of impact may, in fact, extend way beyond the immediate boundaries of the power generation facility.

Land use varies depending of the kind of electricity generation. Processing plants, coal mines, fuel refineries, transportation, and power transmission all require land. In the case of the power generation technologies that do not require fuel, e.g. photovoltaic power, the land area utilised is only for the power generation facilities. For hydropower, however, determining the total land use is challenging. Water reservoir areas must be considered in addition to the power plant site. Further, if the dam utilises water supplied from a catchment area, the total land use could be considered enormous. Yet, the land is not only being used for electricity generation. The water resources in the reservoirs, rivers and catchments are most likely also utilised for agriculture, industrial and domestic water resources, forestry, wildlife, and other uses. Thus, setting boundary conditions is an important step for defining land use in an LCA.

An accident related to electricity generation may impact large areas in a variety of ways. If as dam breaks the flooded region may be quite large and with nuclear power generation there is a risk , albeit small, of releasing radioactive substances in case of an extreme accident. In addition, if the high level radioactive waste from nuclear power generation is not treated and stored adequately, the area of impact may increase drastically. Fossil fuel power plants emit dust, SO_X, NO_X and CO_2 to the air during combustion. Although the dust usually affects only local areas, acid rain, caused by SO_X and NO_X , greenhouse gas emissions can effect nearby regions, neighbouring countries and, possibly, the whole world.

Since large accidents do not happen often, a probability calculation (risk analysis) is necessary to estimate what land areas might be effected by such events. This type of calculation is particularly necessary for comparing the effects of different energy supply systems. After assuming boundary conditions such as the scale, occurrence probability and period of the accidents and after estimating the impacted area, the final value should be presented in terms of the total area affected divided by total amount of energy generated energy during the plant lifetime.

The impact of electricity generation plants on land is not determined by size alone. There are various types of land use such as agriculture, stock farming, tropical and other forests, wasteland and desert, etc., and the impacts to the overall environment depends upon the land use and location. If wastelands or deserts are affected the overall impact on biodiversity or human resource use will probably be small compared to situations where tropical rainforests or agricultural land are exploited or disturbed. If a photovoltaic power system is installed in an unused space, e.g. on the roof of a house, the impact on the land is negligible. Yet if a forest, which is a source of biomass energy, is created on a farmland, the economic impact could be considerable, especially if there is a food shortage in the area.

For analysing the overall effects of electricity generation on land use a risk analysis is useful. For land use, however, quantitative assessments can be difficult to obtain since there can be a large level uncertainty in the data. Table 8.1 shows qualitatively the amount of land, including the plant sites, used by different electricity generation options and the estimated amount that would be effected in case of an accident. Each value represents the amount of required land for producing the same amount of electricity with the different electricity generation systems. In Table 8.1, the area includes not only the power plant site but also related areas (e.g. facilities for fuel supply). “Environmental impact area” indicates the area of expected environmental impact under normal operation conditions and in case of an accident.

Table 8.1 Occupied Area of Energy Supply Systems and Environmental Impacted Area

Generation system	Occupied Area			Environmental Impact Area	
	Generation	Fuel supply	Material supply	Accident	Operation
Hydro	M	N	S	S - L	S
Solar	L	N	M	N	S
Wind	L	N	M	N	S
Biomass	S	L	S	S - L	M
Fossil Fuel	S	M	S	M - L	Ex.L (#)
Nuclear	S	M	S	S - Ex.L (*)	S - Ex.L (**)

N: None, S: Small, M: Medium, L: Large, Ex.L: Extra large
\# The damage caused by acid rain and greenhouse effects is assumed.
* Accident of Chernobyl class is assumed.
** Outside diffusion of radioactive nuclides extending over ultra-long period is assumed.

Hydropower, solar (photovoltaic) power, and wind power generation do not require fuel and therefore no land is disturbed in obtaining fuel to power these options. These renewable power options, however, do have significant land use needs because comparatively large quantities of material are required for their construction, which indirectly requires large areas of land. The electricity generation that uses forest biomass for fuel requires vast land areas for planting trees. If instead forest residues are gathered the specific land requirement becomes considerably smaller since timber harvest then share the environmental burden of forestry. Fossil fuel and nuclear power generation both require considerable amounts of land to obtain, transport, and refine the fuels, but less than is required for biomass energy generation.

The area effected by an accident varies widely according to the way that accident occurrence probabilities are evaluated. Accidents could occur in factories manufacturing photovoltaic cells for solar power generation, but the scope of their effects can be almost completely ignored since it is likely that the accident would only effect a restricted area. The same is true for wind power. Forest biomass can usually contribute to the protection of ecosystems, but if a forest fire breaks out, both the damage and the scope of its effects would be great. Accidents related to fossil fuel power generation systems occur not only at power plants, but also at mines and during fuel transport. The effected areas vary according to the scale of each accident, but if a crude oil tanker has a leak, the environmental harm can be widespread. It is difficult to evaluate the risk of nuclear power plant accidents. The effect of an accident on the scale of the Chernobyl disaster would effect the entire world, but if safe management were practised, then the risk of any accident is negligible.

Power generation systems effect their surrounding environments even when they operate normally. A hydropower plant effects the surrounding area according to its maintenance flow and the water quality it produces. Solar power generation has almost no direct effects, however, semiconductor factories that produce photovoltaic cells also emit pollutants into the environment. The effects of wind power generation include noise pollution, radio interference caused by high frequencies, and harm caused to migratory birds. The form of power generation that most seriously effects the environment during normal operation is fossil fuel power generation. Air pollution caused by SOx, NOx, and CO_2 emitted as exhausted gas leads to acid rain and global warming, respectively. These effects can spread around the world regardless of which country is responsible for the emissions. The same is possible for radioactive substances from nuclear power generation, although such spread is insignificant in daily operation. There is a danger that if the waste materials are not properly managed over time radioactive substances may leak, thus causing severe ecosystem damage. Of course, if thorough safety management is practised, nuclear power generation is one of the most environmentally benign electricity generation options.

The relative quantification of the land surface areas in the table is easily done if only power plants are considered. However, it is difficult to accurately estimate the land use when the indirect land use from fuel and materials are included. It is even more difficult to quantify the data to evaluate the environmental impact on the surrounding areas during normal operation and/or in case of an accident, since there is a high degree of uncertainty regarding the technological properties, regional characteristics, and time scale. If only power plants are considered, however, it is fairly easy to estimate the electricity generation density and then quantitatively compare the properties of the different power generation technologies. The electricity generation density can be calculated by dividing the quantity of power supplied by the unit surface area of land used by the power plant (kWh/m^2).

Land use for power generation varies according to the power generation technology employed at each plant. Fuel storage facilities are included in fossil-fuelled power plants, while in the case of hydropower, the river and the surface area of the reservoir that are the sources of water for hydropower generation are included. Figures 8.1 to 8.3 depict the annual energy output per unit surface area against the power output for run-of-river, reservoir, and regulated dam hydropower facilities in Japan. In hydropower generation, the area required for the hydraulic turbine, plant equipment, and buildings that comprise a hydropower plant are extremely small compared with the surface area of the water resource. The water resource surface area required for hydropower generation is assumed to be the surface area of the river and the reservoir. The calculated water resources are presented for 250 run-of-river, 50 reservoir, and 50 regulated dam hydropower plants. The vertical and horizontal axes for all three figures as logarithmic scales. The figure shows that the annual energy output vs. water surface area is almost identical for the three types: 2 to 10,000 kWh/m^2 for run-of-river type, 5 to 10,000 kWh/m^2 for reservoir type, and 5 to 10,000 kWh/m^2 for regulated dam type. The mean electricity generation density is 100 kWh/m^2. For all three types, the larger the output of the plant, the greater the electricity generation density. The construction of large-scale hydropower plants will increase the electricity generation density by reducing the water surface area required to produce identical quantities of electric power.

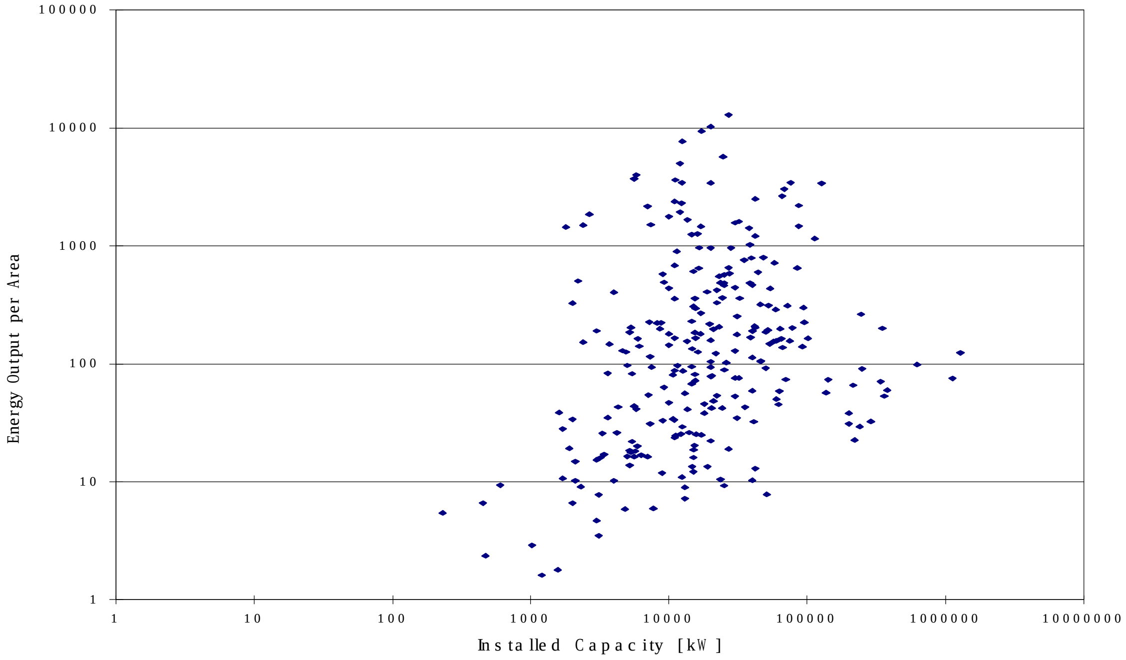


Figure 8.1 Annual Energy Output per Water Surface Area vs. Installed Capacity (Run-of-river type)

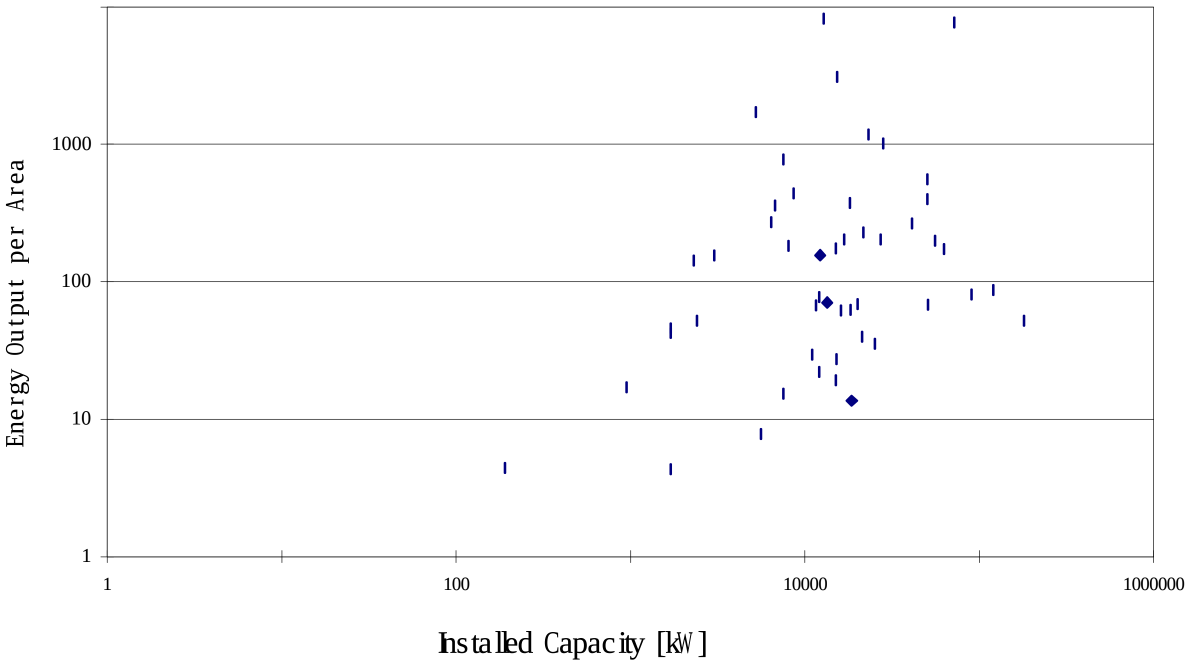


Figure 8.2 Annual Energy Output per Water Surface Area vs. Installed Capacity (Reservoir type)

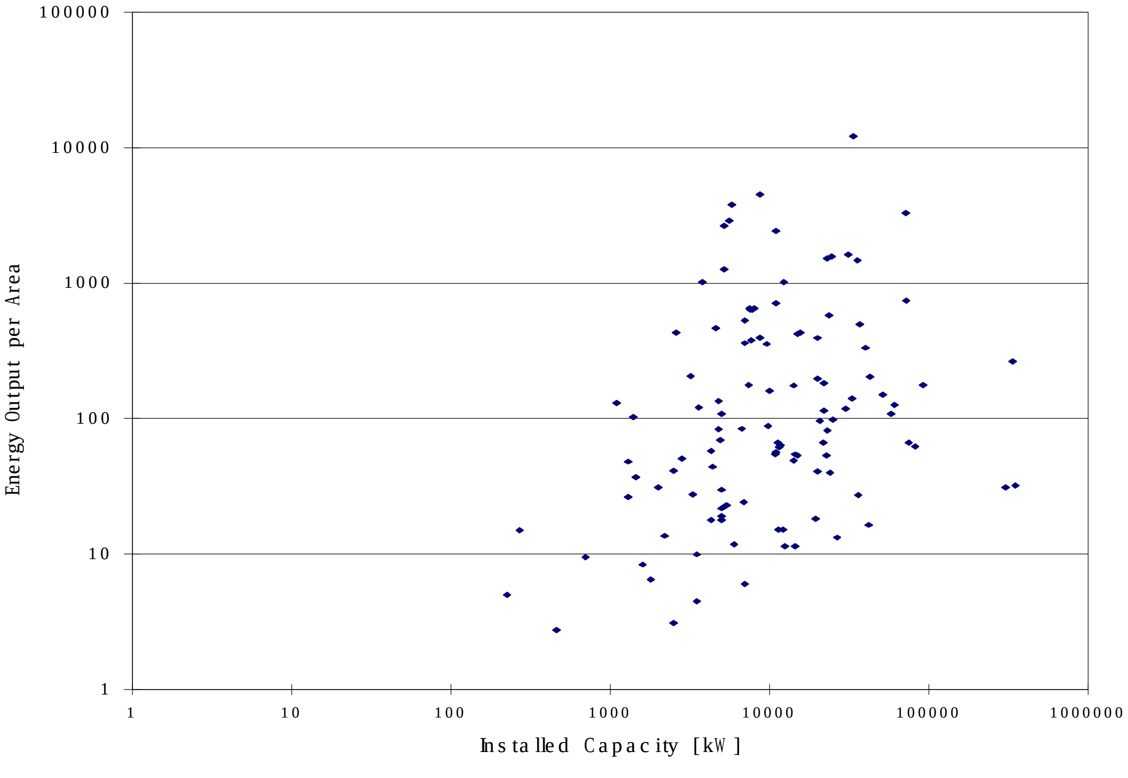


Figure 8.3 Annual Energy Output per Water Surface Area vs. Installed Capacity (Regulation dam type)

To find the electricity generation density of fossil fuel and nuclear power generation technologies, it is necessary to account for the surface area of the land required for fuel supply facilities. In Japan, most fuels are imported from overseas. Therefore, it is difficult to estimate the quantity of land required for fuel supply. The electricity generation densities with each power generation technology were calculated by dividing the quantity of power generated by a power plant in a single year by the surface area of the land occupied by the power plant. The land required for a power plant includes not only the actual power plant building, but also the fuel storage facilities and the management buildings. At a coal power plant, this includes the land for the coal yard, ash dump, and other used land surface at the site. At a LNG power plant, it includes the gasification system and the LNG tanks. Figure 8.4 presents the results of a study of annual energy output per unit power plant site area at a number of fossil-fuelled power plants in Japan. It reveals that regardless of the generated output, the electricity generation density overlaps at about 10,000 kWh/m^2.

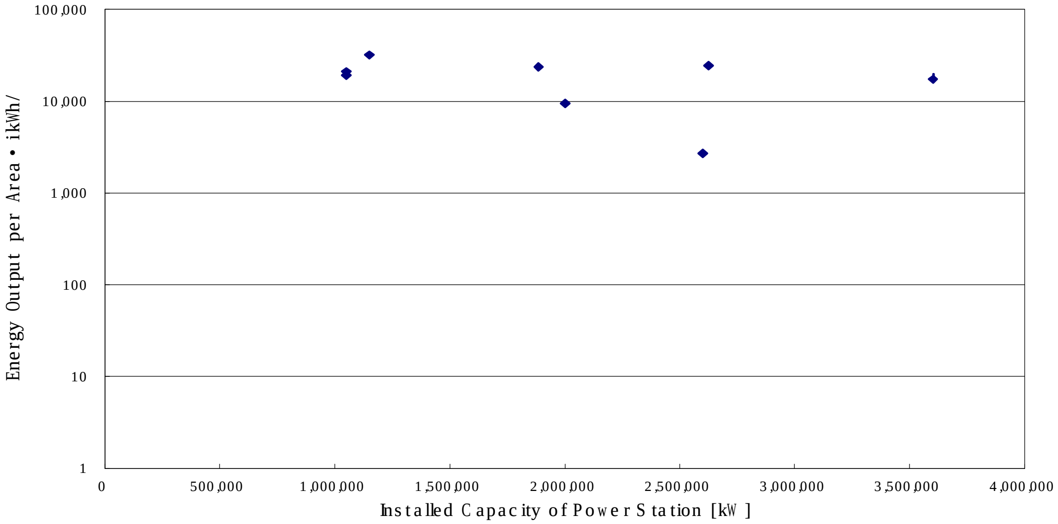


Figure 8.4 Annual energy output per power plant site for fossil fuel fired power plants

Figure 8.5 shows the results of a similar study of nuclear power plants in Japan. It reveals that just as in the case of fossil-fuelled power plants, the electricity generation density of nuclear power plants levels out at about 10,000 kWh/m^2.

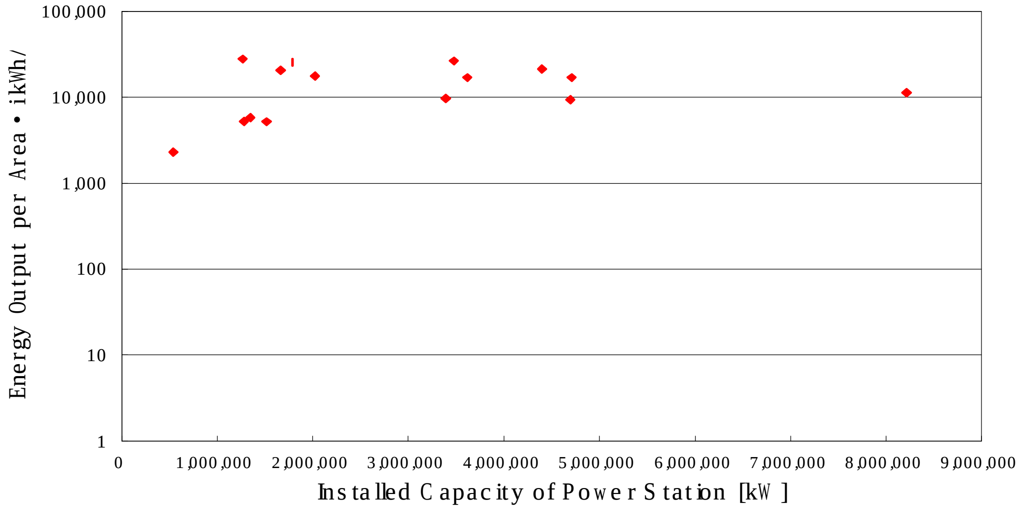


Figure 8.5 Annual Energy Output per Power Station Area for Nuclear Power Plants

The next step is an investigation of the electricity generation density of electricity generation by renewable energy. In Japan, photovoltaic cells are installed on the roofs of about 10,000 homes every year. The average lot size of a house in Japan is 165 m^2 and the capacity of a photovoltaic electricity generation system that can be installed on a roof is about 3 kW. Because a photovoltaic electricity generation system cannot produce power at night and its output is extremely low when it is raining or cloudy, the annual capacity factor of such systems in Japan is about 12%. Calculating the electricity generation density per site surface area of photovoltaic power systems installed on the roofs of houses under these conditions gives a value of 19 kWh/m^2.

Calculations for wind power are presented for a wind farm in California (since presently there are no wind farms in Japan. At Tehachapi, located about 100 miles to the east of Los Angeles, there are approximately 6,000 wind power generators. In one 3-mile section there are approximately 340 wind power generators, each of which generates 275 kW. Calculating the electricity generation density per unit surface area of these sections yields a value of 21 kWh/m^2. This is almost identical to the electricity generation density of photovoltaic power generation. In Europe, the electric power densities of wind power generation are reported as 1-5 MW/km^2 (Sesto & Lipman 1992, Beurskens & de Bruijne 1994) and of 10 MW/km^2 (Curvers, The Netherlands Energy Research Foundation ECN; Petten, The Netherlands, private communication). If their electricity generation is calculated assuming that the annual capacity factor obtained is 20% based on performance, energy density ranges from 2 to 9 kWh/m^2 and 20 kWh/m^2 respectively.

Forests designated only for supply of biomass fuelled electricity generation would cover extremely large areas. Power generation fired by forest biomass, which is also known as wood fired power production, is used in the U.S., Sweden, the Philippines, Brazil, and other countries. Wood fired power generation is performed using conventional technologies: burning wood chips in a fluidised bed and generating electricity with a steam turbine. Recently, integrated gas combined cycle technology, a binary cyclic power generation method in which the medium is gasified in the same way as coal to produce power in two stages using a gas and a steam turbine, has been developed for use with biomass. The use of this technology can raise efficiency to 34%. If poplars or similar fast-maturing trees were planted in Southeast Asia, they could be cut and used in six years. According to trial calculations by the EPRI in the U.S. (1994), in order to constantly operate a 100 MW integrated gas combined cycle , it would be necessary to establish a plantation with a radius of 10 km formed by planting and harvesting concentric circles of trees in six year cycles. A calculation of the electricity generation density of a wood fired power plant per unit area of this plantation obtains a value of 2 kWh/m^2. In Japan, it would take about 40 years to mature to a size that could be harvested. The electricity generation density of a wood fired power plant in Japan is calculated at approximately 0.3 kWh/m^2 and it reveals that a vast quantity of land would be necessary to generate power using forest biomass in Japan.

Figure 9.6 compares the electricity generation density per unit site area of various kinds of power plants. The figure reveals that the electricity generation density of fossil-fuelled power plants and nuclear power plants is about 500 times that of photovoltaic power and wind power generation and is about 5,000 times that of biomass power generation. In other words, to obtain identical quantities of the power, the land required for a fossil-fuelled power plant or a nuclear power plant would be about 1/500 of that required by a photovoltaic or wind power generation, and about 1/5000 of that required by a biomass power generation. In countries like Japan, which is a nation with about 2/3 of its land covered with forests, and most of the remaining land occupied by farms, buildings, roads, etc., it would be difficult to obtain the vast area of land needed for biomass electricity generation. In such countries, fossil-fuelled power plants and nuclear power plants are indispensable.

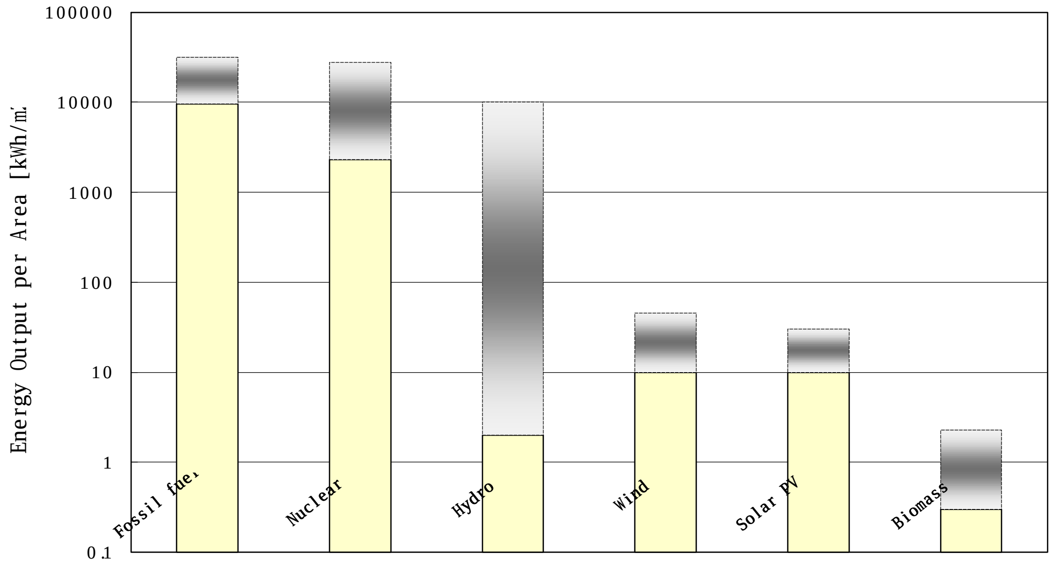


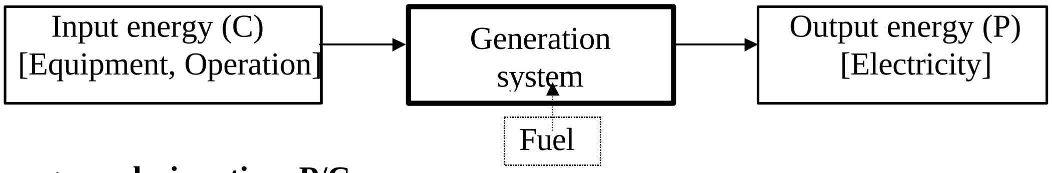
Figure 8.6 Comparison of Electricity Generation Density among Different Power Sources

8.2 Net energy analysis and energy payback time

Net energy analysis is one of the LCAs performed for energy production facilities such as electric power generation technology (Chapman, 1975). By calculating the required energy directly and indirectly for energy production and by comparing the input and output energy during the life cycle of the production facility, this method clarifies the problems in the fabrication, operation and disposal of production facilities. This method was extensively studied in the 1970s and is being developed as a method for analysing the environmental impacts of energy production technologies against a background of increasing interest in environmental problems in the 1990s.

Completing LCA electric power generation systems and other infrastructures is more complicated than generating an LCA for a basic product. The scope of the LCA includes equipment for not only the power generation facility, but also for mining, fuel extraction and conversion, fuel transport, and generation as well as equipment for power transmission, transformation and distribution. The “horizontal system” of a set of facilities required for electric power generation must be studied for the “vertical system” from “cradle to grave.” That is, for each equipment and facility, the input energy for construction, operation, maintenance, and disposal must be examined.

The net energy analyses of electric power generation systems are classified into two types depending on the calculation method: 1) energy analysis ratio, and 2) net supplied energy (Figure 8.7).



Energy analysis ratio = P/C
Net supplied energy = P-C

Figure 8.7 Energy Analysis Ratio and Net Supplied Energy

The energy analysis ratio (P/C) is the ratio of the energy produced by the generation plant (P) to the energy directly and indirectly input to the plant (C). The net supplied energy (P-C) is the net usable energy during the plant life. The value of the net supplied energy depends on the capacity of the power generation plant. The greater the capacity, the greater the value for net supplied energy.

For example, if a nuclear power plant which generates 1,000 MW is compared with a photovoltaic generator which produces 3 kW, the result is that the net supplied energy from the nuclear power generation (the larger power source) is greater. Whenever different types of power generations are compared with each other, each installed capacity must be same. On the other hand, the energy analysis ratio is expressed in terms of the proportion of output/input energies and is thus suited for comparing the different types of technology for electric power generation.

In the net energy analysis, the output energy is secondary energy (P), and the input energy includes both a primary (C1) and secondary (C2) energy. Depending on whether the secondary energies are directly used or are converted to primary energy for use, the result of the energy analysis varies. The energy analysis ratio (R) is expressed by the following four formulas depending on how the primary and secondary energies are converted. Here, α is a coefficient for conversion of the electric power energy to a primary energy [mean power generation unit in Japan: α=9,419 kJ/kWh].

$$R1=3.60\cdot P/(C1+\alpha\cdot C2) \qquad (1)$$

R1 is the value obtained when the output secondary energy is divided by input primary energy. Here, it is assumed that the energy used for the input energy is entirely generated by a fossil fuel; the same definition as for generation efficiency. This equation yields how much electricity is produced per unit of fossil fuel consumed.

$$R2=3.60\cdot P/(C1+3.60\cdot C2) \qquad (2)$$

In equation (2) the R2 value is obtained without converting the output and input energies to the primary energy. This value is significant in the case of the all power generation equipment made by nuclear or natural energy.

$$R3=\alpha\cdot P/(C1+\alpha\cdot C2) \qquad (3)$$

R3 is the value of the output energy divided by the input energy, assuming that all of the power generation equipment is for fossil fuel. The result indicates how many times more energy the electric power generation system in question produces than the fossil fuel electric power generation system.

$$R4=3.60\cdot(P-C2)/C1 \qquad (4)$$

To obtain the R4 value the input energy is subtracted from the output energy and the resulting value thus obtained is divided by the input primary energy. This result expresses the net efficiency of products when all of the power generation equipment belongs to the same system.

The fuel for power generation is not usually included in the input energy, and so the output energy is of a greater value than the input energy. Therefore, the conditions under which a power generation technology is valid as an energy producing plant are as follows: energy analysis ratio >1 and net supplied energy > 0.

Next, we obtain the values for the energy analysis ratio and the net supplied energy for power generation by fossil fuels, nuclear power and renewable energy options. Table 8.2 shows the power generation outputs and annual capacity factors for some power generation plants in Japan. The power generation output values given in the table are for the most typical plant scale used in actual plants. For fossil fuels and nuclear power, the values reported for annual capacity take into account periodic inspections.

For renewable energy power generation the values reported for annual capacity are the maximum obtained under normal operating conditions in Japan.

Table 8.2 Examples of power generation outputs and capacity factors of power plants

Power Generation System	Capacity [MW]	Capacity Factor [%]	Net Efficiency [%]	Power Generation System	Capacity [MW]	Capacity Factor [%]	Net Efficiency [%]
Nuclear	1,000	75	3.4	Wind	0.3	20	10
Oil	1,000	75	6.1	Wave (floating type)	1.0	25	30
LNG	1,000	75	3.5	OTEC	2.5	80	50
Coal	1,000	75	7.4	Solar thermal (tower)	5.0	30	5
Hydro	10	45	0.25	PV (stand alone)	1.0	15	5
Geothermal	55	60	7.0	PV (roof-top)	0.003	15	0

The equipment evaluated includes equipment required for mining, transportation, fuel refinement , waste treatment and waste disposal in addition equipment directly used for electricity generation. The equipment, raw materials and input energies are estimated as accurately as possible for the already commercialised plants, but those technologies for which no commercial plant is available, such as back-end nuclear power generation technology, estimates are made based on the conceptual plants designs. The life expectancy for civil structures, ports and harbours is estimated at 50 years, and the life expectancy for buildings, machines and electrical and chemical factories is 30 years.

The fossil fuel and nuclear electricity power generation systems have complicated fuel supply processes and energy is used in the construction and operation of each process. Which process consumes the largest input energy? Table 8.3 shows the results of a study of input energies by process for fossil fuel and nuclear electric power generation systems over the 30 years life span.

Table 8.3 Input Energies by Processes of Fossil Fuel and Nuclear Power Generation System

<Coal fired plant>

	Input energy [TJ/yr]	Proportion (%)				
		Extraction →	Transportation →	Generation →	Ash Disposal	Sub-total
Manufacturing & Construction	266	1.0	1.2	3.1	2.5	7.8
Maintenance	3152	47.5	40.4	4.2	0.2	92.2
Total	3418	48.5	41.6	7.3	2.7	100

<Oil fired plant>

	Input energy [TJ/yr]	Proportion (%)				
		Extraction →	Transportation →	Refining →	Generation	Sub-total
Manufacturing & Construction	169	2.0	1.0	0.2	3.0	6.2
Maintenance	2559	21.5	19.8	48.2	4.3	93.8
Total	2727	23.5	20.8	48.4	7.3	100

<LNG fired plant>

	Input energy [TJ/yr]	Proportion (%)			
		Extraction →	Transportation →	Generation	Sub-total
Manufacturing & Construction	154	0.2	0.5	0.8	1.5
Maintenance	10509	81.3	16.1	1.1	98.5
Total	10662	81.5	16.6	1.9	100

<Once through type nuclear power generation system : Gaseous diffusion process>

	Input energy [TJ/yr]	Proportion (%)							
		Extraction	A	Enrichment	B	Gene-ration	C	Decommissioning	Sub-total
Manufacturing & Construction	211	0.4	0.1	0.1	0.0	5.4	2.2	0.2	8.5
Maintenance	2282	0.1	4.0	80.5	0.6	6.0	0.2	0.0	91.5
Total	2493	0.5	4.1	80.6	0.6	11.4	2.4	0.2	100

A: Smelting / Uranium fluoride
B: Conversion / Fabrication
C: Spent Fuel Storage

<Plutonium recycle type nuclear1 power generation system: Centrifuge method>

	Input energy [TJ/yr]	Proportion (%)										
		Extraction	A	Enrichment	B	C	Generation	D	E	F	Decommissioning	Sub-total
Manufacturing & Construction	282	0.9	0.1	2.4	0.1	0.1	15.6	0.1	3.8	9.3	0.4	32.7
Maintenance	580	0.2	9.6	19.3	1.8	0.0	17.5	0.3	18.1	0.4	0.0	67.3
Total	862	1.1	9.7	21.7	1.9	0.1	33.1	0.4	21.9	9.7	0.4	100

A: Smelting / Uranium fluoride
B: Conversion / Fabrication
C: Conversion (MOX)
D: Pu conversion
E: Reprocessing
F: Radio waste disposal

Table 8.3 shows that electricity generation technology that requires the largest input energy among the large-scale electric power generation systems is LNG. For LNG plants, the mean annual input energy is 10,660TJ, which is 8 times that of oil power plants and 4 times that of coal power plants. LNG power generation has such a large input energy value since the collection and liquefaction processes require large amounts of energy. For LNG, operating energies account for 81 % of the entire operating energy budget.

Most of the input energy consumed in coal fuelled electricity generation is accounted for by coal extraction and transportation. The transportation energy is greatly dependent on the method and distance of transportation. The consumption increases when the coal is transported over long distances (e.g. by ship to Japan). In Japan, the extraction and transportation costs total 90% of the overall cost of the coal, with extraction accounting for 50% and transportation accounting for 40%.

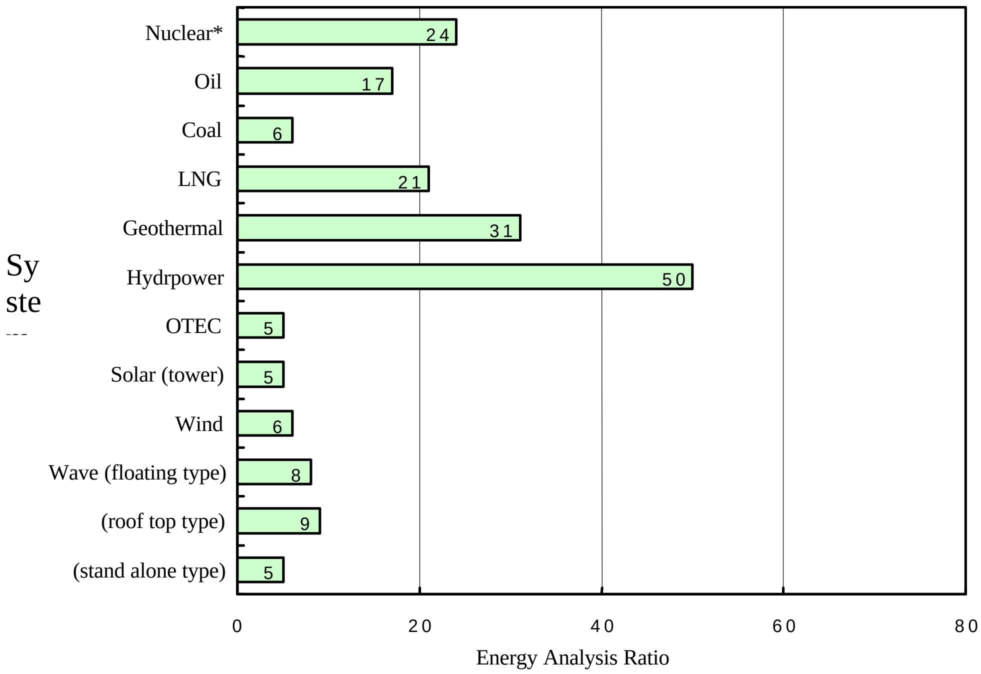
The energy input required for oil fuelled electricity generation, calculated using heavy oil as the fuel, gives the following results: 50% of the input energy is consumed during the refining process, while is used 25% during drilling, 20% during transportation and 5% during power generation.

The value of input energy for nuclear power generation varies greatly depending on the method used to enrich uranium. The input energy for enriching uranium is 2,009 TJ/year for the gas diffusion method, but less than 1/10 of that (or 187 TJ/year) for centrifugal separation. In the gas diffusion method, the input energy accounts for up to 80% of the total energy input required for nuclear power generation of the "once-through" type (i.e. the spent fuel is stored once). By changing the method of enriching uranium to centrifugal separation, the input energy is greatly reduced. By using centrifugal separation for recycling plutonium, the total input energy is 862 TJ/year, and this value is 1/12 or less of that for LNG power generation.

For LNG the input energy may be divided manufacturing & construction energy and maintenance energy components. Table 8.3 shows that most of the input energy is used for the maintenance over the 30 year life span. That is, while the manufacturing & construction energy is primarily consumed at the time of construction, energy is consumed for maintenance purposes throughout the 30-year life span of the plant. The manufacturing & construction energy required by LNG power is only 1.4% of the total input energy. LNG required the smallest manufacturing & construction energy input for all of the evaluated energy options followed by oil power generation at 6.2% and coal power generation at 7.8%. For nuclear power generation, the once-through type using the gas diffusion method requires 8.5% of its input energy budget for manufacturing & construction. This value is nearly the same as that of fossil fuel fired power generation systems. The plutonium recycling type of nuclear power generation with centrifugal separation, however, requires 32.7% of the input energy budget for manufacturing & construction.

The proportions of input energy for the manufacturing and construction and maintenance are different from one of fixed and variable costs. Normally, the fixed cost related to construction of a fossil-fuelled power plant is about 40~60%. The input energy does not include the energy which the fuel has at generation, and if operation and maintenance costs excluded fuel expense from variable cost in generating cost are focused, the proportion of fixed cost rises to 80-90%. That is, the proportional relationship of equipment and operation is completely reversed in generating cost compared to input energy. This is because the generating cost includes the expenses of materials, labour, interest, insurance, etc. in addition to the energy cost, and so compared with the economic value of these elements, the value of the energy is considerably smaller at present.

The energy analysis ratio is an index used to indicate how many times the energy of power generation is greater than the energy consumption for construction and operation of the equipment. A greater value indicates a more efficient energy product system. Figure 8.8 shows the results of calculating energy analysis ratios with the equation (3), for Japanese electricity generation systems.



*:Once through; gas diffusion

Figure 8.8 Energy Ratio of Different Electric Power Systems (lifetime = 30 years)

From Figure 8.8, it can be seen that hydropower generation yields the largest and best energy ratio, followed by geothermal power generation, nuclear power generation and oil power generation in descending order. The reason why hydropower generation has the best value of net supplied energy is that the energy source is water, and the water supply is replenished by rainfall, a natural phenomenon. Therefore, there is no need to transport fuel from an oil field or coal mine to operate a hydropower plant. Since hydroelectricity generation systems effectively utilise natural phenomena for energy production, it is understandable that hydropower was developed as a power generation technology at a very early stage.

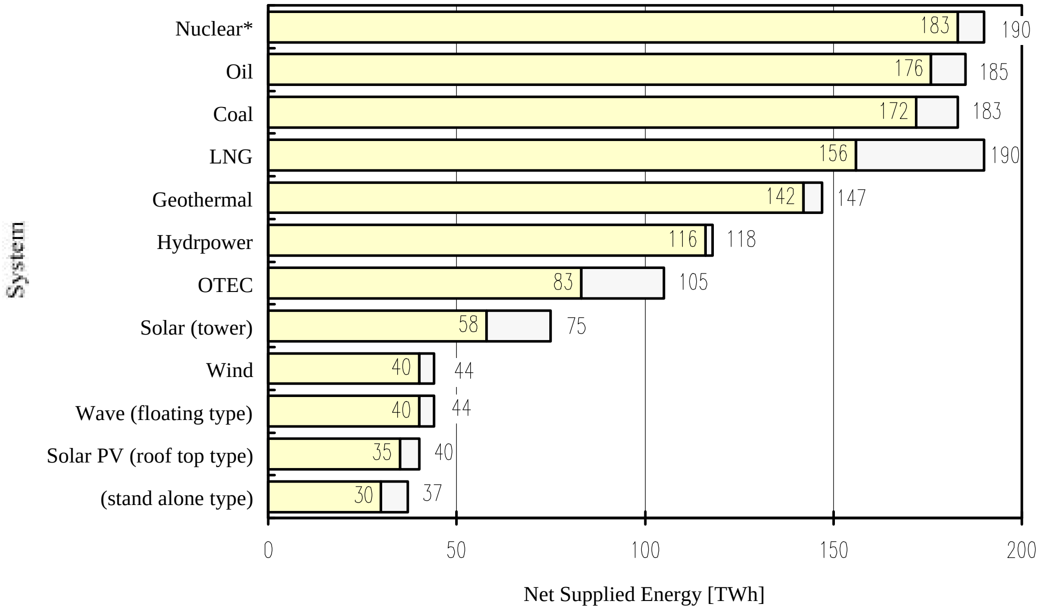
The same applies to geothermal power generation, which uses the heat of magma to generate electricity. Compared with fossil fuel or nuclear power generation, geothermal power generation requires only simple facilities since steam is drawn out of the ground without a boiler. All that is necessary is the installation of a few pipes for underground steam transport and reducing wells. When a smaller quantity of materials is required, the energy analysis ratio improves.

For heavy oil fired power generation, the actual equipment configuration in Japan constitutes 57% of the total, with the remaining power generated by directly burning crude oil. Heavy oil power generation consumes energy during oil refining, included in the input energy, yet its energy analysis ratio is the best among the fossil fuels. LNG power generation has a small energy analysis ratio since the electricity generation density of natural gas is very low. Therefore, a large quantity of energy has to be consumed to raise the density. 10~15% of the produced energy is consumed for the collection and liquefaction of natural gas and 17% or more energy is lost by the time that the natural gas reaches a power plant as LNG. Natural gas can be transported without liquefaction to the buyer through a pipeline, but this requires considerable power for transportation. The gas produced from a gas well is normally at a gas pressure of 20 atmospheres or less, so the pressure must be raised to a pressure of 50~60 atmospheres to be conveyed via a pipeline to the buyer. The energy consumed by this process is equivalent to 10% of the produced gas, and the longer the pipeline, the greater the energy loss. Much energy must thus be consumed even if the natural gas is stored in the gaseous state at low electricity generation density and transported to the customer. The same is true for all natural energies except hydropower and geothermal power. Rarefied energy must be collected using equipment. The energy analysis ratio of an electric power generation system based on natural energy is usually comparatively low.

Figure 8.9 shows the results of the net supplied energies, which express how much energies are actually supplied to society, by the various power generation systems in Japan. The values were calculated by subtracting the input energy for construction and operation from the energy produced during operation. For the purpose of comparison a standardised power plant output of 1,000 MW and a plant life expectancy of 30 years were assumed for each plant.

The value of the net supplied energy greatly depends on the annual capacity factor of the generating equipment. In other words, if the annual capacity factor allowing operation at the rated output is greater, more electricity is generated, and therefore more electric power is supplied to society. It is reasonably possible to raise the annual capacity factor to 75% for fossil fuel electricity generation and nuclear power generation. However, in the case of photovoltaic power generation, it is 12~15% at best for the solar radiation conditions in Japan. For the same equipment capacity, fossil fuel and nuclear power generate 5 to 6 times more electricity than photovoltaic power generation.

From Figure 8.9 it can be seen that fossil-fuelled power generation and nuclear power generation yield large values for net supplied energy in comparison to hydropower and geothermal power. LNG power generation, which does not have a preferable energy analysis ratio, has good value for net supplied energy. Thus, the large fossil fuel nuclear power generation plants provide a larger quantity of electricity to society, as compared to renewable energy plants of the same scale. In addition the net energy supply from fossil fuel and nuclear power plants is 7 to 8 times that of photovoltaic power generation. For today’s industrial society, which consumes huge quantities of electricity, electric power generation systems must supply a large quantity of electric power. Hydro or the other natural energies cannot accommodate such demand, and so we need to rely on fossil fuels and nuclear power for bulk power supply.



*:Once through; gas diffusion enrichment

Figure 8.9 Net Supplied Energies of Electricity Power Generation Systems (1,000MW). For each technology a standardised power plant capacity of 1,000 MW and a plant life expectancy of 30 years were assumed.

From the net supplied energy data, it is possible to calculate the energy payback period (harvested time). This expresses the period over which the energy input to the equipment can be recovered by the annual generated energy. The energy payback period is obtained by the same calculation of the investment payback period used at the time of plant construction. That is, it is obtained by dividing the input energy for equipment construction by the value obtained when the annual input energy for operation is subtracted from the annual generated power.

Energy payback period = Input energy for equipment / (Annual generated power – Annual input energy for operation)

Table 8.4 shows the energy payback periods of electric power generation systems. As seen, the values for fossil fuels and nuclear power are about 0.1 year, while hydropower generation, which is the best among the natural energies, is 0.59 year, and the other options range from 2 to 5 years.

Table 8.4 Energy Payback Period of different electric power systems

System	Payback time [yr]	System	Payback time [yr]
Oil plant	0.09	Hydropower (small)	0.59
LNG plant	0.09	Solar thermal (tower type)	5.61
Coal plant	0.15	Wind	3.39
Nuclear plant	0.11	Geothermal	3.39
Solar PV (stand alone type)	4.76	OTEC	4.58
Solar PV (roof- top type)	2.59		

8.3 Environmental LCA

Using net energy analysis, the amount of CO_2 emitted over the lifecycle of each electricity generation option is derived from the indirect emissions from combustion of fossil-fuelled power plants and the indirect emissions associated with the energy consumed for construction and O&M of the electricity supply system. The system covers the sequence of fuel extraction, transportation, treatment, conversion, transmission and distribution, waste disposal and dismantling of the facility. The life cycle inventory on GHG also includes methane gas leakage during mining of coal or extraction of natural gas and the CO_2 emissions from cement production. Methane is one of the greenhouse gases and it has a global warming potential that is 21 times higher than that of CO_2 for a time horizon of 100 years. The greenhouse effect of an electricity supply system is expressed in terms of the CO_2 emission factor. This factor can be calculated by the following equation:

$$CO_2 \text{ emission factor x } (E1 + E2 + E3 + E4) = \text{Out}$$

Where E1 + E2 + E3 + E4 is the total amount of CO_2 emitted from an electricity supply system during the plant life; E1 is the direct emission from fossil fuel combustion at a power plant; E2 is the indirect emission from construction and O&M; E3 is the indirect emission from cement production, and E4 is the equivalent CO_2 emission from methane leakage.

Table 8.5 gives CO_2 emission data for the commercially available electric power generation systems evaluated in Japan. These systems use fossil fuels, as well as nuclear and renewable energy sources, and outputs are at industrial scale. Table 8.5 shows the results of calculating the CO_2 emission factors of various power sources. The total emissions are broken down into the following factors: equipment fabrication, operation and maintenance, combustion and methane leakage. The values in the table represent the total CO_2 emissions during the 30-year life span divided by the energy generated during the same period. For photovoltaic power generation, small-scale sources (3kW) installed on domestic rooftop (rooftop type) and large-scale, stand-alone units (1,000kW) were both examined.

Table 8.5 CO_2 Emission Factors of Different Power Sources in Japan
Unit: g-C/kWh

Generation System	Equipment Fabrication	Maintenance	Combustion	Methane Leakage	**Total**
Coal	1.09	9.78	246.33	12.69	**269.89**
Oil	0.62	7.21	188.41	3.10	**200.06**
LNG	0.55	24.10	137.27	16.05	**177.67**
Nuclear	1.00	4.46	-	0.24	**5.70**
Hydro	4.63	0.07	-	0.11	**4.81**
Geothermal	1.39	4.63	-	0.27	**6.29**
Wind	6.73	2.41	-	0.37	**9.51**
PV (roof-top)	11.91	3.57	-	0.53	**16.01**
PV (stand alone)	26.24	6.82	-	1.25	**34.31**

In this table, hydropower has the lowest CO_2 emission factor. Nuclear, geothermal and the other renewable energy options also have particularly low emission factors. The emission factor for fossil fuel power generation is much greater than the emission factors for nuclear and renewable energy systems. In addition, the amount of CO_2 directly emitted by combustion of fossil fuels during electricity generation is far greater than the indirect CO_2 from equipment fabrication, maintenance, and methane leakage.

Comparing only the fossil fuel power plants, CO_2 emissions are the largest for coal followed by oil and LNG, respectively. When the fuels are compared and only power generation (combustion) is considered, the ratio of emissions is 100:76:56 for coal, oil and LNG, respectively. When equipment fabrication, maintenance, and methane leakage are included, the ratio is 100:74:66. This change in value for LNG is due to the fact that CO_2 emissions generated during the collection and liquefaction of natural gas are large, and crude natural gas contains much more CO_2. The amount of CO_2 emissions from liquefaction and in the crude natural gas total approximately 25% of emissions produced during LNG electricity generation.

Nuclear power fuel does not emit CO_2. Therefore the contribution of nuclear power to the greenhouse effect is small. In fact, nuclear power contributes 1/30 of the emissions attributed to a LNG electric power generation. Nuclear power generation has a complicated fuel cycle. A variety of materials are required for plant construction, though when the amount of energy required for plant construction is divided and the lifetime of the plant, the total is not very large. However the following kinds of emissions from nuclear power, listed in order of importance, are: CO_2 emitted through the consumption of electricity during uranium enrichment in the gaseous diffusion process, CO_2 emitted indirectly from plant maintenance during life cycle of the plant, and CO_2 emissions from nuclear plant construction.

Exploitation of renewable energy sources has the to suppress the greenhouse effect if the alternatives would imply using fossil fuel. The emission factor for photovoltaic power generation is larger than for nuclear and hydropower generation, but considerably smaller than the factors for fossil fuel power generation systems. The CO_2 emission factor for the roof-top style photovoltaic power generator is considerably smaller than for the stand alone model since the energy required for assembling the rooftop variety is negligible.

The CO_2 emission factor is a value that varies among plants employing the same power generation technology according to the technical properties and types of materials used to construct each system. It also depends on the CO_2 emission factor of the electricity used as input energy, as well as other factors. For any kind of electric power generation system the performance of the plant is one component which considerably influences the CO_2 emission factor. Considering fossil fuel power generation technology, the performance of the plant is one of a set of noted variables that affect the CO_2 emission factor. This set of variables also includes net thermal efficiency, annual capacity, and plant life expectancy. When the CO_2 emission factors of different fossil-fuelled power generation systems are studied, their CO_2 emission factors will be almost identical if their net thermal efficiencies and annual capacity factors are the same and if their CO_2 emission factors are calculated using the same fuel. At nuclear power plants that consume uranium fuel, it is necessary to survey the plant's overall performance and also the technical performance of the plants nuclear fuel cycle as accurately as possible. This careful study is necessary because the nuclear fuel cycle and the uranium enrichment process both have large effects on the CO_2 emission factor. When evaluating hydropower, photovoltaic cell, and wind power plants, which do not depend on fuel, it is necessary to carry out a more detailed study of the raw materials, processing methods, and equipment required for power plant construction in order to obtain accurate CO_2 emission factors.

Table 8.6 presents a comparison of different results obtained from analysing the CO_2 emission factors throughout the life cycles of different electric power generation systems in different countries. The values in the table are obtained from studies of CO_2 and CH_4 as greenhouse gases. CO_2 is the major GHG since energy use constitutes the major component of the life cycle inventories. Overall, the CO_2 emissions from the fossil fuel combustion are much greater than for other electricity generation. Literature values on fossil fuels are in the range of 300, 200, 150 g-C/kWh for coal, oil and natural gas, respectively. However, result by Sullivan indicate a high value due to CH_4 releases associated with fuel production and transportation. He also uses a relatively high global warming potential value of 50-60, compared to 21 as recommended by IPCC (Houghton *et al.*, 1996).

Table 8.6 Estimated CO_2 Emission Factors of Different Electricity Generation Systems (Dones, 1995; San Martin, 1989; Friedrich & Marheineke, 1994; Uchiyama, 1996; Yasukawa et al., 1992; Lewin, 1993; Science Concepts, 1990; Fritsche et al., 1989, and Sullivan, 1993).

	Hard Coal	Oil	Natural Gas(LNG)	Hydro	Nuclear	Wind	Solar PV
Uchiyama	270	187	(178)	4.8	5.7	9.5	8 52
Yasukawa	330	-	-	-	9.0	-	-
Friedrich	256-352	-	-	-	5.2	4.4	76
Dones	265-278	243	210	1.1	2.2-6.5	-	38-70
Lewin	339	-	123	-	7.6	3.0	62
San Martin	263	198	132	2.7	2.1	2.0	1.5
Science Conc.	262	210	146	-	6.8	-	-
Fritsche	253	-	148	-	14.7	4.1	8.7
Sullivan	234	221	337	-	-	-	-

Table 8.6 indicates that the emission factors of nuclear and renewable energies are total 1/10 to 1/100 of the emission factors for fossil fuels. The emission factors of nuclear power and hydropower vary within ranges 2-15 and 1-5 g C-equiv./kWh, respectively. The differences in the emission factors are mainly due to different types of technology and different country specific factors such as plant capacity factor and site preparation.

Hydropower plants are classified as run-of-river or reservoir types. Sources of GHG emissions associated with the construction of hydropower plants are related to the equipment and construction materials, concrete and steel. Water reservoir hydropower requires a large amount of materials and energy for dam construction and reservoir boundary creation. Table 8.7 illustrates the estimated indirect GHG emissions associated with the use of materials and energy for the two different types of hydropower plants: run-of river and reservoir. The size of the plant is also another key parameter. Small plants have relatively high GHG emission factors as indicated in Table 8.7. The emission factors are calculated with a plant life of 100 years for all countries except Japan, in which case a 30-year life span is used.

Table 8.7 Estimated Greenhouse Gas Emission Factors for Hydropower (Uchiyama, 1996; van de Vate, 1996).

Unit: g-C/kWh

Country / Region	**Run-of-river**	**Reservoir (Concrete dam)**	**Reservoir (Earth-rock filled dam)**
Canada	0.25 (large)	0.35 (large)	0.33 (large)
China	-	0.92 (large)	-
Germany	-	3.07 (small)	-
Japan	-	-	4.8 (small)[2)]
Switzerland	0.79 (small)	1.7[1)]	-

1) average of 52 major Swiss hydropower plants
2) life-time : 30 years(machines), 50 years(building & civil structures)

As with hydropower, the energy used to fabricate and maintain the equipment necessary for photovoltaic and wind power systems also has a significant effect on the CO_2 emission factors of these technologies. The elements having the greatest effects on the CO_2 emission factor of photovoltaic power are the manufacturing method, the annual capacity factor, the plant life, and the type of cell material used (e.g. mono-crystalline silicon, polycrystalline silicon, or amorphous silicon) as well as the energy conversion efficiency of the system. Another important element that effects the overall CO_2 emission factor for photovoltaic electricity generation is the amount of energy required for manufacturing the silicon.

The two different varieties of photovoltaic electricity generation systems, rooftop and the stand-alone, have attributes that contribute to the emission factor in different ways. The rooftop type is attached to a building that is also used for other purposes, therefore utilising an otherwise unused space and eliminating the need to build a new foundation to support to photovoltaic cell. On the other hand, the stand-alone is a larger unit and therefore can produce more power, but it requires the construction of a frame or foundation for the exclusive use of the photovoltaic power generation equipment. There are tradeoffs with each of these two models. When the power generation capacity is increased, the added costs of a frame must be considered. In addition, since photovoltaic power generation is influenced by weather conditions, the annual capacity factor varies greatly according to the installation location. The optimum place for installing photovoltaic power systems would be in low latitude deserts, where clouds and rain are rare. However, in such areas, there is usually a low electricity demand and limited access due to their remoteness from urban aggregations.

LCA of photovoltaic cells reveals that most of the input energy is energy used to manufacture the silicon cell material. For this reason, the CO_2 emission factor of a photovoltaic cell is also determined by the method of silicon manufacturing. In Table 8.8, cell materials used in photovoltaic power generation with different CO_2 emission factors are listed. The annual capacity factor of a photovoltaic electric power generation system is about 12% in both Europe and Japan, and the differences in the emission factors based on this 12% annual capacity factor are assumed to be small.

The range of values in the table are reflect the differences in silicon cell composition. Amorphous silicon membrane is only a few microns thick while crystalline silicon is far thicker at 300 to 400 microns. Therefore, the production of amorphous silicon consumes less energy. Since its cell thickness, and therefore efficiency, is less than half that of the crystalline type, large quantities of materials other than silicon wafers are required to make photovoltaic cells with amorphous silicon. The result is that the CO_2 emission factor of an amorphous silicon cell is far smaller than the CO_2 emission factor of a crystalline silicon cell. At this time, however, the silicon used to make photovoltaic cells is high purity, crystalline semiconductor quality silicon that has been rejected for semiconductor use. However, if the photovoltaic cell market expands then specialised factories will start making lower purity silicon for photovoltaic cells, hence improving the CO_2 emission factor (Table 8.8).

Table 8.8 Greenhouse Emission Factors for Solar PV Power (Dones & Frischknecht, 1996; Uchiyama, 1996; Hartmann, 1996; Nates et al., 1996).

Unit: g-C/kWh

	Dones		Uchiyama		Hartmann	Bates
	Current	Future	Current	Future		
PV (roof-top)						
Mono-Si	31-49	12	-	-	71	-
Poly-Si	52-76	-	32	8.1-16	68	27-46
Amorphous-Si	-	7.4	-	8.0	60	
PV (stand alone)						
Mono-Si	47	-	-	-	-	-
Poly-Si	64	-	52	22-34	-	-
Amorphous-Si	-	-	-	29	-	-

An immediate way to reduce the overall amount of CO_2 emissions from electricity generation is to convert current non-renewable fuel use from fossil alternatives with high carbon content (coal and oil) to highly efficient natural gas combined cycle power generation. However, if we rely heavily on natural gas, the stability of future electricity supply may be a concern. The recent worldwide shift toward natural gas use may eventually create a scenario where the available supply of natural gas is not sufficient to meet the demand early in the next century. Thus, in terms of energy security, it is important to look at other energy options, especially coal power generation. The CO_2 emissions from coal may be considerable, but coal power generation is a cheap, reliable method of electricity production. Varying the types of technology used will stable the supply of electricity. In this way, improving coal fired power plant efficiency may be a reasonable economic strategy.

Nuclear and renewable energies, which do not emit CO_2 during generation, are effective in reducing the overall amount of anthropogenic CO_2 emitted to the atmosphere. In addition, fossil fuels are conserved when nuclear power and renewable energy is utilised. Therefore, to help reduce global CO_2 emissions and provide a stable source of electricity supply in the long term, increased reliance on nuclear power and renewable energies may be prudent.

9. CLARIFICATIONS AND CONCLUSIONS

All renewable energy sources and probably most if not all of the fossil fuels can be traced back to the sun. Renewable energy conversion systems make direct use of solar irradiation or extract heat or kinetic energy from the natural transformation of sunlight to biomass, cycling of water or wind. The energy in biomass takes the form of chemical bindings mediated by photosynthetic plants and microorganisms. Human use of natural resources or actually the mere existence of human beings relies on the past and present incoming energy from the sun.

Electricity generation utilises basically all natural energy conversion phenomena including pumping heat from the inner parts of the Earth (geothermal) and absorbing energy released when heavy radionuclides are falling apart (nuclear). It is logic to expect that the specific environmental impacts of electricity production will depend on the character of the energy that is used to create the mechanical power that runs the generator. For example, burning biomass for the purpose of producing one unit of electricity probably requires the gathering of fuel from a larger area than if an equivalent amount of hard coal was used because the energy content per unit weight of hard coal is about twice that of biomass (Table. 9.3). On the other hand, the carbon stored in biomass will be continuously replenished so that an infinite number of future harvests will be possible provided proper management of the area is implemented. This includes for example the bringing back of ash after combustion, since ash contains essential nutrients for sustained plant production.

Table 9.1 The composition of major elements in fuel. Data on coal are based on EMEP/CORINAIR Atmospheric Emission Inventory Guidebook.

Content (%)	**Hard coal**	**Brown coal**	**Oil**	**Natural gas**	**Biomass**
Carbon	77-90	62-73	85	75	50
Hydrogen	4.5-6	4-6	11.4	22	6
Oxygen	3-16	18-30	<1	1	43
Nitrogen	0.7-2	1-2	<1	1	1
Sulfur	0.3-3.5	0.5-6	<3	<1	<<1

Biomass

Biomass is produced where organisms are able to grow and reproduce, i.e. practically everywhere on the globe. However, primary production is particularly high in sunny, humid areas with abundant nutrients. Some shallow, tropical waters are considered to produce the highest biomass per unit area that is of the order of 1000 g C/m2/yr (about twice as much in terms of dry weight). This corresponds to a combustion value of about 10 kcal/g C, with little variation between different kinds of plant biomass (Barnes & Mann, 1994). About the same level of plant production has been achieved in cultures of Poplar, Eucalyptus or Willow that represent growing of biomass which is explicitly directed to fuel production (Perlack *et al.,* 1995). However, the average yield is much lower (Electric Power Research Institute, 1991).

The lower heating value (LHV) of dry wood is about 18 GJ/tonne dry weight or 5 kWh/kg (Van den Broek *et al.,* 1996). With maximum electrical efficiencies of 42 % for BIG/CC the above data combine to give an annual yield of at most 4 kWh_{el}/m^2. However, this is a theoretical estimate that has not yet been realised anywhere and probably never will, because a more feasible use of biomass involves combined heat and power production with resulting higher overall conversion efficiencies but with lower electrical efficiencies.

The minimum production of electricity per unit area from biomass is probably close to zero and is found where biomass fuel constitutes a by-product of other use of organic matter, such as sawing of timber, pulpwood and food crops. In Sweden, for example, the average annual yield of forest residues for burning amounts to about 0.1 kWh_{heat}/m^2.

Since the extraction of fuel is of overriding importance in land requirements of biomass life cycles it may be deduced that a minimum of 0.25 m^2 is needed to generate 1 kWh of electricity by this technology if energy crops are used as fuel. If use is instead made of forest residues or organic waste, fuel must be gathered from a larger area. On the other hand, a reasonable allocation of space to the biomass fuel cycle in such cases means that only a fraction of this area should be attributed to the extraction of fuel. According to the Swedish LCA less than 0,000005 m^2/kWh is used for industrial purpose. The allocation of the differential use of biomass between different services and impact categories pose a particular problem in life cycle analyses and is similar to the division of environmental burdens between beneficiaries of multi-purpose river regulation.

One of the main reasons for using biomass fuel is that it involves virtually no net emission of CO_2. Plants absorb CO_2 through photosynthesis as they grow. Since there is usually a balance between production and decomposition of organic matter in undisturbed ecosystems (Eriksson, 1991) net releases of carbon from burning of biomass can be avoided. In the course of the biomass power generation life cycle, emission of CO_2 is due mainly to the construction of the power plant, the use of fossil fuels for transportation of the biomass to the plant, and, in as much as energy crops are used, the manufacturing of nitrogen fertilisers (Brännström-Norberg & Dethlefsen, 1998). In modern power plants these expenses amount to between 6 and 15% of the carbon sequestered in biomass fuel.

The cycling of other elements is principally the same with no or very low net emissions to the atmosphere. However, nitrogen is particularly interesting in this respect. Nitrogen oxides released as a result of the use of fossil fuels act as fertilisers. In large parts of Europe the deposition exceeds the critical load, i.e. the amounts that primary producers has the capacity to absorb. Since modern biomass fuelled CHP plants largely emit elementary nitrogen, it is thus possible to “clean” forest ecosystems from excess nitrogen (Lundborg, 1997). While only low emissions of air pollutants occur when burning biomass in such plants (Table 9.2), small-scale use of this fuel in stoves in residential buildings has been identified as a health problem, particularly in urban areas (Smith, 1987).

Table 9.2 Exhaust emissions in the life cycle of biomass fuelled power plants (g/kWh_{el}). Lower range for CO2 refers to fuel production, construction and dismantling, whereas the higher ones also include fuel combustion.

CO$_2$	**NO$_x$**	**SO$_2$**	**Source**	**Note**
10-11 (340-341)	0.58-0.67	0.082-0.086	Brännström-Norberg *et al.*, 1996	(1)
13-16 (437-440)	0.37-0.41	0.18	Brännström-Norberg *et al.*, 1996	(2)
17-27	1.1-2.5	0.07-0.16	ETSU, 1995	(3)

(1) CHP/CFB (allocation of emissions: 25% electricity; 75% heat; life span: 40 yrs; range represents two different fuels, i.e. forest residues and willow, respectively)

(2) CHP/BIG (allocation of emissions: 49.6% electricity; 50.4% heat; life span: 40 yrs; range represents two different fuels, i.e. forest residues and willow, respectively)

(3) Bates, 1996

Emissions from other kinds of combustion are primarily a consequence of the chemical composition of the fuel (cf. Table 9.1) and the amount of heat that is generated (Table 9.3 and 9.4). These characteristics are about constant for every fuel. Consequently, only methods that can neutralise emitted compounds can drastically alter the release of greenhouse gases, acidifying substances and nutrients, while changes in efficiencies have less influence on the specific emissions.

Table 9.3 The physical characteristics of different fuels.

Energy source	**Density (kg/m^3)**	**Energy content (kWh/kg) (1)**	**Comment**
Hard coal	800 (3)	6.9	
Brown coal	900-970 (3)	<6.6 (4)	
Crude oil	850	11.9	
Refined oil (4)	835-950	11.7-12.6	
Natural gas	.75	13.9	
Native uranium mineral		9-12	2% U in ore.
Uranium	18,680	140 x 10^3	Natural uranium with a content of 0.71% U^{235}
Enriched uranium	--	880 x 10^3	3.2% U^{235} (5)
Biomass	310-470	3.5 (6)	
Air	1.2	-- (7)	
Water	1000	-- (8)	

Notes:

(1) Typical values or range. Variations are particularly high for biomass.

(3) Bulk density, i.e. density of transported volume (the density of solid coal is 1100-1500 kg/m^3)

(4) Coal with an energy density of less than 23.8 MJ/kg (=6.61 kWh/kg) is defined as brown coal.

(5) Average content of U^{235} in fuel used in Sweden.

(6) Forest residues. 30% moisture (Swedish data)

(7) The kinetic energy of moving air is calculated as ½x p x u^2 (where p = air density; u = linear wind velocity)

(8) 1 kg (= 1 litre) of water that drops 1 m looses energy (= generate heat) corresponding to $9.18x10^{-3}$ kWh.

Table 9.4 Greenhouse gas emission factors for a number of fuels expressed as g CO_2/kWh_{heat} (based on Smith et al., 1994).

Fuel	**CO_2**	**CH_4**	**N_2O**	**Total**
Coal	331 (1)	1.5	8.2	341
Oil	275	2.2	8.2	285
Natural gas	189	0.8	4.1	194
Peat	392	1.2	8.2	401 (2)
Wood	411	11	8.2	430

(1) US average for bituminous coal is 318 g CO_2/kWh_{heat} (Energy Information Administration (EIA) 1992)

(2) 425 g CO_2-equiv./kWh according to (Kivistö 1995)

Coal

As is obvious from Table 9.4, the three basic fossil fuels, coal oil and natural gas, represent different intervals on a continuum that goes from bad to fair in terms of environmental performance. This is not only a result of the differential contributions to atmospheric greenhouse gas emissions, which is high for coal and moderate for natural gas with oil being intermediate. It also relates to the use of resources for the construction of the power plant and for the work required to secure a continuous supply of fuel.

Yet, life cycle analyses of fuel cycles based on coal clearly demonstrate that emissions of greenhouse gases from fuel production, transportation, construction, maintenance and decommissioning of power plants are small compared to those resulting from combustion. Consequently, conversion efficiencies exert a particularly strong influence on the environmental performance of this technology. Using the US average carbon dioxide factor for bituminous coal of 318 g CO_2/kWh_{heat} (Energy Information Administration, 1992) and an average global energy efficiency of 25% implies that specific emissions of carbon dioxide from coal-fired power plants would amount to 1272 g CO_2/kWh_{el} as a world average. An increase of the global average efficiency to the OECD average means a reduction of the specific CO2 emissions by more than 30%. Another 34% would be gained if the most efficient technology was implemented throughout. Still, however, almost 600 g CO_2/kWh_{el} would be directly emitted from the combustion process.

Other steps in the coal cycle with significant contributions of greenhouse gas, involve mining, which frequently releases methane to the atmosphere. According to Riemer (1999) average methane emission per kilogram of coal (hard coal and brown coal combined) mined in the world is estimated at 4.65 g. This adds 13 g CO_2-equiv./kWh_{heat} to the emissions from the coal fuel cycle. Underground mining contributes on average nearly 20 times as much methane per extracted amount of coal as surface mining (Riemer, 1999) on a weight basis.

The total emission of carbon dioxide as well as NO_x and SO_2 in the coal fuel cycle is depicted in Table 9.5.

Table 9.5 Emissions of major gases, expressed as g per kWh$_{el}$, according to some life cycle inventories.

CO_2	**NO_x**	**SO_2**	**Efficiency (%)**	**Life-span (yrs)**	**Source**	**Remark**
770	1.13	1.28		50	Soil and Water Ltd	Hard coal
1100	6.1	2.5				
1149	0.70	0.72	37.6	35	Friedrich & Marheineke, 1996	Hard coal
1175	n.a.	n.a.	36.2	20	Friedrich & Marheineke, 1996	Lignite
894	n.a.	n.a.		25	Kivistö, 1995	Hard coal
955	4.3	11.8			Bates, 1995	Best practice
987	2.9	1.5			Bates, 1995	FGD

Nuclear

The release of radionuclides and the exposure of the population to ionising radiation, that are of largest concern in terms of environmental impact of nuclear power production, is as yet not adequately handled in life cycle analyses. It has so far been costume to present releases as total amounts of different radionuclides per unit electricity produced. However, since the fates of such compounds diverge and different radionuclides are transported along different pathways in ecosystems, fair comparisons should instead be based on calculated doses. The information necessary for accomplishing such calculations is as yet not fully available.

As with renewable energy sources emission of greenhouse gases in the nuclear power life cycle is mainly related to the supply of fuel and the construction. The enrichment process is by far the most energy consuming step in the nuclear power fuel cycle, with gas diffusion being the most energy intensive process, using up 30-40 times as much electricity as is required by gas centrifugation method (Van Engelenburg & Nieuwlaar, 1992). The laser-enrichment method is still under development.

Emissions are largely dependent on the method used and how the electricity for this process is produced. Let us for the sake of simplicity assume that the most costly method is used, i.e. the gas diffusion process, and that all electricity used in this process is produced in a coal fired power plant with a conversion efficiency of 36%, i.e. the average thermal efficiency (LHV) for pulverised coal power plants in OECD countries (Adams *et al.*, 1996). Information of the heat content of nuclear fuel (3.5% U-235) differ between 8.8 x 10^5 kWh/kg (AB Svensk Energiförsörjning, 1998) and 9.9 x 10^5 kWh/kg (Hore-Lacy & Hubery, 1999). The electricity conversion efficiency in nuclear power plants invariably amounts to 33%, which means that 1 kg of uranium fuel produces at least 2.93 x 10^5 kWh$_{el}$. Gas diffusion enrichment use between 3-4% of the generated electricity, i.e. less than 0.12 kWh$_{el}$. With the given efficiency for coal-fired power plants and the average carbon dioxide emission for coal that was presented above, uranium fuel enrichment according these assumptions gives rise to 35 g CO_2/kWh$_{el}$ at most. Emissions during other steps in the nuclear fuel cycle are considerably less as seen in Table 9.6.

Table 9.6 Specific emissions of carbon dioxide from the different steps in the nuclear fuel cycle based on life cycle analysis of nuclear power in Sweden (Tunbrant et al., 1996). Life span is 25 years.

Fuel sub-cycle	**g CO_2/kWh$_{el}$**
Mining	0.0082
Refinement	0.845
Chemical conversion	0.017
Enrichment	1.41
Fuel manufacturing	0.017
Handling of spent fuel	0.17
Sub-Total	*2.5*
Power plant construction and dismantling	0.433
Power plant operation and maintenance	0.072
Underground storage of radioactive waste	0.07
Total	*2.98*

Since other specific emissions than enrichment can be expected to remain roughly the same in different countries, it is unlikely that emission of greenhouse gas from nuclear power will exceed 35 g CO_2-equiv./ kWh$_{el}$. This puts this technology in the same category as strictly renewable energy in this respect. From the above discussion it should also be clear that variations in specific emissions between different life cycle analyses for technologies where releases of air pollutants are mainly coupled to construction, operation and dismantling, are largely dependent on the local power mix. Total emissions of CO_2, NOx and SO_2 as given in a number of other LCA studies of nuclear power are presented in Table 9.7.

Table 9.7 Summary of some exhaust emissions in the life cycle of nuclear power plants (g/kWh$_{el}$).

CO_2	**NO_x**	**SO_2**	**Source**	**Note**
2.8-3	0.017	0.013-0.015	Tunbrant *et al.*, 1996	(1)
10-26	n.c.	n.c.	Kivistö, 1995	(2)
12			Dones *et al.*, 1996	(3)
8-21			IEA (Japan)	

n.c. – not calculated

(1) The lower values refer to 40 yrs life expectancy; the higher ones to 25 yrs.

(2) The lower value refers to centrifuge enrichment; the higher one to gaseous diffusion. Life span is 25 yrs.

Hydroelectric power

The few life cycle analyses that have so far been carried out on hydroelectric power, have clearly demonstrated the difficulties to establish generalities regarding this particular technology. Hydropower has brought prosperity to large regions and to millions of people, but in some cases it has also brought severe negative impacts to local human settlements (McCully, 1996). Hydropower can also have positive or negative effects on fluvial morphology and resulting ecosystem processes, including flow of material and matter (Chambers, 1991). Because of the very wide diversity of hydropower projects, there is also a very wide diversity of social and environmental impacts, and summing all the negative effects to obtain a general characteristic of hydropower would create a completely false image. Individual hydropower projects might have none of these drawbacks, or only one or two which are often offset by mitigation measures. There is no inventory of the positive and negative environmental and social effects of all hydro projects throughout the world. Many of the case studies focus on the controversial projects, and are not representative of the total of all projects.

In recent years attention has been paid to emission of greenhouse gas, i.e. methane from hydroelectric reservoirs. The potential role of reservoirs in this respect was thoroughly discussed in Chapter 6. Two important conclusions can be drawn from this discussion and available life cycle inventories, namely that hydropower plants with specific emissions exceeding 10% of power plants fired with natural gas are probably exceptional cases. Moreover, hydropower is the only electricity generating option that has the capacity to bring about a net sequestration of carbon (cf. the Aswan High Dam that was mentioned in Chapter 6). Although this particular example may be exceptional in the other direction, it points to the fact that it is erroneous to generalise from a few extreme cases to hydropower in general. As mentioned above, it is unlikely that more than the few exceptional cases of hydropower projects (large shallow tropical reservoirs with low generating capacity) exceed more than 10 % of the specific greenhouse gas emissions of natural gas power plants. A more precise estimate would require more fundamental research into emissions from different types of reservoirs, and an accurate inventory of the different types of reservoirs throughout the world. Reliable calculations of specific greenhouse gas emissions from hydropower would also have to consider ecological processes of entire watersheds, i.e. from the inflow to the reservoir to the estuary.

Regarding other emissions and use of resources it is clear that there are environmentally relatively benign hydropower projects as well as those with too high costs in terms of impact on human society and the natural environment. A good decision making process is required to avoid construction of projects in the last mentioned category, while still approving the projects which are a net benefit to society. Decisions should be made on a project-by-project basis, and there is a limitation to the extent one can use specific impacts, i.e. overall impacts divided by the total service provided, as relevant characteristics of an entire energy option such as hydropower. The need to consider each project on its own merits is particularly important when it comes to such social issues as resettlement. Resettling one family of six persons for a 0.1 MW project is not the same as resettling one million persons for a

18,0000 MW project, even if the number of persons resettled per MW is the same. However, project specific factors always make each case unique. For the large project, it may very well be that half a million lives were lost due to floods during the past Century, and the saving of lives in the future is a stronger motivation for resettling a large number of persons than the production of hydroelectricity. With these reservations in mind, one can conclude that there is often an inverse relationship between the size of a project and the specific resource use, i.e. larger projects tend to have lower specific resources uses than smaller projects. This inverse relationship tends to be particularly strong for hydro (cf. Figures 9.1 – 9.5).

Life cycle analyses provide data on resource use or impact per unit of service generated. When electricity production is dealt with in this way, the service is simply expressed as amount of electricity, regardless of when the electricity is available and needed. Since electricity must be produced and consumed at the same time, a high degree of flexibility of a particular energy option provides an extra bonus compared to an unreliable alternative. The dichotomy of firm and non-firm electricity is not easily considered in the numerical output from life cycle analyses. This fact is particularly obvious when comparing systems that use wind and hydro, respectively.

Wind power

Wind power does not constitute a stand-alone option for power generation. On the contrary, a proper use of this resource is only possible in a system setting where complementary means of producing electricity is at hand. The reason for this is that wind is an unreliable resource that is not always available when needed. For example, the average capacity factor for such power plants in Sweden was 24.3% in 1998 (Szadkowski, 1999), as compared to 48% for hydroelectric power in 1997 in this country (Swedish Bureau of Statistics, 1999). In effect, the difference between these two options is even bigger, because the hydropower assets are used to generate peaking power, which means that water is retained above the dams until needed. Before deregulation of the Swedish electricity market, the price of water used for this purpose was coupled to the price of oil, since oil fired gas turbines constituted the only alternative means of producing peaking power. Wind has no price, which means that aeolian power stations should run as much as possible. Since the availability of Swedish windmills on average is close to 100%, therefore, the average low capacity factor of wind power truly reflects the reliability of such power plants.

The results from a simulation done in the Province of Québec, Canada, further reflect this fundamental difference between wind power and hydroelectric power. An increase of 11% in the demand for electricity (0.31 TWh or 60 MW of installed capacity when covered by increased production of hydroelectricity) would require the installation of 82 MW of wind (single wind farm) or 102 MW (seven dispersed wind farms), but would only "save" the equivalent of 2 and 34 MW, respectively, of back-up hydropower (Gagnon & Belanger, 1998). Since existing power supply systems are almost invariably designed to satisfy variations in the demand for electricity, there is usually enough capacity to "absorb" a considerable amount of wind power. Thus, simulations of the supply of large amounts (up to 7.5 TWh) of wind power to the

Swedish electricity grid, which also has a large share of hydroelectricity, demonstrate that the overall efficiency of the system is declining only marginally (Söder, 1994).

The most important feature of wind power is that it saves fuel (water, oil or natural gas) but it frequently also add to the capacity of the system (Tande & Vogstad, 1999). However, in terms of environmental impact wind power should share the environmental burden of complementary means of producing electricity, a fact that has special significance for the allocation process in life cycle assessments and is yet to be resolved.

Another feature of wind power, which makes it a challenge in life cycle analyses is its intrusion on other land use. While the net habitat losses (access roads; foundations - which generally consist of concrete slabs; cable ditches, or poles for the transmission lines) are small, restrictions with respect to afforestation, building etc. must be imposed in order to avoid energy losses or disturbance to settlers from noise. This means that wind power is mainly placed on cereal fields, open meadows, strips of open coast etc. According to a Swedish LCA on wind power (Dethlefsen & Tunbrant, 1996) an area with a radius of 300 m around the power plant is set aside for protective purpose. This corresponds to a specific land use of 0.01-0.015 m^2/kWh. Similar figures are indicated in the guidelines formulated by the New Zealand's Energy Efficiency and Conservation Authority (1995). A comparison between renewable energy sources in this respect is summarised in Table 9.8. There is actually no lower limit but definitely upper limits for these technologies. Wind and hydro display extreme variations. Figures for these two options are calculated based on some Swedish power plants and are displayed solely for reference purpose. Pimentel *et al.* (1994) estimate that the area based production of electricity amounts to about 1 and 8 kWh$_{el}$/m^2 for wind and hydro, respectively.

Table 9.8 Electricity generation per unit area reclaimed for different renewable energy options.

Energy source	**Energy density (kWh$_{(heat)}$/m^2)**	**Electricity output (kWh$_{el}$/m^2)**
Sun	600-1100	--
Biomass	5-25	2
Photovoltaic panel	--	260-480
Wind	--	11 (1)
Hydro	--	15 (2)

(1) 600 MW; capacity factor 0.33; rotor diameter 43 m.
(2) Lule River (several reservoirs, river impoundments and power plants in a cascade).

Conclusion

This study has only considered the direct effects of the various types of power generation, and has not discussed the far-reaching impact on human welfare of climate change resulting from the emission of greenhouse gases. This impact, according to several calculations (e.g. Titus *et al*., 1991) seems to be the most serious one and is primarily induced by the use of fossil fuel. As an illustration, hydropower generated 2,643 TWh of electricity , worldwide, in 1998 (International Energy Agency, 1998). To produce this same amount of electricity by coal generation would have required 1,586 million tons of coal, equivalent to one unit train of 100 coal wagons every 3 minutes for 24 hours per day, 365 days per year. Greenhouse gases and climate change have the capacity to influence all parts of the world including enforcing shifts in natural resources use, increasing prevalence of diseases, and reducing regional biodiversity to mention but a few of the predicted future outcomes. These scenarios have as yet only marginally influenced the practitioners' and the public's attitude to fossil fuelled power that is still expanding at a rate higher than that of other options (International Energy Agency, 1998).

It may be concluded that life cycle analysis and other similar methods for comparing generation options should be expanded to also analyse the actual effects of the release of a given amount of a particular pollutant. For example, they should not stop at calculating the amount of greenhouse gases per kWh of electricity produced, but should be expanded to determine the effect these greenhouse gases have on climate change, human well-being, and the environment. In the absence of such an expanded analysis, and since the emissions of greenhouse gases, acids, and nutrients are invisible to the public, there will always be a tendency to favour alternatives that cause the least impact on the local environment immediately surrounding the power plant, and the overall consequences for the country or the world as a whole will be ignored.

Hydropower (and also wind power) may have relatively stronger impacts on the visual amenity and local environment surrounding the plant site than do other forms of generation, and an LCA analysis quantifies many of these local environmental effects. However, the full advantages of these forms of renewable energy are not brought out by the traditional LCA approach. In reaching decisions about which form of generation is most appropriate in specific situations, both the full advantages and the known disadvantages, should, of course, be taken into account.

Table 9.9 Overview of impacts from different electricity production options except resource use and emission of pollutants.

Impact category	Coal	Oil	Gas	Bio- mass	Nuc- lear	Hydro	Geo- therm.	Solar	Wind
Impact on biodiversity	???	???	??	???	?	???	?	?	??
Accidents	??	?	?	?	??	??	??	?	?
Impact on humans									
Health risks	???	??	??	??	?	??	?	?	?
Social and socio-economic impact	??	?	?	?	?	???	?	?	?
Risk perception	??	??	??	??	???	??	?	?	?
Aesthetic impact	???	??	??	??	?	???	?	??	???

? = no or negligible impact
?? = substantial impact
??? = impact crucial to option

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In addition to these reports, Dr. Uchiyama has provided unpublished data based on life cycle inventories of energy technologies in Japan.

APPENDIX 1

RISK PERCEPTION OF ELECTRICITY GENERATION OPTIONS

The methodology for studying risk perception is described in Chapter 1.

Accuracy

Methodological

The use of verbal terms to represent technologies in the risk perception studies and the use of brief descriptions for obtaining impressions and evaluations of societal decision approaches suffer possible methodological limitations. Responses to these brief verbal terms or descriptions may not be representative of reactions that occur in the flow of everyday life. Nevertheless, making the sets of hazards more specific (e.g., partitioning nuclear power into radioactive waste transport, uranium mining, and nuclear reactor accidents) has had little effect on the factor structure or its relationship to perceived risk probabilities (Buss *et al.,* 1986; Slovic *et al.,* 1985).

Geographical

Exposure to risk varies from country to country, depending on economic conditions, technological infrastructure, public health priorities, and natural hazards, among other things. Perceptions of risk are also likely to vary from one country to another, depending on what people choose to discuss, what the news media choose to report, what cultural norms are viewed as important, and what technical and political opportunities exist for the control of risk (Haddad & Dones, 1991). One study (Hoefer & Raju, 1989) indicates that American citizens generally perceive more risk than French citizens do, especially with respect to nuclear power generation. Another study (Englander *et al.*, 1986) shows that Americans also generally perceive more risk than Hungarians do. Hungarians tended to rank common, everyday risks higher than Americans do; who were more concerned about newer risks from chemicals and radiation. Thus, Hungarians also tended to rank most electricity options worse but the nuclear option better than the Americans do. Nevertheless, the Hungarian factor structure did not radically differ from the American one and the location of electricity options in the two-dimensional factor space also did not differ very greatly. In summary, it can be said that the factor space has been quite robust over different investigations and subjects.

Social

The factor space only shows the average risk perception of the studied groups (U.S. college students or a cross section of the Austrian population). Of course, there are big differences in individual risk perceptions. It has been shown that knowledge, personality, political orientation, cultural biases, hierarchy, individualism, and egalitarianism influence risk perception. It has also been suggested that risk perception is a social process: Individuals choose what to fear to support their preferred way of life. Women seem to generally perceive more risk than the men (Hoefer & Raju, 1989, Dake & Wildavsky, 1989) do.

Temporal

Risk perception will vary with time and available information. How these variables could have influenced risk perceptions since the studies have been performed and how they might do so in the future is discussed for each option separately. As the studies used here are already rather old (1977-1979) and much scientific research on impacts of technology has been done recently, it is well possible that perceptions of risks have changed substantially since. Newer data would be welcome and may present a better picture of current public risk perceptions.

Coal

In the psychometric paradigm study carried out in 1979 by Slovic *et al.* referred in Chapter 1, fossil electric power options rate lowest on the ‘unknown risk’ factor. Concerning dread, only nuclear power is perceived (far) worse, but fossil power is still in the vicinity of hydropower. Much research that may have changed this rating has been done since:

- Public discussion about acidification and its effects has only started on a broad scale as late as 1980 when the first international scientific conference on acid rain took place in Norway. (The topic was introduced to the world community at the UN environmental conference in Stockholm 1972).
- Research on global warming has lead to scenarios with large potential catastrophes and has also revealed much uncertainty about consequences.
- Much research has been done on carcinogenic substances (e.g., arising from combustion processes) in recent years.
- Newer research has shown that human health impact pathways (e.g., of photochemical smog, acidification, carcinogenic substances) are often not known well and can hardly be quantified.

Such ‘new’ impacts on human health are diffuse, not easily observed, involuntary, partly global, partly potentially catastrophic, partly delayed in their effects, and mostly impossible to protect oneself from. These are characteristics that greatly influence risk perception. This will have led to a higher score on the ‘dread’ as well as the ‘unknown risk’ factor in the meantime. On the other hand, some very substantial improvements have taken place in the meantime, which might also have influenced risk perceptions:

- New technologies enable cutting many emissions substantially.
- Occupational health conditions have been greatly improved in many coalmines (Roberts & Ball, 1995).

Future advances in scientific knowledge may lead to the following developments:

Even though scientific insight in the possible health effects of coal power has and will increase, it is not likely that the ‘unknown risk’ factor score will decrease soon. On the contrary, scientific research continually uncovers recently unknown possibilities of risks of coal power (e.g., health threats from dust from open cast coal mines - Edwards, 1997) that have to be examined and understood yet. This might well lead to a further increase in the ‘unknown risk’ factor score. With such new insights and better hints at possible effects of global or regional problems like global warming or acidification, the ‘dread’ factor is almost certainly bound to increase too. This development is probable in spite of technological development e.g., because it will not be possible to cut carbon dioxide emissions, one of the main concerns of combustion plants, in the near future.

Oil

In principle, for oil power the same considerations as for coal power are valid, as they are very similar technologies, both being based on combustion of fossil fuels. Still, there are some notable differences important for risk perception:

- Oil power is considered to be a ‘cleaner’ technology than coal power, due to its higher energy density, which causes less total emissions.
- Transport of oil is connected with higher and especially more potentially catastrophic risks than transport of coal (oil tanker catastrophes).
- Oil power may be more familiar as everybody’s car runs on the same type of fuel.

Taking these considerations into account, risks of oil power will be perceived very similarly as those of coal power, but both the ‘dread’ factor and the ‘unknown risk’ factor may score a little bit lower. For future developments the same considerations as for coal power are valid.

Natural Gas

Natural gas is considered to be the ‘cleanest’ of the fossil fuels. Its total emissions are in fact considerably smaller than those of the other fossil fuel technologies are. On the other hand it is the newest fossil fuel power technology and as such the most unfamiliar one. It might also give rise to fears about explosion accidents. This leads to the conclusion that its risks will be perceived more or less equally as those of oil power.

Future developments may lead to a greater familiarity with the use of natural gas to produce electricity and to fewer concerns about explosions - that is, if none occur. The perception of health risks from natural gas will thus probably be more favourable than for the other two fossil fuel options, but will still stay in their vicinity.

Nuclear

Nuclear power is the most controversial electricity technology. While some people perceive nuclear power as beneficial and connected only with low risks, others think that it is utterly unacceptable. This polarisation has led to conflicts and demonstrations where the opposing parties speak a wholly different language.

Questionnaire studies of people opposed to nuclear power show that they judge its benefits as being quite low and its risks as being unacceptably great. Some have attributed this reaction to fear of radiation's invisible and irreversible contamination, threatening cancer and genetic damage. However, use of diagnostic x-rays, a technology that incurs similar risks, is not similarly dreaded. Others have attributed the negative attitude towards nuclear power to the association with nuclear weaponry (Slovic *et al.,* 1985). But this cannot be the sole reason for what is often seen as public irrationality either, because other technologies that have been developed and used for military purposes are undisputed in their commercial use. In fact, many aspects contribute to a public attitude that is not as irrational as it seems and may be well founded. Some of these aspects shall be discussed here.

Unsolved technical problems

The problem of disposal of high-level and medium-level radioactive waste has not been solved to date; at least not in the sense that final depositories for spent fuel are established. As this waste remains a potential hazard for thousands of years, very reliable solutions are called for. Opposition against disposal programmes is always very big. A study in the USA has assessed the main technical criticism of the opponents of such sites (Kraft, 1989).

Table 1 Technical criticism of nuclear waste siting in percentage of total number of people making criticism (Kraft, 1989).

waste technology is unproven	32
limited scientific knowledge understanding geology	28
analysis of transportation problem incomplete	28
site characterisation involves many technical uncertainties	25
level of risk unacceptable	22
inadequate planning	17
isolation of radioactive material from biosphere cannot be guaranteed	13
need to explore alternative technologies (breeder reactors, solar power)	6
waste repository should be located where wastes are produced	4

Unclear benefit assessments

There are two disputed benefit issues. First, it is not sufficient to show that a hazardous process benefits society as a whole. The people most at risk want to be sure that the benefit to them outweighs the hazard. Here the difference to medical radiation, where personal benefits usually far outweigh the risks, becomes apparent. In nuclear power, the society as a whole benefits from the produced energy, while the people living near a power plant, who shoulder most of the risks, get only a small proportion of the benefit. Second, there is a genuine debate over whether nuclear energy does provide society with a net benefit, especially as its economic costs can be considerably high, partly due to extensive safety measures and the unsolved problem of highly radioactive nuclear waste disposal (United Nations Scientific Committee on the Effects of Atomic Radiation, 1991). There are many examples of nuclear power plans that have been abandoned.

Terrorism potential

There are mainly two items of concern. First, a nuclear power plant could be sabotaged or destroyed by a terrorist or enemy assault, leading to a catastrophe. Second, plutonium or other radioactive material could be stolen from a power plant and be used to make nuclear weapons or as a poison.

Democracy issue

There are several reasons why a nuclear power plant may be considered as an anti-democratic installation:

- The sites of nuclear power plants are often determined outside democratic decision pathways. People feel they are forced into living with a nuclear power plant nearby without having any rights to do anything against it.
- The possibility of sabotage or theft calls for massive security measures in and around a nuclear power plant, which gives rise to fears about one's country turning into a police state.
- Laws in several countries guarantee special juridical status of nuclear installations (e.g., in the USA the Price-Anderson Act limits nuclear liability).

Imprecision of risk assessments

The assessment of effects from radiation exposure is imprecise. Models that should predict effects are mainly based on animal experiments, which can only serve as indices, not as proof. Especially the effects of long-term low-level radiation can only be tested insufficiently on animals. Recent research on late damage of radiation has accentuated these problems.

Inappropriate measurement of harm in risk assessments

Risk assessments normally only try to quantify excess mortality in number or financial terms. Measurements of the cost of disability or disease are neglected or only very crude. At best, they attempt some rough assessment of life impairment from gross injury. Impact of lesser damage to the quality of life as well as human distress and frustration are not taken account of (United Nations Scientific Committee on the Effects of Atomic Radiation, 1991). At worst, it is stated that disease and injury are proportional to the expected number of premature deaths without statistically proving this.

Catastrophic potential

Catastrophes, however infrequent they may be, are feared more than small dangers, however common those may be. Clearly, other forms of energy production have quite big catastrophic potentials too, mostly even with higher probabilities of actually occurring, but no such catastrophes equal the ones that can be imagined arising from nuclear power (United Nations Scientific Committee on the Effects of Atomic Radiation, 1991). Nuclear weaponry has undoubtedly played its role in the production of these fears. The core meltdown at the nuclear power plant in Chernobyl 1987 with its vast consequences has magnified these fears, especially in Europe.

Involuntariness and lack of personal controllability

There is a substantial difference between voluntary and involuntary risks. Some people gladly embrace especially high risks for fun. Both smoking and driving involve taking voluntary risks, which is one reason why many people find them acceptable. But while the freedom to risk one's life and health seems to be a necessary part of liberty, the freedom to impose such risks on others is not. The public is acutely aware of this and consistently takes a harsher view of imposed and involuntary risks. When people feel impotent in the face of such a risk, i.e. when they have no control over it or no means of protecting themselves actively from it, they are even less tolerant. Radiation from the nuclear fuel cycle is seen as embodying all these undesirable characteristics (United Nations Scientific Committee on the Effects of Atomic Radiation, 1991).

Moral and ethical questions

Radioactive wastes remain dangerous long into the future, well over time spans for which the safety of waste deposits can be guaranteed. People doubt whether it is right to bequeath these hazards to subsequent generations that will have no benefits from their production (United Nations Scientific Committee on the Effects of Atomic Radiation, 1991).

Availability

Discussion and media coverage on the risks of nuclear power may have magnified public fears to a further extent than for other power options. But the influence is in both directions: Public opinions and interests influence what is published, while the media contributes to public discussion. There is a second aspect of availability, namely the ability to measure even extremely low levels of radiation. This might lead to a certain exaggeration of actual radioactive emissions.

Advantages

According to some, nuclear power is perceived to be the best electricity option. Their arguments are maybe more pragmatic than opponents' arguments:

- Nuclear power does not give rise to substantial amounts of greenhouse gases.

- There are no direct flue gas emissions from nuclear power (that could lead to environmental or human health problems).
- Nuclear power is presently the only large-scale power option that is not site-specific with the two above advantages and is thus thought to be a good technical solution to solve environmental problems without changing our way of life.
- Safety standards are very high and accident probabilities are extremely low.

Conclusion

All these aspects contribute to the perception of risks from nuclear power production. In a psychometric paradigm study carried out in the USA in 1979 nuclear power rates highest on the dread risk factor and very high on the unknown risk factor. Even if the occupational and public mortality and morbidity risks may be lower than those of other power options (see impact categories ‘accidents’ and ‘health risks’), this leads to the fact that nuclear power is the most controversial and criticised electricity option, and is, by a part of the public, perceived to be the worst solution to meet electricity demands.

Present and future developments

Information about low risk probabilities and high safety standards and familiarisation with nuclear power may have reduced the ‘unknown risk’ factor score, but the catastrophe at Chernobyl 1986 may have increased the dread perception of nuclear power since the risk perception studies used here were carried out. On the other hand, accentuation of risks of fossil fuel power has turned the focus away from nuclear power somewhat, which may have led to less radical opposition against nuclear power. Furthermore, in Western Europe and North America few plans exist to extend nuclear power broadly, greatly due to earlier opposition and economical problems, so that few controversies about new plants can be expected there. Nevertheless, most of the above mentioned problems will stay acute, so that broad acceptance of nuclear power cannot be expected in the near future.

Biomass fuel

Biofuel power is based on a combustion process and principally uses the same technology as other combustion power plants. Thus, risks arising from the use of biofuel will probably be perceived similarly to those of gas or oil power.

Still, several reasons might presently lead laypersons to perceive risks of biofuel plants lower than those of fossil fuel plants might. First, biofuel is, if managed accordingly, a renewable energy source that does not contribute grossly to global warming. Second, if biofuel is used renewably, power plants are apt to be much smaller than fossil fuel plants because fuel availability is limited.

Hydro

Apart from nuclear power, hydropower is the electricity technology that has started the most intense controversies in the most recent years. Most large dams are severely opposed. There are many reasons for this, only some of which are directly connected with risks to human health although risk arguments are frequently put forth in the debate. Most opposition arises either because of anticipated social and socio-economic impacts (e.g., resettlement, loss of land, fishing restraints, water supply) or because of nature conservation issues in a broad sense. While existing hydropower in developed countries is generally accepted opposition against new hydropower in developing countries is particularly strong. Unfortunately, opposers to hydropower have put very few suggestions regarding development of alternative energy options and analyses of the potential role of hydropower for improving the economy in such countries forth.

Even though resettlement, land loss, fishing restraints etc. can indirectly lead to severe health consequences and connected perceptions, they will not be further handled here as they are included in the impact categories 'economics, 'land', and 'social and socio-economic impact.' The most important direct health risks from hydropower are induced seismicity, dam breaks, emergency flooding, and increase of water-borne diseases (in tropical and sub-tropical countries). They are very local and so the risk perception will vary extremely from region to region.

In the psychometric paradigm study carried out among U.S. college students, hydropower scored rather low on the 'dread' factor, and high on the 'unknown risk' factor. The 'unknown risk' factor score may be explained by the unpredictability of causes of catastrophes (e.g., extreme weather situations). The 'dread' factor will probably vary extremely from region to region. People that do not live in a region threatened by a dam break or influenced by water regulation will not see great dread connected with hydropower, even more so as it does not directly give rise to any emissions during operation (that could pose regional or global hazards). People living in flood prone areas will perceive the risks much differently. On average, dams are considered to be quite safe, but if the view of the potentially affected people is taken as an indicator, hydropower is probably considered one of the riskier electricity technologies.

Risk perception of dams will in the future not change greatly as it is an old technology that will not undergo substantial technical advancement. Large dams will always be confronted with resolute opposition and strongly negative attitudes, while small plants and run-of-river schemes, if appropriately planned, be considered much less risky and therefore also much more favourably.

Geothermal

Geothermal power is a relatively unknown technology. By some laypersons it might be connected with earthquakes or volcanic activities. Most people, once familiar with it, would probably judge it to be a relatively safe technology without major catastrophic potential or unknown risks. It can be concluded that people unfamiliar with the technology will rate geothermal power high on the 'unknown risk' factor and rather low on the ‘dread’ factor. With increased familiarity the ‘unknown risk’ score will probably drop significantly.

Wind

Wind power is a new electricity technology with old roots: windmills. Basing on simple mechanical principles, it is a technology that is easy to understand by laypersons. It is a renewable technology without any direct emissions from operation and without any catastrophic potential. These aspects make wind power a technology without dreaded or unknown risks. Thus, human health risks of wind power are perceived to be low. On land, this perceptions is not bound to change in the future, but if big wind power farms are installed at sea, these might pose new risks, e.g. on navigation.

Solar

Solar power is a renewable energy technology without any direct emissions from operation and without any catastrophic potential. Thus, potential hazards of solar power are not dreaded and the risks to human health are considered to be low. Nevertheless, it is a fairly new technology still very much in development, and it is often connected with high energy costs and the use of toxic chemicals in production, which makes laypersons characterise risks of solar power as unknown.

At least two developments might lead to a decrease in the ‘unknown risk’ factor score: First, development of new solar power technologies without toxic chemicals might change public perceptions. Second, wider use of solar power might make people more accustomed to the technology. On the other hand, incidents (e.g., fires etc.) leading to release of toxic substances would probably alter public perception in a more unfavourable direction.

Comparisons

Comparisons using the psychometric paradigm approach

Figure 1 from a study carried out among U.S. college students in 1979 shows the location of the risks of some electricity options as well as some other risks in the factor space.

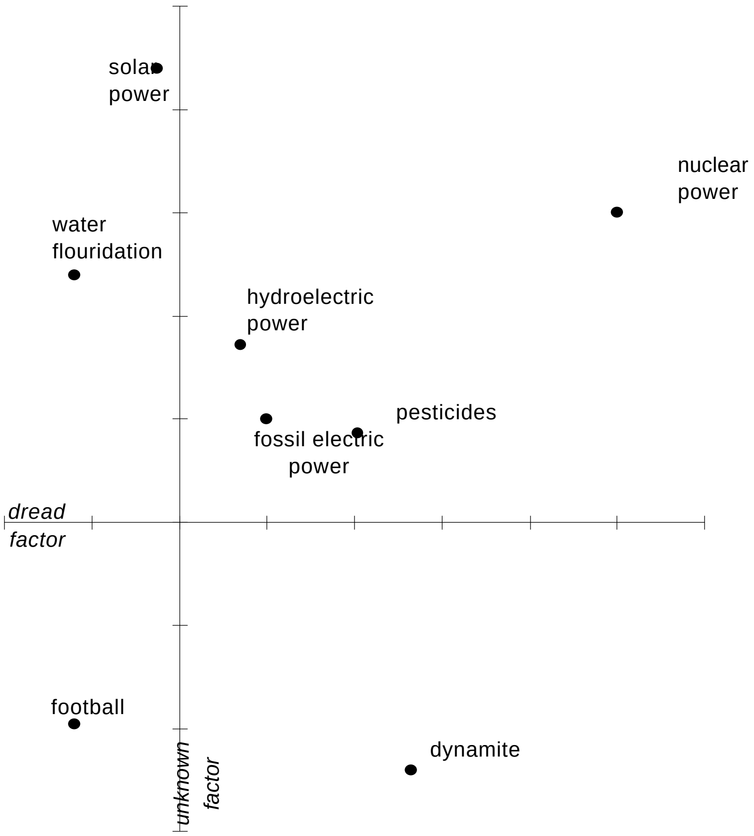


Figure 1 Location of risks in the 2-dimensional factor space, obtained in a study with U.S. college students 1979, n=175. The dread factor is projected on the x-axis (dread increasing towards the right) and the unknown risk factor on the y-axis (unknown risk increasing upwards) (adopted from (Slovic et al., 1985).

There might have been some changes since the study was carried as indicated in the descriptions of each technology above. In summary, the following trends for the included options and locations for the omitted options are probable (Table 2).

Table 2 Anticipated change in the risk perception of different energy production options as evidenced in the public debate in recent years.

Option	**'Dread' factor development**	**'Unknown' risk factor development**	**Comments**
Coal	increase	slight increase	compared to fossil power
Oil	increase	slight increase	slightly lower than coal on both factors
Natural gas			may rate like oil power on both factors
Nuclear	steady	slight decrease	
Biofuel			may rate lower in 'dread' and same in 'unknown' as oil
Hydro	steady	steady	'dread' may be perceived higher by people if the frequency of flood catastrophes continue to increase
Geothermal			'dread' close to fossil, 'unknown' like solar but may drop quickly
Wind			'dread' close to solar, 'unknown' lowest of all
Solar	steady	decrease	

As an exact quantification is impossible in the face of lack of recent data for this review, in combination with accuracy problems, the semiquantitative approach below (Table 3) is adopted. It attributes one of three possible orders of magnitude to each relevant factor of risk perception. Mortality risk orders of magnitude are taken from the categories 'health risks' and 'accidents'.

Table 3 Summary of current state of risk perception. 0 - low score (not dreaded; known risk; low mortality risk); + - medium score (modestly dread; modestly unknown; medium mortality risk); ++ - high score (very dreaded; very unknown; high mortality risk).

Option	**Dread factor**	**Unknown risk**	**Mortality risk**
Coal	+	+	++
Oil	+	+	+
Natural gas	+	+	+
Nuclear	++	++	0
Biofuel	+	+	+
Hydro	+	+	++
Solar	0	++	0
Wind	0	0	0
Geothermal	+	++	0

Comparisons using the risk-benefit perception approach

A survey carried out in Austria in 1978 and 1979 revealed general attitudes towards different energy options (see Figure 2). The distributions were virtually the same for the fossil fuels coal and oil, as well as for the solar and hydro options.

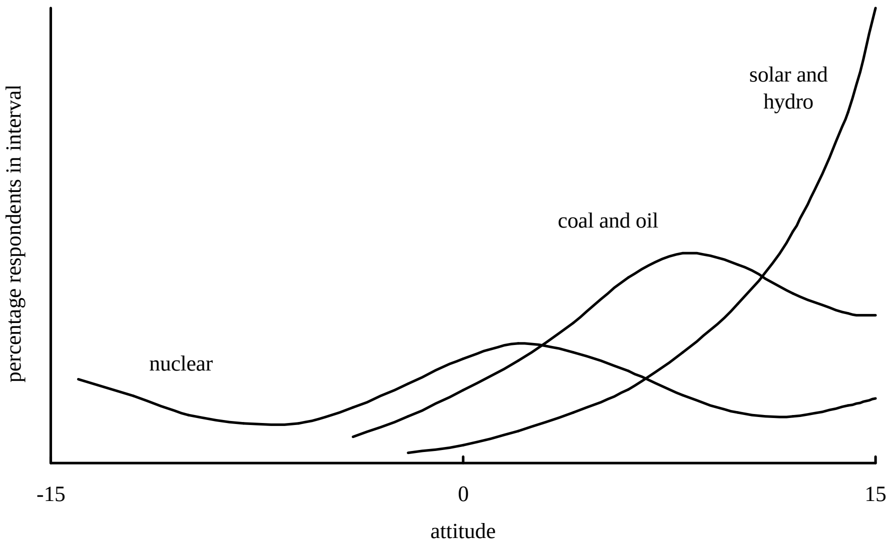
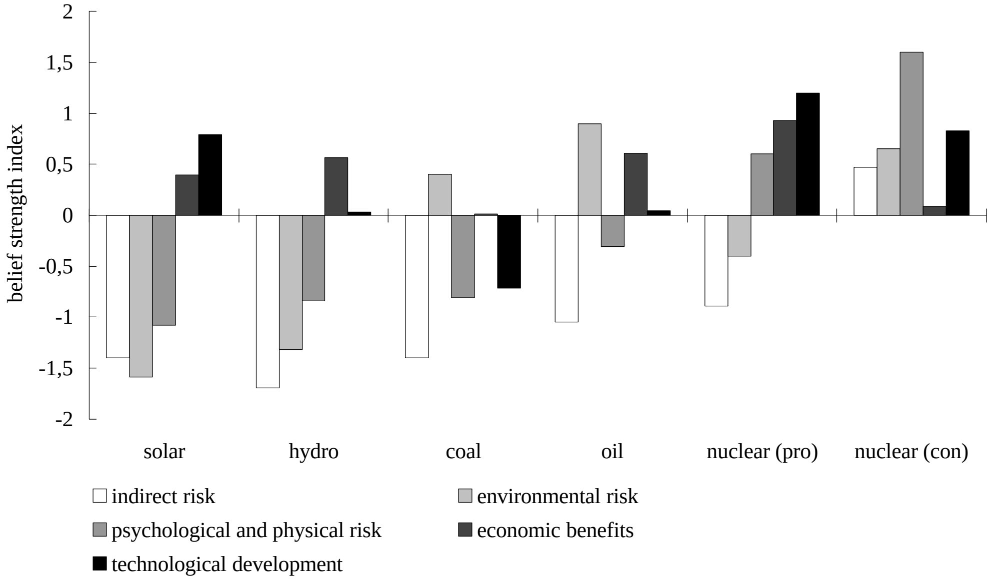


Figure 2 Smoothed frequency distribution of attitudes towards energy systems. Sample of Austrian public 1978; n = 211 (Thomas, 1981).

For fossil fuels most respondents were moderately favourable, while there were few very negative or highly positive attitudes. The attitude towards solar power and hydropower was most frequently very favourable with virtually no negative attitudes. There was only a polarisation for nuclear power. Still attitudes were most frequently near the middle of the scale but there were clusters of highly positive as well as highly negative attitudes. This distribution will be taken account of in the following assessment of five risk and benefit belief dimensions. Today, the picture might look slightly different. Recent accentuation of hazards from fossil fuels (e.g., global warming and acidification) will in the meantime have probably lead to a lower average attitude and there would probably be some very negative attitudes too, leading to a slight polarisation. Attitudes towards nuclear, solar and hydropower will probably not have changed substantially.

Studies have shown that such attitudes are mainly formed by risk and benefit perceptions (DeLuca *et al.*, 1986). The risk and benefit approach of the study carried out in Austria only considers the responses of those respondents whose attitudes for nuclear power were either very favourable or very negative, a group of 48 and 47 people respectively. Their beliefs about the other energy options, solar, hydro, coal and oil were surprisingly similar and were aggregated in Figure 3 to give a picture that is thought to be representative for the general population. Beliefs about nuclear power differed substantially, as was to be expected, and are shown separately for each group. It should be noted that the belief dimensions ‘psychological and physical risk’ and ‘indirect risk’ are made up of similar characteristics as ‘unknown risk’ and ‘dread risk’ factors in the psychometric paradigm study.

Figure 3 Beliefs about five energy systems. Subgroups of Austrian public sample 1978. Pro nuclear group n=48; con nuclear group n=47 (Thomas, 1981).



The results correlate well with the attitudes towards the energy systems, i.e. risk beliefs correlate with negative attitudes and benefit beliefs correlate with positive attitudes. The two groups judged indirect risk, environmental risk and economic benefits of nuclear power quite opposite, while both groups judged psychological and physical risks as well as technological development of nuclear power high. Interestingly, nuclear energy is the only option that is connected with indirect risk (by the con group) and psychological and physical risks (by both groups), which together contain similar characteristics as the dread risk and unknown risk factors in the psychometric paradigm (Thomas, 1981).

Here again, issues scientifically researched and publicly debated are thought to have influenced these perceptions since they were studied. Especially the environmental impact of coal power would most probably be judged more seriously today because of the climate change debate and the political activities in that field.

Conclusions

The results of the psychometric paradigm study are outstanding, even when considering possible changes in the meantime. Nuclear energy risks are considered very unknown and by far the most dreaded. The group of fossil fuels (coal, oil and natural gas) together with hydro and, possibly, biofuel can be viewed as a second group of electricity technologies, which is only considered to have moderate dreadful risks. The third group, the new renewable technologies solar/photovoltaic power and, possibly, wind and geothermal power do not seem to pose any dreadful hazards, but they are thought not to be known well enough.

The risk-benefit perception study confirms these findings by indicating that renewable technologies, based on perception of low risks and high benefits, are met with a positive attitude. Fossil fuels are considered by more neutral attitudes due to the fact that environmental impacts are perceived as high. Nuclear energy is, by some, considered as unacceptable. It is thus a very controversial option, but it is well possible that the fossil fuel option is now also more controversial than in the past (Table 8.3).

APPENDIX 2

ABBREVIATIONS

AP	Acidification Potential
BCP	Brown Coal Power
BOD	Biological Oxygen Demand
CML	Provisional Ecotoxicity Method
CO_2	Carbon dioxide
COD	Chemical Oxygen Demand
ECA	Ecotoxicological Classification factor for Aquatic systems
ECT	Ecotoxicological Classification factor for Terrestrial systems
ELU	Environmental Load Units
EP	Eutriphication Potential
ETH	Eidgenössische Technische Hochschule (Zürich); Swiss Federal Institute of Technology
GWa	GigaWattYear
GWP	Global Warming Potential
HC	Hydro Carbon
HCP	Hard Coal Power
IEA	International Energy Agency
kBq	kiloBequerel
LCIA	Life Cycle Impact Assessment
m^2a	square meter years
MJ	MegaJoule
MTC	Maximum Tolerable Concentration
N	Nitrogen
NMVOC	Non Methane Volatile Organic Compounds
NO_X	Nitrogen oxide, usually NO and NO_2
O_2	Oxygen
O_3	Ozone
ODP	Ozone Depletion Potential
OECD	Organisation for Economic Cooperation
P	Phosphorus
POCP	Photochemical Ozone Creation Potential

QRA	Qualitative Risk Assessment
RA	Risk Assessment
SO_X	Sulphur oxide, usually SO and SO_2
TJ	TeraJoule
UCPTE	Union pour la coordination de la production et du transport d’électricité
VOC	Volatile Organic Compound

APPENDIX 3

GLOSSARY

Acid Mine Drainage	Drainage of water from areas that have been mined for coal of other mineral ores. The water has a low pH because of its contact with sulphur-bearing material and is harmful to aquatic organisms.
Acid Rain	Rainfall with a pH of less than 7.0. Long-term deposition of these acids is linked to adverse effects on aquatic organisms and plant life in areas with poor neutralising (buffering) capacity.
Acidification	1. A complex chemical and atmospheric phenomenon that occurs when emissions of sulphur and nitrogen compounds and other substances are transformed by chemical processes in the atmosphere, often far from the original sources, and then deposited on earth in either wet or dry form. The wet forms, popularly called "acid rain," can fall as rain, snow, or fog. The dry forms are acidic gases or particulates. 2. The direct impact of emitted acid substances on the environment. Acidification is linked to adverse effects on aquatic ecosystems and terrestrial plant life, especially in areas with poor neutralising (buffering) capacity. Acids can also leach out poisonous trace metals from the rock matrix in the soil, thus causing damage to flora, fauna and humans.
Aerosol	A suspension of liquid or solid particles in a gas.
Airborne Particulates	Total suspended particulate matter found in the atmosphere as solid particles or liquid droplets. Chemical composition of particulates varies widely, depending on location and time of year. Airborne particulates include windblown dust, emissions from industrial processes, smoke from the burning of wood and coal, and motor vehicle or non-road engine exhausts. exhaust of motor vehicles.
Biodiversity (or Biological diversity)	Refers to the variety and abundance of species, their genetic composition, and the natural communities, ecosystem, and landscapes in which they occur.
Biological Oxygen Demand (BOD)	An indirect measure of the concentration of biologically degradable material present in organic wastes. It usually reflects the amount of oxygen consumed in five days by biological processes breaking down organic waste.
Biomass	All of the living material in a given area; often refers to vegetation.
Biotope	An area or habitat of a particular type, defined by the organisms that typically inhabit it, e.g. grassland, woodland etc., or on a smaller scale a microhabitat.
Brown Coal	Lignite and parts of the sub-bituminous coals, with a heat content less than 23.8 MJ/kg on ash-free weight basis, are often referred to as brown coal.

Chemical Oxygen Demand (COD)	A measure of the oxygen required to oxidise all compounds, both organic and inorganic, in water.
Combustion	1. Burning, or rapid oxidation, accompanied by release of energy in the form of heat and light. A basic cause of air pollution. 2. Refers to controlled burning of waste, in which heat chemically alters organic compounds, converting into stable inorganics such as carbon dioxide and water.
Cut-Off	cut-offs define the system boundaries of a Life Cycle Inventory at a specific process chain by stating which processes are not included in the system.
Ecological Impact	The effect that a man-made or natural activity has on living organisms and their non-living (abiotic) environment.
Ecosystem	The interacting system of a biological community and its non-living environmental surroundings.
Ecotoxicity	The virulence of poisons released to the environment.
Emission	Pollution discharged into the atmosphere from man-made facilities.
Erosion	The wearing away of land surface by wind or water, intensified by land-clearing practices related to farming, residential or industrial development, road building, or logging.
Eutrophication	1. A process in which the nutrient levels and productivity within a water body increase, often resulting in depletion of dissolved oxygen. due to higher levels of nutritive compounds such as nitrogen and phosphorus. Algae and other microscopic plant life become super-abundant, thereby "choking" the water body. 2. An increase in nutrient levels in the soil, leading to impacts on flora and fauna.
Fauna	1. A term used to describe the animal species of a specific region or time. 2. All animal life associated with a given habitat, country, area, or period.
Flora	1. A term used to describe the entire plant species of a specified region or time. 2. The sum total of the kinds of plants in an area at one time. All plant life associated with a given habitat, country, area, or period. Bacteria are considered flora.
Flue Gas	The air coming out of a chimney after combustion in the burner it is venting. It can include nitrogen oxides, carbon oxides, water vapour, sulphur oxides, particles and many chemical pollutants.
Global Warming Potential (GWP)	GWPs are weighting factors to assess the effect of greenhouse gases on global warming in terms of CO_2-equivalents. GWPs describe the contribution to radiative forcing, taking into consideration the atmospheric lifetimes and absorption properties of the gases.
Greenhouse Effect	The trapping of a proportion of the heat radiated from the Earth's surface by water vapour, carbon dioxide (CO_2) and other compounds in the lower atmosphere, and its re-radiation back to the surface. If the

	levels of e.g. carbon dioxide in the atmosphere progressively increase as a result of human activity it is thought that this will eventually increase the natural greenhouse effect and result in a rise of temperature in the lower atmosphere leading to wide-spread climate change.
Habitat	The place where a population (e.g., human, animal, plant, micro-organism) lives and its surroundings, both living and non-living.
Hard Coal	Coal with an energy content greater than 23.8 MJ/kg on ash-free dry weight basis.
Heavy Metals	Metallic elements with high atomic weights (specific gravity of 5.0 or higher), e.g., mercury, chromium, cadmium, arsenic, copper, zinc and lead; can damage living things at low concentrations and tend to accumulate in the food chain.
Human Health Risk	The likelihood that a given exposure or series of exposures may have or will damage the health of individuals.
Impact Category	Group of life cycle impacts (e.g. greenhouse effect) that illustrate the connection among certain inventory results (e.g. CO_2, CH_4) and a specific indicator (e.g. global warming potentials) and endpoint (e.g. global warming).
Leachate	Water that collects contaminants as it trickles through wastes, pesticides or fertilisers. Leaching may occur in farming areas, feedlots, and landfills, and may result in hazardous substances entering surface water, ground water, or soil.
Life Cycle Impact Assessment (LCIA)	Examines a system's life cycle inventory results to better identify their possible environmental relevance and significance. Uses numerical indicators for selected environmental issues, called impact categories, to condense and simplify the inventory results.
Limiting Factor	A condition whose absence or excessive concentration, is incompatible with the needs or tolerance of a species or population and which may have a negative influence on their ability to thrive or survive.
Mitigation	Measures taken to reduce adverse impacts on the environment.
Non-Renewables	Resources that are considered not to be renewable, i.e. limited resources (e.g. fossil fuels, metal ores etc.).
Nutrient	Any substance assimilated by living things that promotes growth.
Organic	1. Referring to or derived from living organisms. 2. In chemistry, any compound containing carbon.
Oxidant	A substance containing oxygen that reacts chemically in air to produce a new substance; the primary ingredient of photochemical smog.
Ozone (O_3)	Found in two layers of the atmosphere, the stratosphere and the troposphere. In the stratosphere (the atmospheric layer 11 to 16 km or

	more above the earth's surface) ozone is a natural form of oxygen that provides a protective layer shielding the earth from ultraviolet radiation. In the troposphere (the layer extending up 11 to 16 km from the earth's surface), ozone is a chemical oxidant and major component of photochemical smog. It can seriously impair the respiratory system. Ozone in the troposphere is produced through complex chemical reactions of nitrogen oxides, which are among the primary pollutants emitted by combustion sources; hydrocarbons, released into the atmosphere through the combustion, handling and processing of petroleum products; and sunlight.
Ozone Layer	The protective layer in the atmosphere, about 25 km above the ground, that absorbs some of the sun's ultraviolet rays, thereby reducing the amount of potentially harmful radiation reaching the earth's surface.
Ozone Layer Depletion	Destruction of the stratospheric ozone layer which shields the earth from ultraviolet radiation harmful to life. This destruction of ozone is mainly caused by the breakdown of certain chlorine and/or-bromine containing compounds (chlorofluorocarbons or halons), which break down when they reach the stratosphere and then catalytically destroy ozone molecules.
Ozone Depletion Potential (ODP)	ODPs are weighting factors to assess the destructive effect of gases on ozone layer depletion in terms of CFC-11-equivalents. ODPs are dependent on the atmospheric lifetime of the compounds, the release of reactive chlorine or bromine from the compounds and the corresponding ozone destruction within the stratosphere.
Particulates	1. Fine liquid or solid particles such as dust, smoke, mist, fumes, or smog found in air or emissions. 2. Very small solid particles suspended in water. They vary in size, shape, density, and electrical charge, can be gathered together by coagulation and flocculation.
pH	An expression of the intensity of the basic or acid condition of a liquid. The pH may range from 0 to 14, where 0 is the most acid, 7 is neutral. Natural waters usually have a pH between 6.5 and 8.5.
Photochemical Oxidant	Air pollutants formed by the action of sunlight on oxides of nitrogen and hydrocarbons.
Provisional Ecotoxicity Method (CML)	Method for assessing toxic impact of chemicals to the environment.
Renewables	Resources that are considered to be unlimited or restorable.
Risk Analysis (RA)	RA emerged in the USA to address human health concerns with cancer and has since evolved to include other health and environmental concerns. RA evaluates hazards or effects that may occur from the studied system combined with the likelihood of those effects taking place.

Static Reserve Life	Calculated time span that a non-renewable resource will last based on present known resources and the current use.
Threshold	The lowest dose of a chemical at which a specified measurable effect is observed and below which it is not observed.
Trace Metals	trace metallic elements found in surface waters and sediments.
Volatile Organic Compound (VOC)	Any organic compound that participates in atmospheric photochemical reactions.
Water Table	The level of groundwater.
Weighting Factor	Factor that converts a life cycle inventory result into a common numerical scale within an impact category for aggregation with other inventory results to a total potential impact result.