COMPARISON OF ENERGY SYSTEMS USING LIFE CYCLE ASSESSMENT

A Special Report of the World Energy Council

July 2004

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Published July, 2004 by:
World Energy Council
5th Floor, Regency House
1-4 Warwick Street
London W1B 5LT
United Kingdom

ISBN 0 946121 16 8

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FOREWORD

Issues are sometimes the subject of studies whose results may be different than expected or even contradictory. Such was the case a few years ago with the question of the influence of electromagnetic fields. Following nearly 1,000 studies on the same subject, the contribution of UNIPEDE (International Union of Producers and Distributors of Electrical Energy) was not to add the 1,001st study but to proceed to a review of existing studies. The utility of such a work is undeniable.

A comparable approach was adopted by the World Energy Council (WEC) for life cycle assessment (LCA). WEC decided to include life cycle assessment of various energy production forms in its 2002-2004 Studies Work Programme; the objective was to identify existing LCA studies, review them and prepare a special, easily understood compilation report. The objective of the work was not to compare total costs (including all identified externalities) because LCA has a more limited scope than environmental impact assessment.

The three WEC goals of energy accessibility (related to the direct costs of energy), energy availability (related to the security/reliability dimension) and energy acceptability (environmental externalities) are reviewed, but in general, existing LCA studies only cover a subset of all possible impacts. LCA often refers to the comparison across different energies and uses, but the study also relies on works dedicated to a single energy and brings them into the overall compilation, even though the comparison with other studies may lose some of its relevance.

This special report takes into account the whole energy production chain from exploration and extraction to processing, storage, transport, transformation into secondary fuels and final use. Hence the report considers each primary energy according to its point of origin and its final use. It provides WEC members and the international community with a comparison of the different energies based on the full life cycle assessments that have been performed in the last 10-15 years.

I want to thank the Study Group, especially its chairman, Ami Rastas, and its project leader, Pekka Järvinen, for the very high quality of the work. I would also like to mention the great part played by Risto Lautkaski and Seppo Vuori from VTT (Finland) and to thank Didier Beutier, AREVA (France); Christine Copley of the World Coal Institute (UK); Luc Gagnon, Hydro-Québec (Canada); and Bertrus Postmus, Gastransport Services (Netherlands) for their valuable comments.

At a moment when decision-makers are facing difficult issues regarding climate change, I am sure that this report will prove to be a very timely one.

François Ailleret
Chair, WEC Studies Committee
July 2004

EXECUTIVE SUMMARY

A. OBJECTIVES AND SCOPE

A rapidly growing number of people around the world are becoming concerned about environmental issues, including depletion of natural resources, emissions and pollution, deforestation and soil degradation. The environmental performance of products, services and processes has become one of the key issues in today's world, and it is important to examine ways in which negative effects on the environment are assessed. One of the analytical tools that can be used for this purpose is *life cycle assessment* (LCA). The objective of LCA is to describe and evaluate the overall environmental impacts of a certain action by analysing all stages of the entire process from raw materials supply, production, transport and energy generation to recycling and disposal stages --following actual use, in other words, "from the cradle to the grave".

Final and intermediate results of an LCA will help decision-makers select the product or process that has the least impact on the environment. This information can be used, together with other factors such as cost and performance data, to select a product or process. LCA includes the transfer of environmental impacts from one medium to another (e.g., eliminating air emissions by creating a waste water effluent instead) and/or from one life cycle stage to another (e.g., from use and reuse of the product to the raw material acquisition phase). Without an LCA, the transfer might not be recognised and properly included in the analysis because it is outside the typical scope or focus of product selection processes.

The World Energy Council (WEC) decided to include a comparative LCA study of various energy production forms in its 2002-2004 Studies Work Programme. The objective was to identify existing LCA studies, review them and prepare a compilation report. There was no intention to conduct a new study.

The results of this work are presented in accordance with the following final uses:

- Electricity;
- Space heating;
- Transportation.

B. ELECTRICITY

As energy in the form of electricity is an important input into many industrial processes, and as there are several alternatives for energy production, many LCAs on electricity production have been carried out at numerous institutes and companies throughout the world. Combined production of electricity and district heating has also been studied. Emissions that are considered are greenhouse gases, sulphur dioxide, nitrogen oxides, particles and radioactive materials. Figure B.1 presents a comparison of greenhouse gas emissions from fossil, renewable and nuclear energy systems. The emissions have been divided into direct (stack) and indirect (other stages of the life cycle) emissions. The range of the assessed emissions is indicated by presenting the highest (high) and lowest (low) values from various LCA studies.

Figure B.2 presents greenhouse gas emissions for renewable and nuclear energy systems on a scale that allows comparison between the different alternatives. A common feature of these energy sources is that the emissions of greenhouse gases and other atmospheric pollutants arise from other stages of the life cycle than power generation. Such stages are raw material extraction, component manufacture, fuel and material transportation and construction and dismantling of facilities. The emissions from these stages depend on many different factors, for example, the country-specific mix of electric power production. In countries where most of the electricity is produced from fossil fuels combustion, the emissions are greater than in countries using fewer fossil fuels in power production.

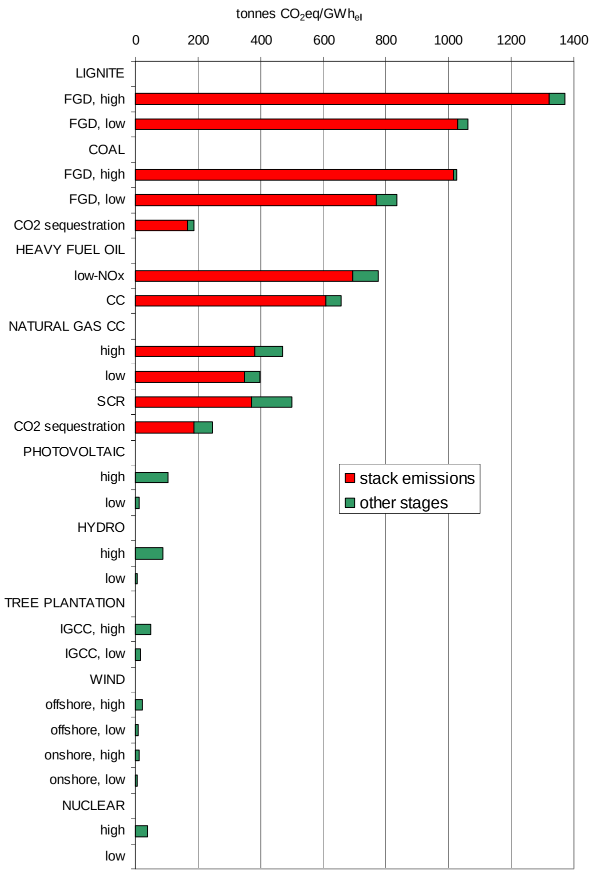

Figure B.1 (cf. Figure 6.1)

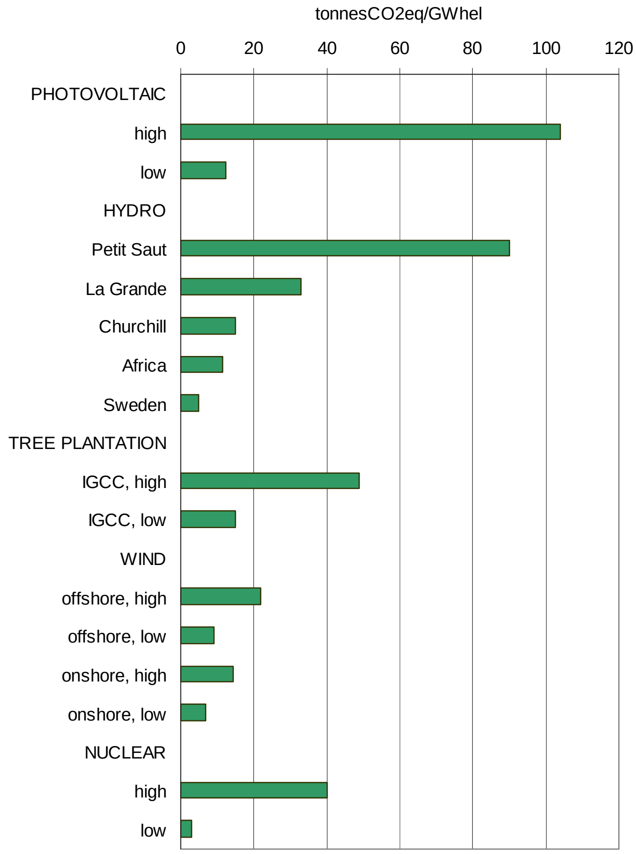

Figure B.2 (cf. Figure 6.2)

Figure B.3 is a summary of greenhouse gas emissions for fuel cycles with combined heat and power production (CHP). The total greenhouse gas emissions are expressed as tonnes of CO_2 equivalent per 1 GWh of exergy produced. Exergy is a measure of how large a part of a quantity of energy can be converted into mechanical work.

C. SPACE HEATING

Figure C.1 is a summary of greenhouse gas emissions from alternative space heating systems. The heat is produced by stoves burning coal products and by boilers burning light fuel oil, natural gas, liquefied petroleum gas or wood chips. The electricity fed into the electric heaters is produced either at natural gas, fuel oil or coal-fired condensing power stations.

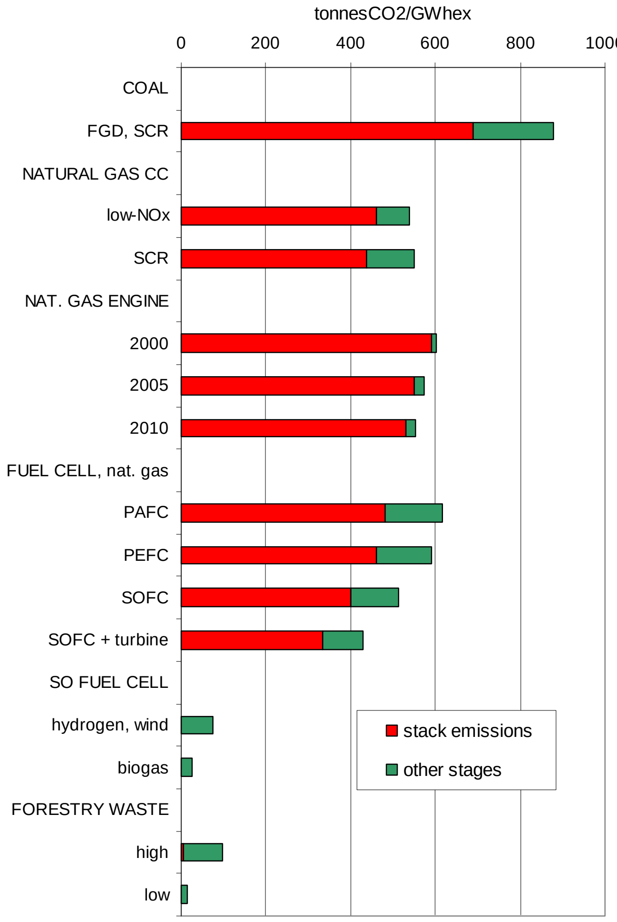

Figure B.3 (cf. Figure 6.3)

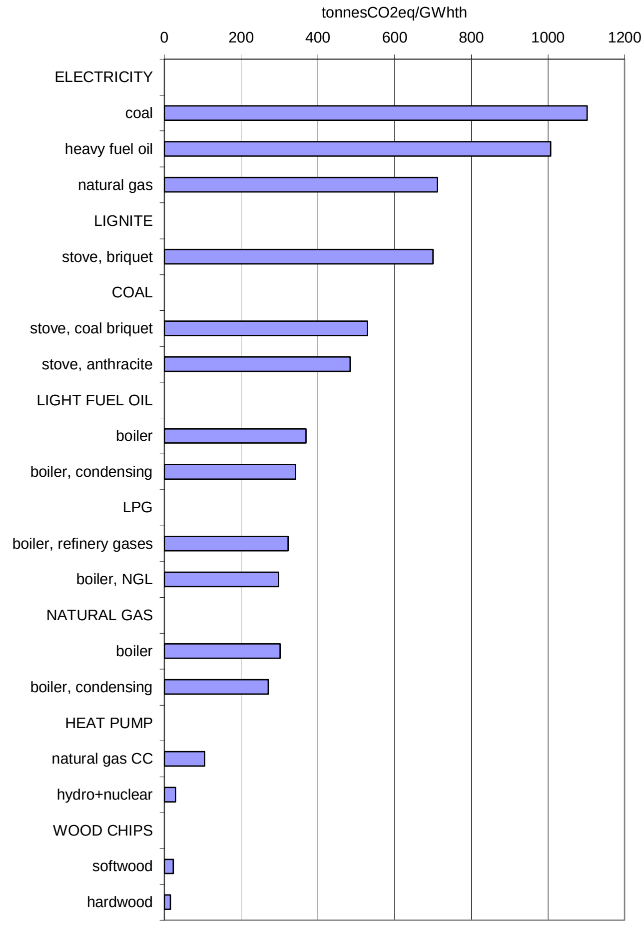

Figure C.1 (cf. Figure 6.4)

D. TRANSPORTATION

Life cycle assessment has been applied to comparative evaluation of alternative automotive fuels and technologies which are expected to become available in the near future. At present, 99% of the energy consumed in road transportation is based on crude oil. Carbon dioxide emissions result not only from fuel combustion by the vehicle, but also from fuel extraction, transport, production and distribution. Road traffic is a major source of carbon dioxide emissions in industrialised countries and is expected to be a major source of new emissions in developing countries as the personal disposable income of their population rises with economic growth.

Alternative fuel chains can involve the use of alternative primary energy sources, innovative fuel production technologies, new automotive fuels or innovative vehicle power-trains. Primary energy sources besides crude oil can be natural gas, biomass, hydro, wind or solar energy.

Since there are so many combinations of fuel power-trains, it has been customary to perform the life cycle assessment in two stages. The first stage is called “well-to-tank” and comprises fuel extraction, transport, production and distribution. The second stage is called “tank-to-wheel” and comprises conversion of fuel energy into motion of the vehicle. A complete life cycle assessment combines the results of these two stages and is called “well-to-wheel”. Greenhouse gas emissions from selected fuel power-train combinations are shown in Figure D.1.

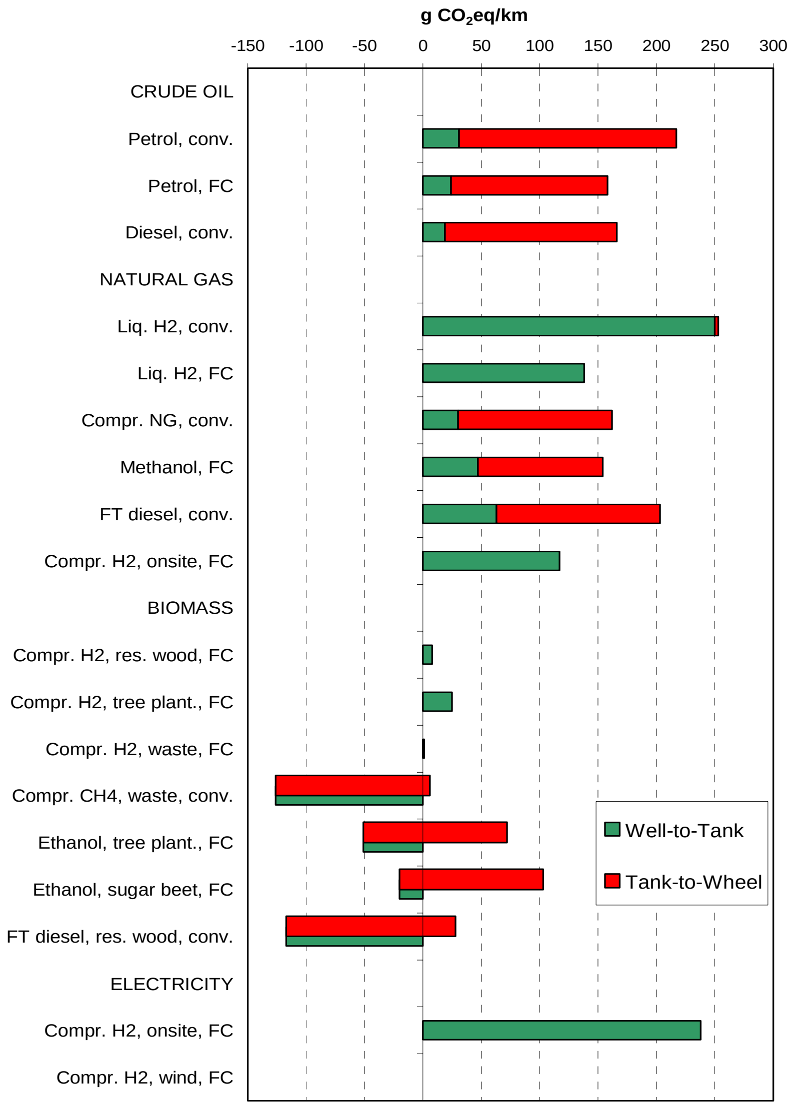

Figure D.1 (cf. Figure 6.5)

E. OTHER EFFECTS

Life cycle evaluation of emissions from energy production and transportation has been the principal target of studies because of international conventions for emission control and the direct and indirect impacts on health and environment. For life cycle assessments of energy production, other factors related to rational use of energy, natural resources and land have also been considered. This kind of analysis has been used to compare fossil and renewable energy cycles with each other. Since many renewable energies (particularly solar and wind) are "dilute", more materials and larger land areas are required than for the fossil energies.

There are comparative studies on the land requirements of different electricity generation options. The problem with such comparisons is that the calculated areas are not fully comparable. The area may have other simultaneous uses not related to electricity generation. For example, a hydropower reservoir may also be used for flood control or irrigation and sometimes for fishing and recreation. A tree plantation area may also be used for recreation. Solar photovoltaic modules are usually installed on roofs that have no alternative use.

One way to compare different electricity generation options is to calculate the so-called life cycle energy payback time. This concept is defined as the time required for the electricity generation equipment to produce the amount of energy equal to the energy used to build, maintain and fuel this equipment, converted to the corresponding amount of electrical energy. Another way to present the result of such an analysis is to calculate the so-called life cycle energy payback ratio. This is the ratio of the net electrical energy produced over a plant's lifetime to the energy required to build, maintain and fuel the plant over its lifetime.

F. OBSERVATIONS

Questions pertaining to energy accessibility (related to the direct costs of energy), energy availability (related to the security/reliability of supply) and energy acceptability (environmental impacts and externalities) form a framework for decision-makers that helps measure the relative merits of different options. LCA can be useful in matters related to environmental impacts, but only a subset of these impacts is normally included in an LCA. It can also be argued with reason that some of the externalities cannot be covered by the LCA methodology – or any other analytical method – but must be addressed within the political process.

Energy options differ in the nature and scale of their environmental impacts. The relative characteristics of various primary energy sources in the context of a few key factors which play a crucial role in the decision-making, and which in most cases are covered in LCA studies, are illustrated in Table F.1.

Table F.1. Relative characteristic features of various primary energy sources in view of key factors related to decision-making based on results of LCA studies

Factors important for decision-making	Combustion based				Nuclear	Hydro	Wind	Solar
	Coal	Oil	Gas	Biomass				
Energy accessibility (related to the direct costs of energy)	F	M	M	M	F	F	D	D
Energy availability (related to the security/reliability dimension)	F	M	M	M	F	F	D	D
Energy acceptability (environmental externalities)	D	D	M	F	F	F	F	F

Relative rankings in the perspective of factors important for decision-making:

- **F** = energy source in **favourable** position
- **M** = energy source in **medium/neutral** position
- **D** = energy source in **disfavoured** position

In addition to the results of LCA studies, a number of other factors must be taken into account in decision-making on energy systems. For example, the long-term potential impacts caused by the increased greenhouse gases in the atmosphere or future impacts brought about by potential releases from nuclear waste repositories are difficult to compare or to add to other types of impacts. Furthermore, the gradual depletion of primary energy resources is leading to the exploitation of less favourable resources and therefore to increased environmental impacts.

Normally, LCAs are made for a specific purpose. If a comparative study is made, the analyst has two or more alternatives to compare. One of these may be the option of not building the plant and importing the electricity instead. There may be several alternative plant sites.

When results of these types of studies are put together, one must exercise caution. The results may not be easily exportable to different methodologies, and if the reports are not transparent, the choices the analysts have made cannot be tracked. Some of these choices may be very case-specific, and using the results of such studies in different circumstances could lead to wrongly-based decisions.

However, adding LCA to the decision-making process provides an understanding of impacts on human health and the environment not traditionally considered when selecting a product or process. This valuable information provides a way to account for the full impacts of decisions, especially those occurring outside the site, that are directly influenced by the selection of a product or process. LCA is a tool to provide better information for decision-makers and should be included with other decision criteria such as cost and performance to make a well balanced decision.

1. INTRODUCTION

In the last few decades, the recognition of environmental and socio-economic issues has increased enormously. The public is becoming increasingly aware that the consumption of manufactured products and offered services at least to some extent contributes to adverse effects on resources and the quality of the environment. These effects can occur at all stages of the life cycle of a product or service, from the raw material extraction through product manufacture, distribution and consumption and including a number of waste management options.

Life cycle assessment (LCA) was developed more than 30 years ago as a tool for analysing environmental issues. It may be used as an instrument for information and planning, for uncovering the "weak points" in the life cycle of products and services as well as for comparison of possible alternatives. The results of an LCA may further be used to improve the environmental compatibility of products and services.

Energy production has obvious health and environmental impacts. There are significant variations between different energy production forms in this respect. Therefore it is important to apply LCA methodology for comparison of health and environmental impacts of various energy forms. The depth and breadth of LCA studies have differed considerably, depending on the goal of the particular study.

The World Energy Council (WEC) decided to include LCA of various energy production forms in its 2002-2004 Studies Work Programme. The objective was to identify existing LCA studies, review them and prepare a compilation report. The intention was not to produce a new study. *The objective was therefore limited to providing WEC members and the international community with a comparison of the different energy production forms based on the full LCA studies performed during the last 10–15 years*. "Full LCA" means that one has to take into account the whole production chain, from exploration and extraction, processing and storage to transport, transformation into secondary fuels and final use.

A study group (see Annex A) reporting to the WEC Studies Committee was established for the WEC LCA study. The study group members were invited to identify relevant completed or ongoing LCA studies for the study. The group held two meetings: on 13 December 2002 in London and on 13 September 2003 in Kyiv. Experts from the Technical Research Centre of Finland (VTT) participated in preparing this compilation report.

In Chapter 3 of this report, a general description of the LCA method is given. In Chapter 4, the benefits and limitations of LCA are presented, possible uses of LCA results are discussed briefly and an introduction to LCA in electricity generation is provided. Chapter 5 presents a summary of gaseous, particle and radioactive emissions from energy production and use and describes international cooperation for emission control. Comparison results are presented in Chapter 6 in accordance with the following final uses:

- Electricity;
- Space heating;
- Transportation.

Qualitative observations and conclusions on LCAs for various primary energy sources are drawn in Chapters 7 and 8, and possible areas for future research are indicated.

All assessment methodologies have their limitations, and it is important to understand that this is also true for LCA. For instance, the nature of choices and assumptions made in LCA may be subjective. Comparing results of different LCA studies is only possible if the assumptions and context of each study are the same. Generally, the information developed in an LCA study should be used only as part of a much more comprehensive decision process or to understand the broad or general trade-offs.

2. GOAL AND SCOPE OF THE STUDY

The World Energy Council decided to launch this review of life cycle assessment (LCA) studies and their results as part of its Work Programme in order to illustrate what LCA is, how it has been applied to energy production and use, what kinds of results the method has produced and how these results can be used.

Of the three WEC goals of energy accessibility (related to the direct costs of energy), energy availability (related to the security/reliability dimension) and energy acceptability (environmental impacts or externalities), LCA is mainly associated with energy acceptability.

The WEC study *Drivers of the Energy Scene* [see Ref. 2.1 at the end of this chapter] stimulates reflection on how the global energy system has worked in practice, what the dynamics of the energy markets have been and how the goals of energy accessibility, energy availability and energy acceptability have impacted on gross domestic product (GDP) and vice versa.

The *Drivers* report focuses on past GDP and energy trajectories, examines the challenges the energy scene faces today and addresses the most important economic, social, environmental and technological feedbacks, stating that:

> "Among the factors that may affect GDP growth negatively is the environment: climate change has become both a political and a scientific issue because of global warming, the phenomenon which occurs when the atmosphere cannot recycle all the anthropogenic greenhouse gas emissions. Given that the largest share of these emissions originates from the production and use of energy, mainly from the burning of fossil fuels and the direct release of gases such as methane, there is the possibility that national or global emissions targets might result in taxation or regulations which lead to a strong increase in energy prices.
>
> Thus, while the environment or energy acceptability has not been a major driver of the energy scene so far, it could become a key factor in the future, possibly with negative impacts for the GDP growth at least in the order of magnitude of a series of serious energy shocks". [Ref. 2.1]

This study attempts to illustrate how the results obtained by one specific method, LCA, can help decision-makers in assessing the multitude of environmental impacts which the various energy options have.

The balanced consideration of environmental impacts in decision-making is facilitated if the impacts can be examined on a common scale. Expert assessment methodologies for converting the impacts to a common scale have been developed from several starting points. Examples of such methodologies include life cycle assessment, methods for the evaluation of external environmental costs and methods utilising collective expert opinions created in a more or less structured way by various expert panels.

In LCA, the objective is to describe the overall environmental impacts of a certain operation by analysing all stages of the entire process chain from raw materials extraction, production, transport and energy generation to recycling and disposal stages following actual use -- in other words, "from the cradle to the grave".

In the evaluation phase, the objective is to measure the various environmental impacts on a single scale. The LCA methods produce environmental impact scores; in the methods for evaluation of external environmental costs, the environmental impacts are expressed in monetary terms. Assessment by the expert panel method uses experts' opinions for evaluation instead of direct exposure-impact chains.

In this report, a general description of the LCA method is given, a number of recent energy LCA studies are reviewed and a compilation of their results is presented. The studies have been selected with the requirement of using only original studies as source material to ensure that all data can be traced back to the original references. The amount of LCA literature is vast, but an effort has been made to give a good overview of it. The compilation is not complete, but keeping in mind that the limited goal of the study was to provide WEC members and the international community with a comparison of the different energies based on the full life cycle analyses performed in the last ten years, we believe that the original objective and the integrity of the task have not been compromised.

Life cycle assessment contributes to the WEC policy actions outlined in WEC's millennium statement, *Energy for Tomorrow's World – Acting Now!* [Ref. 2.2], specifically Policy Action 2: Keep All Energy Options Open; Policy Action 4: Price Energy to Cover Costs and Ensure Payment; Policy Action 7: Ensure Affordable Energy for the Poor; and Policy Action 8: Fund Research, Development and Deployment. By summarising existing studies on the topic, WEC will also be consistent with Policy Action 9: Advance Education and Public Information.

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References for Chapter 2

2.1. World Energy Council. *Drivers of the Energy Scene*. World Energy Council: London. 2003. ISBN 0 946121 10 9

2.2. World Energy Council. *Energy for Tomorrow's World – Acting Now!* World Energy Council: London. 2000. Available online at: www.worldenergy.org

3. THE LIFE CYCLE ASSESSMENT METHOD

Society has become concerned about the issues of natural resource depletion and environmental degradation. The environmental performance of products and processes has become a key issue, which is why ways to minimise the effects on the environment are investigated. One tool for that purpose is called *life cycle assessment* (LCA)[1]. This concept considers the entire life cycle of a product. In the case of this study, the product is the electrical power or energy produced.

LCA is a general method suitable for analysing products, processes or services regardless of their nature or extent. The method was launched in the 1960s as a way to analyse packaging alternatives and other bulk commodities. Later on, the method was further developed and used for analysing non-goods products, including electricity generation alternatives. LCA is a product-oriented tool for analysing the environmental impacts that a specific product, process or service causes. In this chapter, a general description of the LCA procedure is given.

The life cycle of a product begins with the extraction of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. In an LCA, an attempt is made to include all stages of a product's life in an evaluation, assuming they are interdependent, i.e., that one operation leads to the next. LCA makes it possible to estimate the cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, ultimate product disposal, etc.). Therefore, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product selection.

Specifically, LCA is a technique to assess the environmental aspects and potential impacts associated with a product, process or service, by:

- compiling an inventory of relevant energy and material inputs and the associated emissions to the environment;
- evaluating the potential environmental impacts associated with identified inputs and emissions;
- interpreting the results to facilitate making a more informed decision.

Inputs may be divided into the following stages:

- Raw materials;
- Manufacturing;
- Use/reuse/maintenance;
- Recycle/waste management.

Outputs may be listed as the following:

- The products;
- Atmospheric emissions;
- Waterborne wastes;
- Solid wastes;
- Co-products;
- Other releases.

The LCA process is a systematic approach that consists of four stages: goal definition and scoping, inventory analysis, impact assessment and interpretation as illustrated in Figure 3.1.

[1] The standardised term is "life cycle assessment". It has been customary to use the term "life cycle analysis". For the purposes of this report, these terms may be considered synonymous.

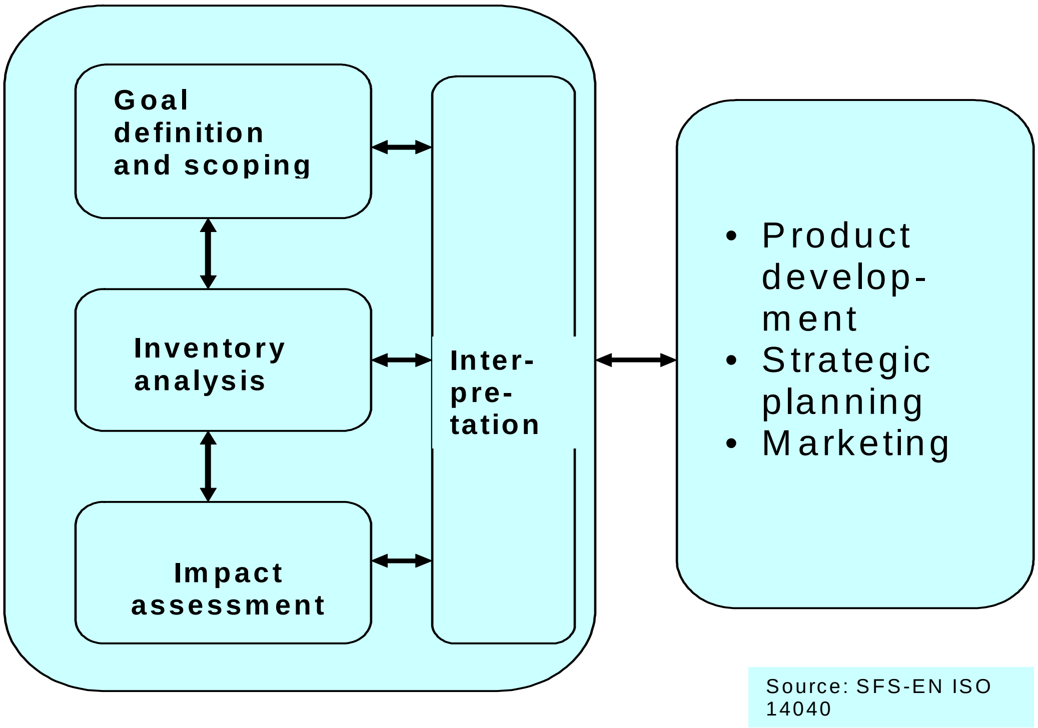

Figure 3.1. Stages of a life cycle assessment [Ref. 3.1], showing the three main phases: goal definition and scoping, inventory analysis and impact assessment; each of these phases is shown connected to an overarching phase titled "Interpretation"

3.1. Goal Definition and Scoping

Goal definition and scoping is the phase of the LCA process that defines the purpose and method for including life cycle environmental impacts in the decision-making process.

The following six basic decisions should be made at the beginning of the LCA process to make effective use of time and resources:

- Define the goal(s) of the project.
- Determine what type of information is needed by the decision-makers.
- Determine how the data should be organised and the results displayed.
- Determine what will or will not be included in the LCA.
- Determine the required accuracy of data.
- Determine ground rules for performing the analysis.

3.2. Inventory Analysis

A life cycle inventory (LCI) analysis is the process of quantifying the energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes and other releases for the entire life cycle of a product, process or activity.

In the life cycle inventory phase of an LCA, all relevant data are collected and organised. Without an LCI, no basis exists to evaluate comparative environmental impacts or potential improvements. The level of accuracy and detail of the collected data is reflected throughout the remainder of the LCA process.

Results of the Life Cycle Inventory

The outcome of the inventory analysis is a list containing the quantities of pollutants released to the environment and the amount of energy and materials consumed in the life cycle of the product. Depending on the scope, the energy content of material inputs can further be traced to fuel and material use of the upstream processes if required. The information may be organised by life cycle stage, media (air, water, land), specific process or any combination of these that is consistent with the ground rules defined in the goal definition and scoping phase for reporting requirements.

Key Steps of a Life Cycle Inventory

Life cycle inventory may be divided into separate phases in several ways. The following description is adopted from two U.S. Environmental Protection Agency guidelines [Refs. 3.2, 3.3]. The combination of these two guidance documents provides the framework for performing an inventory analysis and assessing the quality of the data used and the results. The two documents define the following steps of a life cycle inventory:

- Develop a flow diagram of the processes being evaluated.
- Develop a data collection plan.
- Collect data.
- Evaluate and report results.

The process flow is divided into a series of interconnected *unit processes*. Their connections within the process chain are analysed. For each of these steps, all inputs and outputs are analysed. Finally, all these are summed up to give a comprehensive picture of the total process. Figure 3.2 illustrates the unit process concept.

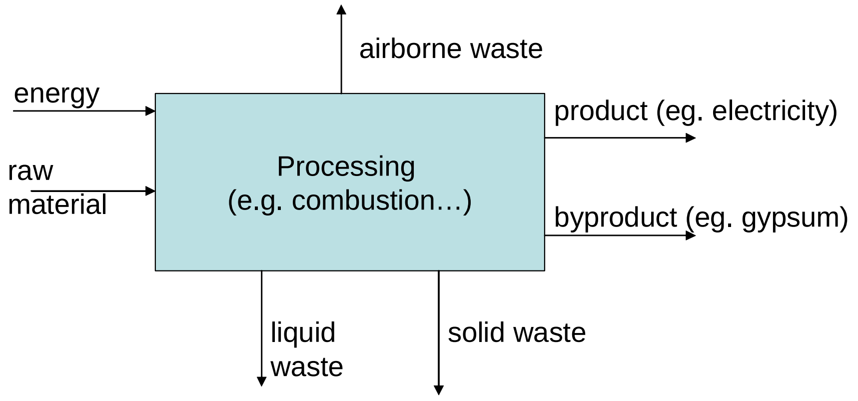

Figure 3.2. Unit process input/output template

No pre-defined list of data quality goals exists for all LCA projects. The number and nature of data quality goals necessarily depend on the level of accuracy required to inform the decision-makers involved in the process. In each project, a decision must be made on where site- and process-specific data is needed and where approximate or generic data are sufficient. One method to reduce data collection time and resources is to obtain non-site-specific inventory data. Several organisations have developed databases specifically for LCA that contain some of the basic data commonly needed in constructing a life cycle inventory.

When documenting the results of the life cycle inventory, it is important to thoroughly describe the methodology used in the analysis, to define the systems analysed and the boundaries set and to note all assumptions made in performing the inventory analysis.

3.3. Impact Assessment

The life cycle impact assessment (LCIA) phase of an LCA is the evaluation of potential human health and environmental impacts of the environmental resources and releases identified during the life cycle inventory (LCI). Impact assessment should address ecological effects and human health effects; it may also address resource depletion.

A life cycle impact assessment attempts to establish a linkage between the product or process and its potential environmental impacts. For example:

- What are the impacts of 9,000 tonnes of carbon dioxide or 500 tonnes of methane emissions being released into the atmosphere?
- Which is worse?
- What are their potential impacts on smog or global warming?

An LCIA provides a systematic procedure for classifying and characterising these types of environmental effects. Typical impact categories and examples of stressors associated with these impact categories are listed in Table 3.1. The table is meant to be an example and is by no means comprehensive.

Emissions or environmental stressors within one impact category can be made commensurable based on their physico-chemical properties. Using science-based characterisation factors, an LCIA can calculate the impacts each environmental release has on problems such as smog or global warming. This enables taking into account their relative threat, even though the absolute impacts of, for example, climate change, are debatable and disputed.

An impact assessment can also incorporate value judgements. For instance, in a region where pollutant concentrations exceed target levels, air emissions could be of relatively higher concern than the same emissions in a region with better air quality.

The results of an LCIA provide a checklist showing the relative differences in potential environmental impacts for each option. For example, an LCIA could determine which product/process causes more greenhouse gases or which could potentially kill more fish.

Table 3.1. Commonly used life cycle impact categories; adapted from US EPA guidelines and principles [Ref. 3.2]

Impact Category	Scale	Relevant LCI Data	Common Characterisation Factor	Description of Characterisation Factor
Global Warming	Global	Carbon Dioxide (CO_2)	Global Warming Potential	Converts LCI data to carbon dioxide (CO_2) equivalents
		Nitrous Oxide (N_2O)		Note: Global warming potentials can be 50, 100 or 500-year potentials
		Methane (CH_4)		
		Chlorofluorocarbons (CFCs)		
		Hydrochlorofluorocarbons (HCFCs)		
		Methyl Bromide (CH_3Br)		
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs)	Ozone Depleting Potential	Converts LCI data to trichlorofluoromethane (CFC-11) equivalents
		Hydrochlorofluorocarbons (HCFCs)		
		Halons		
		Methyl Bromide (CH_3Br)		
Acidification	Regional	Sulphur Oxides (SOx)	Acidification Potential	Converts LCI data to hydrogen (H+) ion equivalents
	Local	Nitrogen Oxides (NOx)		
		Hydrochloric Acid (HCL)		
		Hydrofluoric Acid (HF)		
		Ammonia (NH_4)		
Eutrophication	Local	Phosphate (PO_4)	Eutrophication Potential	Converts LCI data to phosphate (PO_4) equivalents
		Nitrogen Oxide (NO)		
		Nitrogen Dioxide (NO_2)		
		Nitrates		
		Ammonia (NH_4)		
Photochemical Smog	Local	Non-methane volatile organic compounds (NMVOC)	Photochemical Oxidant Creation Potential	Converts LCI data to ethane (C_2H_6) equivalents.
Terrestrial Toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents	LC_{50}	Converts LC_{50} data to equivalents.
Aquatic Toxicity	Local	Toxic chemicals with a reported lethal concentration to fish	LC_{50}	Converts LC_{50} data to equivalents
Human Health	Global	Total releases to air, water and soil.	LC_{50}	Converts LC_{50} data to equivalents
	Regional			
	Local			
Resource Depletion	Global	Quantity of minerals used	Resource Depletion Potential	Converts LCI data to a ratio of quantity of resource used versus quantity of resource left in reserve
	Regional	Quantity of fossil fuels used		
	Local			
Land Use	Global	Quantity disposed of in a landfill	Solid Waste	Converts mass of solid waste into volume using an estimated density

3.4. Interpretation

Life cycle interpretation is a systematic technique to identify, quantify, check and evaluate information from the results of the life cycle inventory (LCI) and the life cycle impact assessment (LCIA) and communicate them effectively. Life cycle interpretation is the last phase of the LCA process.

The International Organization for Standardisation (ISO) has defined the following two objectives of life cycle interpretation:

- To analyse results, reach conclusions, explain limitations and provide recommendations based on the findings of the preceding phases of the LCA and to report the results of the life cycle interpretation in a transparent manner;
- To provide a readily understandable, complete and consistent presentation of the results of an LCA study, in accordance with the goal and scope of the study [Ref. 3.5].

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4. COMPARING ALTERNATIVES USING LIFE CYCLE INTERPRETATION

While conducting the LCI and LCIA, it is necessary to make assumptions, engineering estimates and decisions based on the values of the involved stakeholders. Each of these decisions must be included and communicated in the final results to explain conclusions drawn from the data clearly and comprehensively.

In some cases, it may not be possible to state that one alternative is better than the others because of uncertainty in the final results. This does not imply that efforts have been wasted. The LCA process will still provide decision-makers with a better understanding of the environmental and health impacts associated with each alternative, where they occur (locally, regionally or globally) and the relative magnitude of each type of impact in comparison to each of the proposed alternatives included in the study. This information more fully reveals the pros and cons of each alternative.

4.1. Benefits of Conducting an LCA

An LCA comprehensively encompasses all processes and environmental releases for a given environmental issue, beginning with the extraction of raw materials and the production of energy used to create the product through the use and final disposition of the product. LCA extends normal environmental analyses in its treatment of the whole product life cycle. Thus the impacts originating outside local, regional and even national jurisdiction are also accounted for.

Conducting LCAs gives a product-centred approach to environmental protection, in line with the concepts of *product stewardship* or *extended product responsibility*. Specifically, LCA gives information on which stage of a product's life cycle results in the major environmental stresses and thus helps actors in the various stages of the product life cycle -- manufacturers, retailers, users and disposers -- share responsibility for reducing the environmental impacts of products. Information from an LCA can aid in focussing efforts where they are most effective in decreasing the environmental impacts.

When deciding between two alternatives, LCA can help decision-makers compare all major environmental impacts caused by products, processes or services.

Final and intermediate results of an LCA will help decision-makers select the product or process that results in the least impact on the environment. This information can be used with other factors, such as cost and performance data, to select a product or process. LCA data identifies the transfer of environmental impacts from one media to another (e.g., eliminating air emissions by creating a wastewater effluent instead) and/or from one life cycle stage to another (e.g., from use and reuse of the product to the raw material acquisition phase). If an LCA were not performed, the transfer might not be recognised and properly included in the analysis because it was outside the typical scope or focus of product selection processes.

4.2. Limitations of Conducting an LCA

Performing an LCA can be resource- and time-intensive. Depending on how much detailed information the users wish to cover in an LCA, gathering the data can be problematic, and the availability of data can greatly impact the accuracy of the final results. Therefore it is important to weigh the availability of data, the time necessary to conduct the study and the financial resources required against the projected benefits of the LCA.

The purpose of conducting an LCA may be to provide more background information for decision-makers to facilitate better and more fact-based decisions, especially by providing a particular type of information (often unconsidered), with a life cycle perspective on environmental and human health impacts associated with each product or process. However, LCA does not take into account technical performance, cost or political and social acceptance. Therefore, it is recommended that LCA be used in conjunction with these other parameters.

LCA will not determine which product or process is the most cost-effective or which works best. Therefore the information developed in an LCA study should be used as one component of a more comprehensive decision process assessing the trade-offs with cost and performance.

4.3. LCA and Life Cycle Cost

Another use of the term life cycle is associated with cost estimates. The term life cycle cost (LCC) is used when estimating the costs associated with the construction and use of an installation over its entire working life.

A fundamental difference between LCA and LCC is the way future loads are handled. In LCA, the present worth factor of environmental loads equals 1. In an LCC calculation, the present worth is a function of the depreciation factor used and the time span considered.

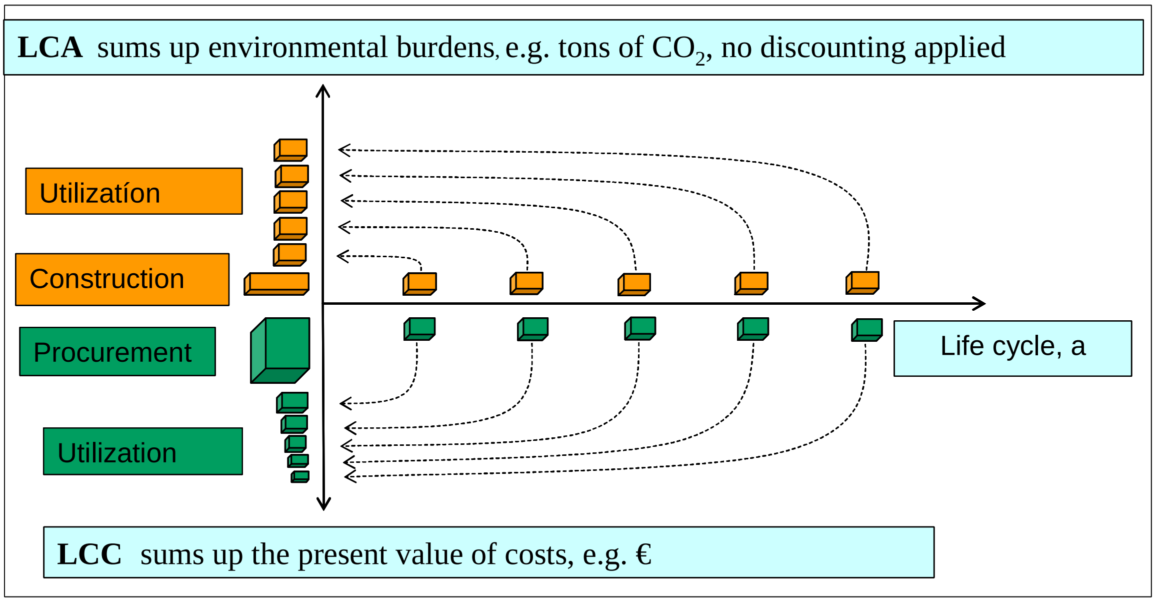

Figure 4.1. Handling of future impacts or costs in LCA and LCC

4.4. Uses of LCA Data

The results of an LCA can have several uses in addition to their use as an aid in decision-making. They can be used for informing consumers, education, marketing, etc. For some applications, there are rules about how LCA results must be obtained and applied, such as:

- Providing guidance on the goals and principles that should frame all environmental labelling programs and efforts, including practitioner programs and self-declaration [Ref. 4.1], or
- Giving guidance on the design and use of environmental performance evaluation and on identification and selection of environmental performance indicators for use by all organisations, regardless of type, size, location and complexity [Ref. 4.2].

Environmental labelling

Environmental labelling is understood as the qualification of products/processes for one or several environmental indicators. The label infers that a product/process from the labelled technology has markedly better environmental characteristics than, for example, a reference product or the average product on the market. The environmental impacts of both the reference system and the system in question are derived from an LCA study.

Environmental product declaration (EPD)

The intention of the environmental product declaration (EPD) [Ref. 4.3] is to develop an environmental profile of a certain product, taking into account its production and usage. The profile strongly depends on site-specific data. The approach is realised by using site-specific data for main processes and generic data for background processes, with less influence on the environmental profile. LCI data covers energy carriers, material inputs, land use, main products and by-products, emissions and several categories of waste.

4.5. LCA Aspects and Stages of Electricity Generation

The main difference between electricity and normal bulk commodity production is that the supply and consumption of electricity must be balanced at each point in time. In modern societies, this means that the production must be adapted to the consumption. When comparing results of LCA studies of the various methods of generating electricity, it is necessary to understand that all generation options may not be true alternatives for a specific purpose. Furthermore, it should be understood that various energy production options bring about completely and genuinely different types of impacts, such as greenhouse gas effects and hypothetical accidents or long-term potential radiological impacts of nuclear waste disposal. The aggregation or comparison of these types of impacts is unavoidably involved with significant uncertainties, which emphasises the importance of the transparent description of all assumptions.

Some plants are suitable for base-load operation, while others are used for peak production. Plants with intermittent motive force need backup either from storage or from a different type of plant.

In electricity generation systems, plants with different operational characteristics are included. The system characteristics play an important role in making decisions on new plant investment. The grid capacity, existing backup arrangements, type of loads and several other factors all need to be taken into account. In some cases, co-production of power and heat may be feasible. In open electricity markets, the cost of alternative supply is important.

In larger production systems, the addition of one large plant affects the system characteristics in a minor way, whereas adding a similar plant in a smaller system can have a major impact on the operation of the generation system. Recognising that customers normally purchase their electricity through a distribution operator, the electricity the customers use is not a product of a single plant but a mixture from all operating plants in a system. The environmental characteristics of the electricity used are determined by the system and vary with time. These variations cannot be included in an LCA comparing different production alternatives.

The life cycle of electricity generation plants can be divided into the following main life cycle phases:

- **Fuel preparation:** Exploration/prospecting of fuel resources, fuel resource extraction and processing (of fuel used in studied electricity generation system, i.e., not relevant for PV, wind, geothermal and hydro), including transport;
- **Infrastructure:** Construction of power plant, including exploration/prospecting of ores, minerals, etc., extraction of ores and minerals, material manufacture, production of components, construction and deconstruction of vehicles and roads, transport;
- **Operation:** Power plant operation, including normal malfunctions, production of operational chemicals, incineration of operational waste, disposal processes, handling of fuel residues (for example, biomass ash), reinvestments in machines, transport;
- **End-of-life processes:** Incineration of waste and disposal processes (material leaving the system for new life cycles is accounted for, but no environmental burden is included);
- **Background infrastructure:** Construction, deconstruction and reinvestments in suppliers facilities;

- **Transmission/distribution infrastructure:** Construction/deconstruction and maintenance of transmission/distribution networks;
- **Transmission/distribution to the customer:** Losses on high, medium and low voltage power networks.

In the published literature, most often only stages up to the electricity production phase are included. Thus meaningful comparisons cannot be made for the other stages. Specifically, the end-use viewpoint cannot be fully evaluated if the transmission and distribution stages are not included in the study. The infrastructure is also usually left out of the studies.

In this report, only published data has been used for the comparisons. As a result, there are many gaps in the tables. These gaps must not be interpreted as the non-existence of emissions; rather, they indicate non-existent data in the specific study.

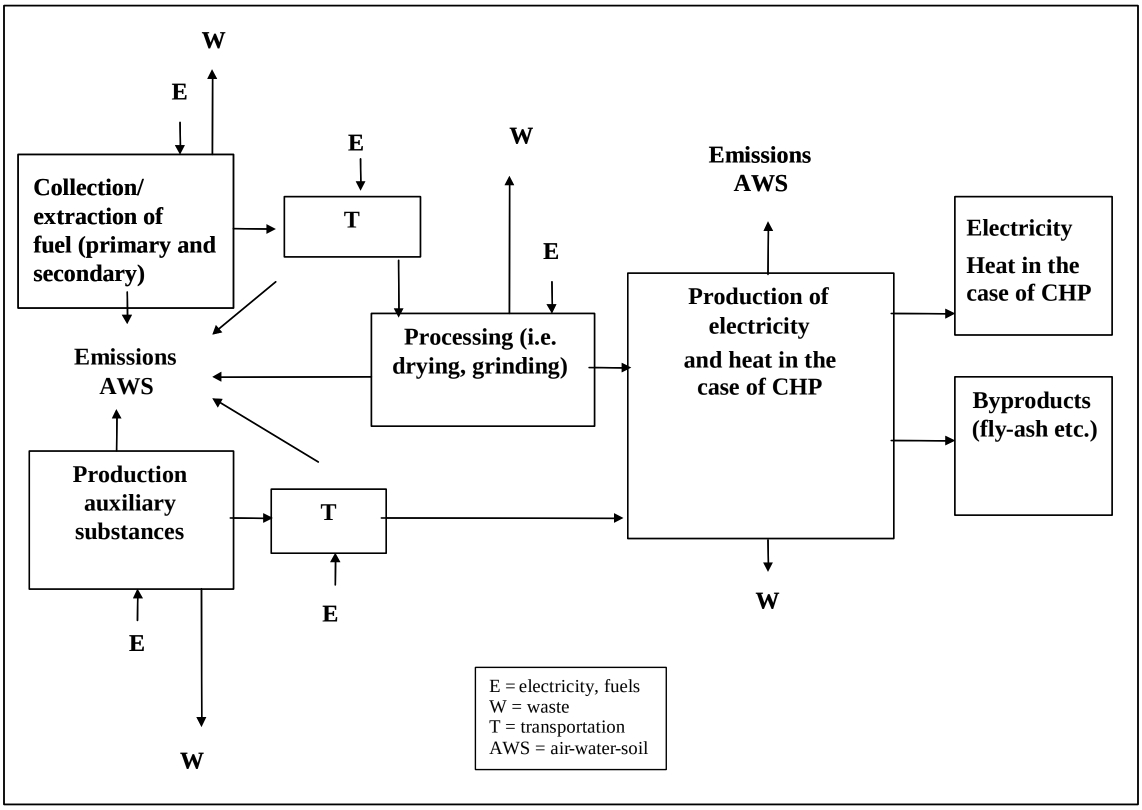

Figure 4.2. Illustration of life cycle scope of electricity generation and electricity and heat cogeneration systems adapted from Setterwall, et al [Ref 4.4]

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5. BACKGROUND FOR ENERGY AND ENVIRONMENT STUDIES

5.1. History of Electric Power and Transportation

James Watt's construction of a rotary-motion steam engine in 1781 may be considered as the starting point of the Industrial Revolution. For the first time in history, man had at his disposal a means to do mechanical work anywhere and any time without resorting to muscle power. The previous alternatives, waterwheel and windmill, were available only at certain places or times. Mills utilising the kinetic energy of flowing water had to be situated along rivers, and windmills could be used only when the wind velocity was high enough to rotate the millstones.

In 1807, Robert Fulton launched the first commercially successful steamship, and in 1815, George Stephenson constructed the first steam locomotive. Steam engines were also used to run industrial machines, although the water turbine constructed by James Francis in 1855 was a viable alternative for riverside sites. However, the rotary motion had to be transmitted to machines by a system of gears, shafts, belts and pulleys.

Michael Faraday discovered the effect of electromagnetic induction in 1831, and in 1837, Thomas Davenport constructed the first electric motor running with direct current from a galvanic cell. In 1881, Thomas Edison began the manufacture of electric generators. His first generators were driven by steam engines. In 1888, Gustav de Laval constructed the first steam turbine, which subsequently replaced the steam engine as motive power for generators.

In 1882, the world's first hydropower plant began operating in Appleton, Wisconsin (USA). This power plant was a run-of-river type. A few years later, dams were constructed to create artificial water storage areas and to control water flow rate.

The advantage of electricity was that high voltage transmission lines could be used to transfer power over long distances with few losses. This fact made it possible to produce electricity where it was available at least cost, for example, at rapids or coal mines, and to use it where needed. The first electric devices were light bulbs and electric motors, but new applications are still being invented.

In 1876, Nikolaus August Otto built the first four-stroke piston cycle internal combustion engine running on liquid fuel. Gottfried Daimler and Karl Benz constructed the first practical automobiles employing Otto's engine in 1886, and in 1893, Rudolf Diesel developed the first internal combustion engine which could operate without spark ignition. The first modern oil well was drilled in Baku in 1848. The next year, Abraham Gesner distilled kerosene from crude oil. Michail Dietz invented the kerosene lamp in 1857. Crude oil refining began in the USA around 1860. Petrol became the principal oil product after Henry Ford started line production of cars in 1908.

When petrol, diesel oil and other light and medium distillates are extracted from crude oil, the remaining product is used to produce heavy fuel oil and bitumen. Heavy fuel oil is used as an energy source for industrial processes and oil-fired power plants.

In 1858, the first natural gas pipeline was constructed in Pennsylvania (USA). The gas was used as a fuel for streetlights. After the Second World War, extensive natural gas pipeline networks were constructed in America, Europe and Asia.

Up to the 1950s, hydropower and coal or oil-fired power plants produced practically all electricity. The first commercial nuclear power plant began operation in 1957.

5.2. International Cooperation to Control Emissions

In December 1952, some 4,000 extra fatalities were recorded in Greater London during a four-day fog. The coal smoke from fireplaces, power plants and factories was trapped above the city, resulting in an exceptionally high concentration of air pollutants. Similar pollution episodes had occurred earlier in industrial regions (Meuse Valley, Belgium, in 1930 and Donora, Pennsylvania, USA, in 1948) with a small number of fatalities, but with a large proportion (43% in Donora) of the population suffering health problems. In December 1961, a similar episode occurred in Greater London, with 700 fatalities.

The significant increase in morbidity and mortality during the pollution episodes:

- left little doubt about causality in regard to the induction of serious health effects by very high concentrations of particle-laden air pollutant mixture;
- stimulated the establishment of air monitoring networks in major urban areas and control measures to reduce air pollution;
- stimulated research to identify key causative agents contributing to urban air pollution effects and to characterise associated exposure-response relationships [Ref. 5.1].

The immediate solution was to ban the use of low-grade coal with high ash content for heating purposes. Later, particle emission control in power plants was made more effective. An effective measure to improve urban air quality was to build higher stacks.

In the 1960s, scientists observed a link between sulphur emissions in continental Europe and the acidification of lake and river systems in Scandinavia. The emitted sulphur dioxide oxidised in the atmosphere and turned rainwater into dilute sulphur acid. This phenomenon is called acid rain. In the following years, more evidence was found that air pollutants could cause damage hundreds of kilometres from the point of emission. This new type of challenge to international cooperation led to the signing in 1979 of the Convention on Long-Range Trans-boundary Air Pollution under the auspices of the United Nations Economic Commission of Europe.

The Convention activities initially focused on reducing the effects of acid rain through control of sulphur emissions. The Protocol on Reduction of Sulphur Emissions, signed in 1985, established commitments for parties to reduce yearly sulphur emissions by at least 30% from 1980 levels as soon as possible but by 1993 at the latest. By 1995, nineteen parties which had ratified the Protocol had achieved reductions exceeding 50%. The second Sulphur Protocol, signed in 1994, was based on the concept of "critical loads", assigning each country a reduction target based on the effects of its sulphur emissions on the region's ecosystems.

Nitrogen oxide emissions also contribute to acid rain, but to a lesser degree than sulphur oxide emissions. Nitrogen oxides, together with volatile organic compounds, are also precursors of ozone and other components of summertime smog. The Protocol Concerning the Control of Emissions of Nitrogen Oxides was signed in 1988 and came into force in 1991. Parties were required to limit their nitrogen oxide emissions to 1987 levels (the base year for the USA was 1978) by the end of 1994 and to apply the best available technology to major new stationary and mobile sources. Of the 25 parties to the Protocol, nineteen have either reduced their emissions below the 1987 levels or stabilised them at those levels.

Major sources of volatile organic compounds (VOCs) include the incomplete combustion of motor fuels and the industrial uses of certain paints, glues and inks. The Protocol Concerning the Control of Emissions of Volatile Organic Compounds was signed in 1991 and came into force in 1997. The Protocol required parties to reduce their VOC emissions by at least 30% by 1999, using either 1988 or any year between 1984 and 1990 as the base year.

A Protocol on nitrogen oxides and related substances was drafted in 1999. This Protocol targets acidification, eutrophication and the effects of ground-level ozone on crops, forests and human health. This so-called Multi-Pollutant, Multi-Effects Protocol has not yet come into force, but many countries already follow it [Ref. 5.2].

Evidence of human interference with the climate first emerged in 1979 at the First World Climate Conference. In 1988, the Intergovernmental Panel on Climate Change was established to marshal and assess scientific information on the subject. The United Nations Framework Convention on Climate Change was opened for signing in 1992 and came into force in 1994. In 1997, the Conference of the Parties to the Climate Convention drafted a first Protocol for emission control. This Protocol gives emission quotas to industrialised countries; developing countries do not have such quotas. The Protocol was signed in 1997 in Kyoto. The Kyoto Protocol also includes a list of gases and activities on which limitations are imposed and briefly defines the mechanisms which may be used to attain national quotas.

The negotiations on complementing the rules in the Kyoto Protocol were suspended in The Hague in 2000 but resumed in Bonn in 2001. The rules agreed on in Bonn were adopted a few months later in Marrakech. Although the USA opted out of the Protocol, the other parties reached an agreement at a political level on all questions (the Marrakech Accords). The Protocol will come into force providing it is ratified by at least 55 countries and providing their emissions cover over 55% of the emissions of the industrialised countries. As of April 2004, 64 countries have ratified the Protocol, and it has been accepted, approved or accessed by 58 countries. The total emissions of industrial countries which have ratified the Protocol, however, amount to only 44.2% [Ref. 5.3].

Greenhouse gas emissions and the resulting climate change are currently seen as the most crucial environmental problem. This is a global problem, since it depends on the total global emissions. Its main cause is the carbon dioxide (CO_2) emissions resulting from fossil fuel use. Deforestation of tropical areas contributes 10-20% to global CO_2 emissions. Other emissions, mainly methane (CH_4) and nitrous oxide (N_2O), contribute about 20% to the total emissions of greenhouse gases. In this estimate, the emissions of these gases have been converted to equivalent emissions of CO_2 using conversion factors proposed by the Intergovernmental Panel on Climate Change in 1996 [Ref. 5.4].

5.3. Particulate Matter

The term particulate matter (PM) is equivalent to the term atmospheric aerosol and defines a suspension of airborne solid particles and/or droplets of various sizes. Size and chemical composition are regarded as the most important characteristics of such particles, while surface area and possibly particle number may also be important. A single particle usually contains a mixture of chemical and physical (solid, liquid) constituents. The PM_{10} concentration is the mass per volume unit (µg/m^3) of particles with an aerodynamic diameter smaller than 10 micrometres (µm). The larger particles contained in the PM_{10} size fraction reach the upper part of the lung. The smaller particles of this size fraction (in particular $PM_{2.5}$ and $PM_{1.0}$, with diameters smaller than 2.5 and 1.0 µm) penetrate more deeply into the lung and reach the alveolar region. PM is often differentiated by chemical constituents (e.g., sulphates, heavy metals and organics), as well as by source-related constituents (e.g., diesel soot). Today, it has become common practice to denote the $PM_{2.5}$ as the "fine fraction" and particles with diameters between 2.5 and 10 µm ($PM_{2.5-10}$) as the "coarse fraction".

Large and very small particles have a limited atmospheric residence time due to deposition or coagulation. Particles in the size range between approximately 0.1 and a few µm remain in the atmosphere much longer (typically several days to a week) and can consequently be transported over long distances (1,000 kilometres or more).

PM is emitted directly from "primary" sources (primary PM) and is also formed in the atmosphere by the reaction of precursor gases (secondary PM). Other common distinctions are natural/anthropogenic sources and combustion/non-combustion sources. The emission estimates from non-combustion sources have a high degree of uncertainty.

A large body of new scientific evidence that has emerged in the last decade has strengthened the link between ambient PM exposure and health effects. New analyses have shown that, at the current PM concentrations in Europe, death from causes such as cardiovascular and lung disease is advancing by at least a few months on the population, average. Furthermore, there are robust associations between ambient PM and increases in lower respiratory symptoms and reduced lung function in children and chronic obstructive pulmonary disease and reduced lung function in adults. There is no evidence for a threshold below which ambient PM has no effect on health. It has not been possible to establish a causal relationship between PM-related health effects and one single PM component. PM characteristics found to contribute to toxicity include metal content, the presence of polycyclic aromatic hydrocarbons and other organic components; endotoxin content and small (less than 2.5 µm) and extremely small (less than 0.1 µm) size.

Epidemiological studies suggest that a number of emissions sources are associated with health effects, especially motor vehicles and coal combustion. Toxicological studies show that particles originating from internal combustion engines, coal burning, residual oil combustion and wood burning have strong inflammatory potential [Ref. 5.5].

5.4. Emissions of Radioactive Substances and Radiological Impacts

With the exception of thermal releases and resource depletion, the most significant environmental and health impacts of the nuclear fuel cycle differ drastically from the impacts caused by other energy sources (cf. Table 7.2). The common denominator of public and occupational impacts of nuclear power production is related to the emission of radioactive substances and the resulting radiological impacts. The use of nuclear power and other radiation-related activities is controlled by the requirements on radiation protection. Recommendations for the protection of people from the harmful effects of ionising radiation are made by the International Commission on Radiological Protection (ICRP) [Ref. 5.6]. National regulatory authorities have developed regulatory systems that generally follow the broad lines of ICRP recommendations. The system of radiological protection recommended by ICRP has the following main principles:

(1) General justification of a practice;

(2) Exposures received should be kept as low as reasonably achievable;

(3) Economic and social factors should be taken into account;

(4) Exposure of individuals should be subject to dose limits.

The main impact indicators considered in the full energy chain analyses of nuclear power, for example, in the ExternE-studies [Ref. 5.7], are the public and occupational radiation exposures. The public exposures are evaluated both as individual annual exposures and as collective dose commitments. According to the definition, the latter is a global integral over a specified time interval. In the UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) and the ExternE studies, very long integration times (10^4 or 10^5 a) have been employed. The recent trend, however, is to truncate the integration to a shorter period (500 a as noted in Ref. 5.10). The main results of this recent study by OECD are reproduced in Table 5.1.

Radiation exposures from the nuclear fuel cycle are partially due to the enhanced natural radiation exposures in the front end of the fuel cycle (i.e., extraction and processing of uranium and the enrichment) and partially due to radionuclides produced during the nuclear power plant operation. One way to put the impacts of the nuclear power production chain into perspective is to compare them to other sources of radiation exposure. Figure 5.1 is derived based on the results presented in the UNSCEAR reports [Refs. 5.8, 5.9].

Table 5.1. Summary dose estimates for the public and workers from major fuel cycle stages [Ref. 5.10]

Fuel cycle stage	**Public (generic calculations)**			**Workers (operational data)**	
	Collective dose truncated at 500 years (manSv/GWa)		**Average annual individual dose to the critical group (mSv/a)**	**Annual collective dose (manSv/GWa)**	
	Once-through	**Reprocessing**		**Once-through**	**Reprocessing**
Mining and milling	1.0	0.8	0.30-0.50	0.02-0.18	0.016-0.14
Fuel conversion and enrichment	0.0009		0.020	0.008-0.02	0.006-0.016
Fuel fabrication				0.007	0.094
Power generation	0.6	0.6	0.0005-0.0008	1.0-2.7	1.0-2.7
Reprocessing, vitrification	Not applicable	1.2	0.40	Not applicable	0.014
Transportation	Trivial	Trivial	Trivial	0.005-0.02	0.005-0.03
Disposal	(*)	(*)	(*)	Trivial	Trivial
Total	**1.6**	**2.6**	**Not applicable**	**1.04-2.93**	**1.14-2.99**

(*) No releases during the first 500 a

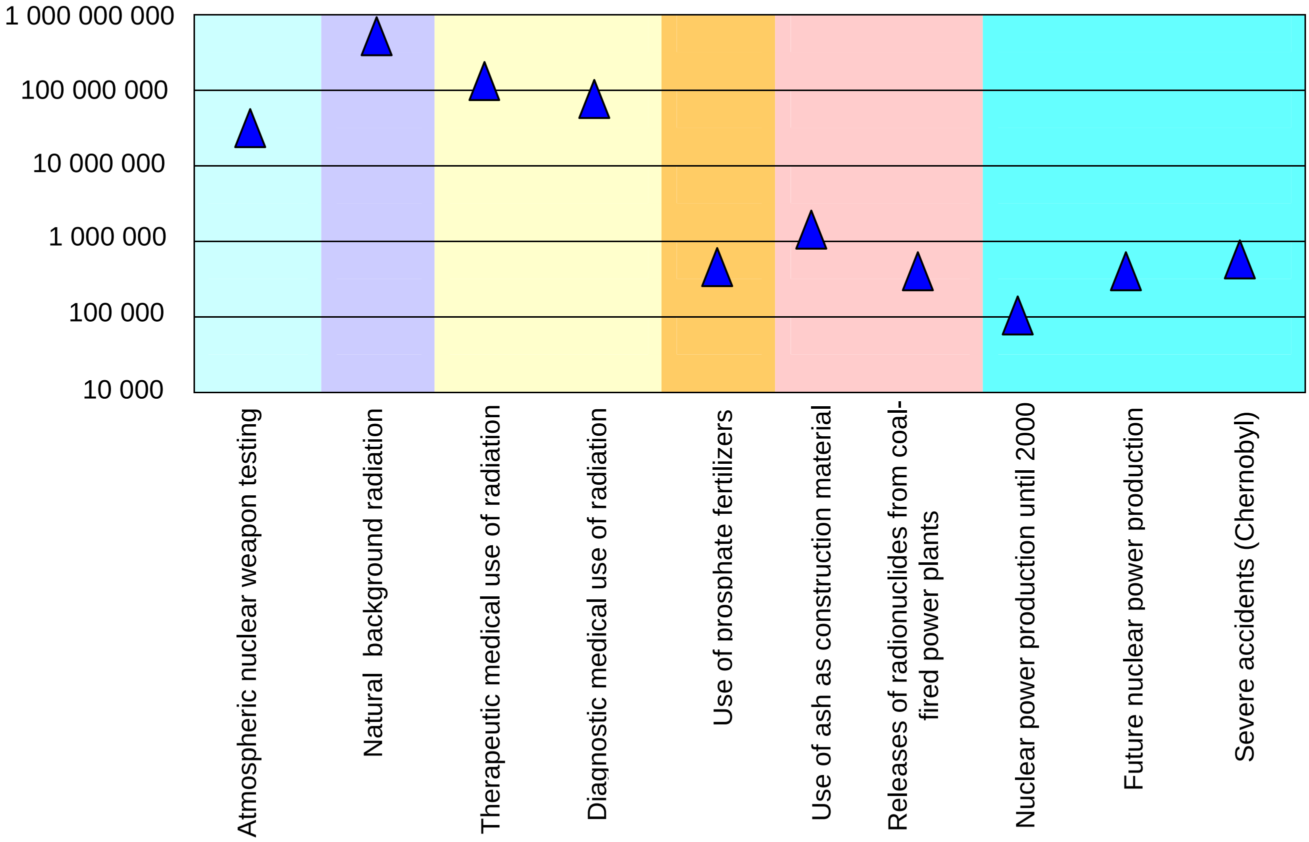

Figure 5.1. Comparison of public radiation exposures (manSv) caused by different practices or activities/events derived from the data in [Refs. 5.8, 5.9]

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6. LIFE CYCLE ASSESSMENT OF ENERGY PRODUCTION AND TRANSPORTATION

6.1. Comparative Assessment of Alternative Energy Sources

In the 1970s, a number of assessments were performed to compare alternative energy sources on the basis of public and occupational health effects from the production of a certain amount of electric energy (1 GWa). The assessments considered full fuel cycles consisting of extraction, preparation and transportation of fuel and electricity generation. The fuel cycles considered were uranium, coal and oil. Health effects were evaluated based on the number of deaths from accidents and diseases as well as on cases of diseases per GWa of electric energy.

After the first oil crisis in 1972, many industrialised countries set out to search for energy sources other than oil. In particular, those countries with few or no fossil energy resources have developed and harnessed renewable energy sources, mainly biomass and wind. Many industrialised countries have already harnessed most of their hydropower resources, but hydropower is still a viable source of renewable energy in several developing countries. The development of solar and fuel cells has been prompted by the need of electricity sources for space technology.

Different approaches have been adopted to support decision-making on energy and environment issues. One way to combine different environmental impacts of energy is to evaluate the so-called external costs or externalities. These are defined as costs that are not included in the price of energy. Many impacts of energy production on the environment include such costs to the society. In principle, society can include (internalise) some of the external costs in the price of energy, e.g., by imposing taxes. In practice, however, it may be difficult to assess the costs since the knowledge of many environmental impacts is limited, the impacts may occur only after a long delay or the natural values or resources have no market values.

The most comprehensive study into external costs undertaken so far has been the European Commission's ExternE (Externalities of Energy) Research Project. The project was undertaken by researchers from all EU Member States (excluding Luxembourg), Norway and the United States. The methodology used to calculate the external costs is called impact pathway methodology. This methodology begins by measuring emissions. Then the dispersion of pollutants in the environment and the subsequent increase in ambient concentrations is monitored. After that, the impact on issues such as crop yield or health is evaluated. The methodology concludes with an assessment of the resulting cost [Ref. 6.1].

Within the European Commission R&D Programme Joule II, the ExternE Project has developed and demonstrated a unified methodology for quantification of externalities of different power generation technologies. It was launched in 1991 as the EC-US Fuel Cycles Study and continued from 1993 to 1995 as the ExternE Project. In this project, the methodology was applied to selected case studies representing coal, lignite, oil, gas, nuclear, hydro and wind. Along with other projects, the work was continued from 1996 to 1998 as the ExternE National Implementation Project. This project generated more than 60 case studies for fifteen countries and twelve fuel chains. New fuel chains considered in the National Implementation Project were:

- hydropower;
- orimulsion (mixture of bitumen and water, replacing heavy fuel oil);
- waste incineration;
- peat;
- biomass: energy crops gasification;
- biomass: agricultural residues gasification;
- biomass: forestry residue or waste wood combustion.

The original objective of the project was to collect an extensive data set that could be used to look at a range of issues, including:

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

Life cycle assessment has also been used to assess different energy systems from an environmental viewpoint. LCA aims to account for all material flows, direct or indirect, induced by an energy cycle. Since induced flows occur at many geographically different points under a variety of different conditions, it is not practicable to model the fate of all emissions. Usually, only the total emissions of greenhouse gases or other pollutants are evaluated. This method is also called life cycle emissions assessment. This approach can be justified for greenhouse gases and other pollutants with long residence times in the atmosphere. For sulphur dioxide, nitrogen oxides, ozone and particulates, however, this approach is unsatisfactory [Ref. 6.11].

The goal of the European Union research programme, ECLIPSE (Environmental and Ecological Life Cycle Inventories for present and future Power Systems in Europe), was to provide potential users with:

- a coherent methodological framework, including application-dependent methodological guidelines and data format requirements related to the quantification of environmental impacts from new and decentralised power systems in Europe, based on a life cycle approach;
- a harmonised set of public, coherent, transparent and updated LCI data on new and decentralised energy systems; the work covered about 100 different configurations of photovoltaic, wind turbine, fuel cell, biomass and bio-fuelled combined heat and power production (CHP) technologies [Ref 6.2].

The report *Hydropower and the Environment* [Ref. 6.3] presents a summary of life cycle assessments of energy systems published between 1992 and 1998. The energy systems were grouped in three categories according to their ability to meet fluctuations in electric energy demand:

1. Systems capable of meeting base-load and peak load:
    - Hydropower with reservoir
    - Diesel
2. Base-load options with limited flexibility:
    - Hydropower, run-of-river
    - Coal
    - Lignite
    - Heavy fuel oil
    - Nuclear
    - Combined cycle gas turbines
    - Large fuel cell
    - Biomass: energy plantation
    - Biomass: forestry waste combustion
3. Intermittent options that need backup production:
    - Wind power
    - Solar photovoltaic

In the USA, the National Renewable Energy Laboratory has performed a series of life cycle analyses to compare fossil fuel and biomass combustion. The effect of carbon dioxide capture from flue gases and its sequestration in underground disposal sites has also been considered. The following energy systems have been studied [Ref. 6.8]:

- Coal
- Natural gas combined cycle
- Tree plantation and biomass gasification combined cycle
- The previous systems with carbon dioxide sequestration

The University of Wisconsin has performed life cycle analyses for natural gas combined cycle, solar photovoltaic, windpower and nuclear power [Refs. 6.32, 6.44, 6.45].

The Australian research project *Coal in a Sustainable Society* [Ref. 6.34] considered, among others, the following energy systems:

- Lignite, pulverised firing
- Coal, pulverised firing
- Coal, pressurised fluidised bed combustion
- Coal, integrated gasification combined cycle
- Coal, integrated gasification combined cycle, CO_2 recovery
- Coal gasification, where the hydrogen produced operates a solid oxide fuel cell
- Natural gas combined cycle
- Tree plantation and biomass gasification combined cycle
- Solar photovoltaic
- Wind power
- Nuclear power

In the following sections, results of recent life cycle assessment studies have been presented in tabular and graph form. Only original studies have been used as source material to ensure that all data can be traced back to the original references. The original studies of electricity generation systems (Sections 6.2 and 6.3) were published between 1996 and 2004. However, they are not included in the publication *Hydropower and the Environment* [Ref. 6.3]. The studies of combined heat and power production (Section 6.4) were published between 1997 and 2004. There are fewer life cycle assessment studies of space heating than of electricity; two of them are discussed in Section 6.5. Only two life cycle assessment studies of transportation are discussed in Section 6.6. These studies were published in 2002 and 2004, respectively.

6.2. Electricity from Fossil Fuel Combustion Cycles

Table 6.1 is a summary of life cycle emissions for fuel cycles based on fossil fuel combustion. The emission data has been extracted from National Renewable Energy Laboratory studies [Refs. 6.5–6.8], ExternE National Implementation Project reports [Refs. 6.9–6.20], the Vattenfall brochure [Ref. 6.21], Maier's thesis [Ref. 6.32] and the *Coal in a Sustainable Society* report [Ref. 6.34]. The sites of existing power plants are given. Several analyses, however, are performed for future or hypothetical power plants. In such cases, only the name of the country is given. Other data given for each power plant are net electrical capacity, load factor (the ratio of full load hours to total hours in a year in per cent) and net thermal efficiency.

For each fuel cycle, the total greenhouse gas emissions are expressed as tonnes of CO_2 equivalent per 1 GWh of electricity produced. Emissions of methane (CH_4) and nitrous oxide (N_2O) have been converted to equivalent emissions of CO_2 with the conversion factors (21 for CH_4 and 310 for N_2O) proposed by the Intergovernmental Panel on Climate Change in 1996. The total emissions of sulphur dioxide (SO_2), nitrogen oxides (NOx) and particles have been expressed as kg/GWh.

The Australian lignite-fired power plant at Loy Yang has no equipment to reduce sulphur dioxide emissions. The Greek lignite-fired power plant at Agios Dimitrios uses lignite ash for flue gas desulphurisation (FGD). Sulphur dioxide emissions vary due to various uncontrollable parameters of the system. The German power plant at Grevenbroich uses flue gas desulphurisation. These power plants are located near lignite open pit mines.

The Australian coal-fired power plant with pulverised firing at Bayswater has particle emission control (fabric filters) but no control for sulphur dioxide or nitrogen oxides emissions. All other existing or hypothetical coal-fired power plants in Table 6.1 have effective control technologies for sulphur dioxide, nitrogen oxides and particles emissions. Power plants with pulverised firing are equipped with flue gas desulphurisation. The emission of nitrogen oxides is controlled either with low-NOx burners or selective catalytic reduction (SCR). The copper oxide process (CuO) removes both sulphur dioxide and nitrogen oxides from the flue gases. Other combustion processes assessed are atmospheric fluidised bed combustion (AFBC), pressurised fluidised bed combustion (PFBC) and integrated gasification combined cycle (IGCC). For particle control, electrostatic precipitators or fabric filters are used.

In the hypothetical US plant with carbon dioxide sequestration, 90% of the CO_2 is captured from flue gas by chemical absorption and is transported by a 300 km pipeline into an underground disposal site. In the hypothetical Australian plant with IGCC and carbon dioxide recovery, 90% of the CO_2 is captured, compressed and disposed of in deep sea aquifers.

The heavy oil-fired power plants in Table 6.1 have varying sulphur dioxide emissions, depending on the sulphur content of the fuel. Flue gas desulphurisation is installed only in the hypothetical UK plant with combined cycle. All existing power plants in Table 6.1 have low-NOx burners.

All natural gas combined cycle power plants in Table 6.1 have similar combustion and emission control technologies. The hypothetical US power plant uses selective catalytic reduction to control NOx emissions. In the hypothetical US power plant with carbon dioxide sequestration, CO_2 is captured and transported in the same way as in the hypothetical coal-fired power plant.

Table 6.1. Electricity from fossil fuel combustion cycle

	Capacity	Load facto	Efficiency	CO2eq	SO2	NOx	Particles	Ref.
	MW			t/GWh	kg/GWh	kg/GWh	kg/GWh	
Lignite								
Loy Yang	2000	88 %	31 %	1144	2830	2130	113	[6.34]
Grevenbroich, FGD	800	74 %	40 %	1062	425	790	511	[6.13]
Ag. Dimitrios, FGD	330	68 %	37 %	1372	890-1574	1054-1106	947	[6.14]
Coal								
Bayswater	2500	70 %	36 %	932	3600	2230	81	[6.34]
Australia, PFBC	1000	70 %	42 %	803	140	540	70	[6.34]
Australia, IGCC	1000	70 %	44 %	766	150	590	21	[6.34]
Australia, IGCC-CO2	1000	70 %	36 %	130	150	810	28	[6.34]
Australia, H2, SOFC	1000	70 %	70 %	500	14	79	1	[6.34]
Meri-Pori, FGD, SCR	560	74 %	43 %	860	820	625	170	[6.11]
France, FGD	600	40 %	38 %	1085	1360	2220	130	[6.12]
Germany, FGD	600	74 %	43 %	898	326	560	182	[6.13]
Amsterdam, FGD	630	72 %	44 %	980	412	720	17	[6.16]
Pego, FGD	1200	65 %	37 %	834	794	1892	258	[6.17]
Spain, FGD	1050	86 %	33 %	1026	1187	1819	1279	[6.18]
UK, FGD	1800			960	1100	2200	160	[6.20]
UK, FGD+SCR	1800			972	1100	700	160	[6.20]
UK, AFBC	1800			1075	1100	1000	160	[6.20]
UK, PFBC	1800			1010	1000	500	30	[6.20]
UK, IGCC	1800			823	200	700	30	[6.20]
USA, low-NOx	425	60 %	35 %	959	2500	2350	9800	[6.6]
USA, CuO	404	60 %	42 %	757	720	540	110	[6.6]
USA	600			847				[6.8]
USA, CO2 seq.	600			247				[6.8]
Heavy fuel oil								
Cordemais, low-NOx	700	17 %	39 %	866	5260	1200	130	[6.12]
Greece	120	80 %	37 %	777	3639	1450	311	[6.14]
Monfalcone, low-NOx	640	57 %	40 %	774	2160	990	170	[6.15]
Stenungsund, low-NOx	820	11 %		825	620	750		[6.21]
UK, combi, FGD	528			657	1030	988	16	[6.20]
Natural gas combined cycle								
Australia	624	70 %	49 %	439	1	1400		[6.34]
France	250	68 %	52 %	433		710		[6.12]
Germany	778	74 %	58 %	398	3	277	18	[6.13]
Italy	680	68 %	47 %	448		460		[6.15]
Eemshaven	1669	75 %	55 %	421		312	32	[6.16]
Tapada do Outeiro	918	86 %	48 %	440				[6.17]
Spain, low-NOx	624	95 %	52 %	407	171	259		[6.18]
Sweden	900	86 %		440	15	100		[6.19]
UK, low-NOx	652	90 %	52 %	411		460		[6.20]
USA, SCR	505	80 %	49 %	499	324	570	133	[6.7]
USA, CO2 seq.	600			245				[6.7]
Cass County	620	75 %	48 %	469				[6.32]

6.3. Electricity from Renewable and Nuclear Energy Cycles

Table 6.2 is a summary of life cycle emissions for renewable and nuclear energy cycles. The emission data has been extracted from the report *Benign energy?* [Ref. 6.4], National Renewable Energy Laboratory studies [Refs. 6.5–6.8], ExternE National Implementation Project reports [Refs. 6.9–6.20], Vattenfall Environmental Product Declaration documents [Refs. 6.22–6.26], ECLIPSE Project reports [Refs. 6.27–6.31], the theses of Maier [Ref. 6.32] and Turkulainen [Ref. 6.33], the *Coal in a Sustainable Society* report [Ref. 6.34] and the brochure by Hydro-Québec [Ref. 6.43]. The names of existing nuclear and hydro power plants are given in Table 6.2. Also in Table 6.2, the data on Swedish hydropower are averages over four (Lule älv river) and three (Ume älv river) plants representing the different schemes in each river. The Canadian La Grande complex consists of nine plants.

A common feature of these energy sources is that the emissions of greenhouse gases and other atmospheric pollutants arise from other stages of the life cycle than power generation. Such stages are raw material extraction, component manufacture, fuel and material transportation and construction and dismantling of facilities. The emissions from these stages depend, among other factors, on the national mix of electric power production. In countries where most of the electricity is produced from fossil fuel combustion (e.g., USA, 61%), the emissions are greater than in countries using fewer fossil fuels in power production (e.g., Switzerland, 3%).

However, greenhouse gases (carbon dioxide and methane) are emitted from hydroelectric reservoirs due to the natural degradation of flooded vegetation and soil by microbes. Actual emissions vary considerably between individual schemes, depending on the flooded area, vegetation type, soil type and temperature. In addition, the emissions vary with time. As a result, average emission values are difficult to estimate. Large run-of-river schemes have very small reservoir sizes (or none at all) and so do not give rise to significant emissions of greenhouse gases [Ref. 6.4].

No net carbon dioxide emissions are assumed to arise from the biomass combustion fuel cycle because the carbon contained in the fuel has been absorbed from the atmosphere by living plants. In the hypothetical integrated gasification combined cycle power plant with CO_2 sequestration, the estimated greenhouse gases emissions of the fuel cycle are negative. This is because trees in the energy plantation absorb carbon dioxide from the atmosphere, and the CO_2 formed during power generation is disposed of underground.

The solar photovoltaic (PV) systems in Table 6.2 represent four PV technologies: single-crystalline silicon, multi-crystalline silicon, amorphous silicon and copper indium gallium diselenide. The Australian study has been carried out for a 400 kW solar farm consisting of 50% amorphous and 50% multi-crystalline silicon solar panels supported by galvanised steel framing on concrete foundations. In the other studies, photovoltaic modules are placed on slanted roofs as retrofit.

The life cycle emissions of wind power depend on the amount of material and work needed to construct the wind turbines. The amount of electricity produced by a wind turbine during its life also depends on the load factor of the turbine. This factor is determined by the local wind statistics and the dimensions and other properties of the wind turbine. Note that the Swedish results are averages of eleven wind turbines with sizes ranging from 0.225 to 1.75 MW and load factors ranging from 16–30%. Several of the original studies were actually conducted for wind farms consisting of a number of wind turbines. However, the number of turbines in a wind farm is not expected to affect the life cycle emissions significantly.

The greenhouse gas emissions from a nuclear fuel cycle are due to the fossil fuel-based energy and electricity needed to mine and process fuel and for the construction and materials of fuel cycle facilities. Most of the energy is consumed to enrich the content of the isotope U-235 in natural uranium. The gas diffusion method consumes about 40 times more electricity than the gas centrifuge method. The highest figure (40 t/GWh) refers to a cycle where enrichment is based on the gas diffusion method, and the US electricity production mix (65% fossil fuel-based) is assumed. On the other hand, in the Swedish cases, the enrichment is performed either by centrifuge method in the UK or by gas diffusion in a French facility for which the electricity is produced by nuclear power.

Table 6.2. Electricity from renewable and nuclear energy cycles

	Capacity	Load factor	CO2eq	SO2	NOx	NMVOC	Particles	Ref.
	MW		t/GWh	kg/GWh	kg/GWh	kg/GWh	kg/GWh	
Solar photovoltaic								
Australia, amor.+multi	400 kW		104	320	1330		55	[6.34]
Germany, single-cryst.	4,8 kW		55	104	99		6	[6.13]
Germany, multi-cryst.	13 kW		51	114	82			[6.13]
Italy, single-cryst.	1 kW		43	182	84	14	25	[6.28]
Italy, multi-cryst.	1 kW		51	215	99	16	31	[6.28]
Italy, amorphous	1 kW		44	203	99	12	55	[6.28]
Italy, GIGS	1 kW		45	185	90	12	35	[6.28]
USA, amorphous	8 kW		12,5					[6.32]
Hydro with reservoir								
Africa	1600	64 %	8-15	20-60	8-13			[6.4]
Itaipu, Brazil	12600	68 %	3,5-6,5	9-24	3-6			[6.4]
Churchill, Canada	5428	73 %	10-19					[6.4]
Petit Saut, Guayana	116	55 %	60-120					[6.4]
Hydro, river system								
La Grande, Canada	15300	58 %	33					[6.43]
Lule älv, Sweden	1492	34 %	5,1	1,6	4			[6.22]
Ume älv, Sweden	704	51 %	4	1,6	4,6			[6.23]
Tree plantation								
Australia, IGCC	110	80 %	36	290	610		26	[6.34]
France, IGCC	40	70 %	17,7	40	350		40	[6.12]
UK, IGCC	8	85 %	15,1	45	485		79	[6.20]
USA, IGCC	113	80 %	49	302	686	595	42	[6.5]
USA, IGCC, CO2 seq.	600		-667					[6.8]
Wind								
Australia, onshore	0,6	21 %	12,2	59	73		3,5	[6.34]
Denmark, onshore	0,5	25 %	14,5	32	48			[6.10]
Denmark, offshore	0,5	29 %	22	45	76			[6.10]
Finland, onshore	0,6	23 %	8,4	22	26			[6.33]
Germany, onshore	0,25	25 %	6,9	15	20		4,6	[6.13]
Greece, onshore	0,23	35 %	8,2	79	32			[6.14]
Sweden. onshore	0,23-1,75	20 %	10,3	23	23			[6.26]
UK, onshore	0,3	31 %	9,1	87	36			[6.20]
ECLIPSE, onshore	0,6	29 %	7,4	22	15	1,5	7,8	[6.27]
ECLIPSE, onshore	1,5	29 %	12,4	58	24	2,4	14	[6.27]
ECLIPSE, offshore	2,5	46 %	9,1	35	21	2,4	11	[6.27]
Nuclear								
Australia, PWR	1000	80 %	40	157	240		0,6	[6.34]
Germany, PWR	1375	89 %	20	32	70			[6.13]
Forsmark, BWR	3095	87 %	3	11	9			[6.25]
Ringhals, BWR+PWR	3530	82 %	3	11	9			[6.26]
Sizewell, PWR	1258	84 %	12					[6.20]

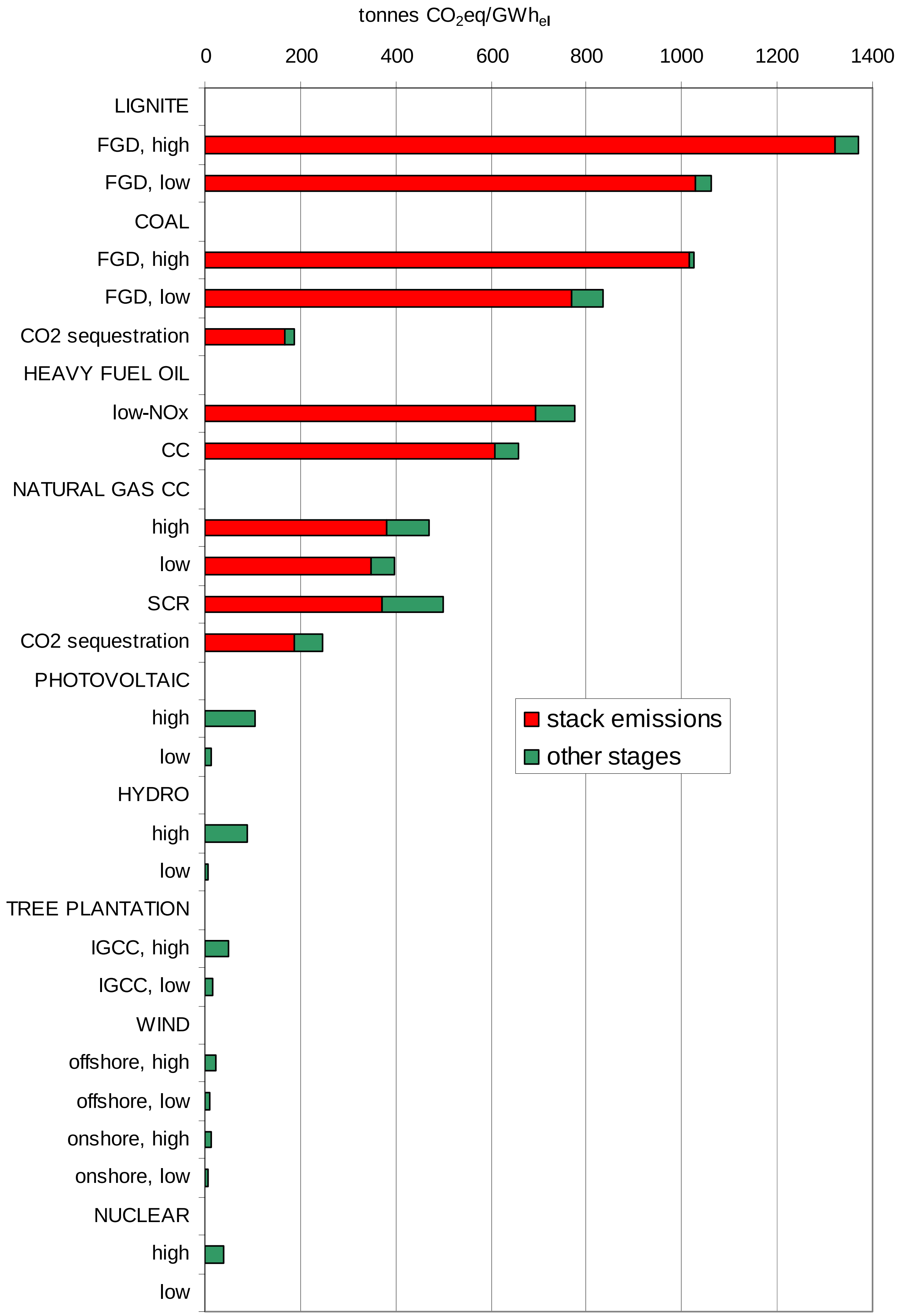

Figure 6.1. Greenhouse gases emissions from alternative electricity production systems (tonnes of carbon dioxide equivalent per GWh of electricity generated)

Figure 6.1 presents a comparison of greenhouse gas emissions of fossil, renewable and nuclear energy systems. This figure has been adapted from the presentation of the results of the Comparative Assessment of Energy Sources Programme performed between 1994 and 1998 and organised by the International Atomic Energy Agency [Ref. 6.42]. The emissions have been divided into direct (stack) and indirect (other stages of the life cycle) emissions. As noted in Ref. 6.42, the range of assessed emissions has been indicated by presenting the highest (high) and lowest (low) values in Tables 6.1 and 6.2. In addition, the impact of certain emission control technologies (CO_2 sequestration, low-NOx burners and selective catalytic reduction) on the greenhouse gas emissions can been seen in Figure 6.1. Note that these values represent only a limited number of energy systems and do not necessarily cover the ranges of the respective technologies. Figure 6.2 presents the results for renewable and nuclear energy systems on a scale that allows comparison between the different alternatives shown in Table 6.2.

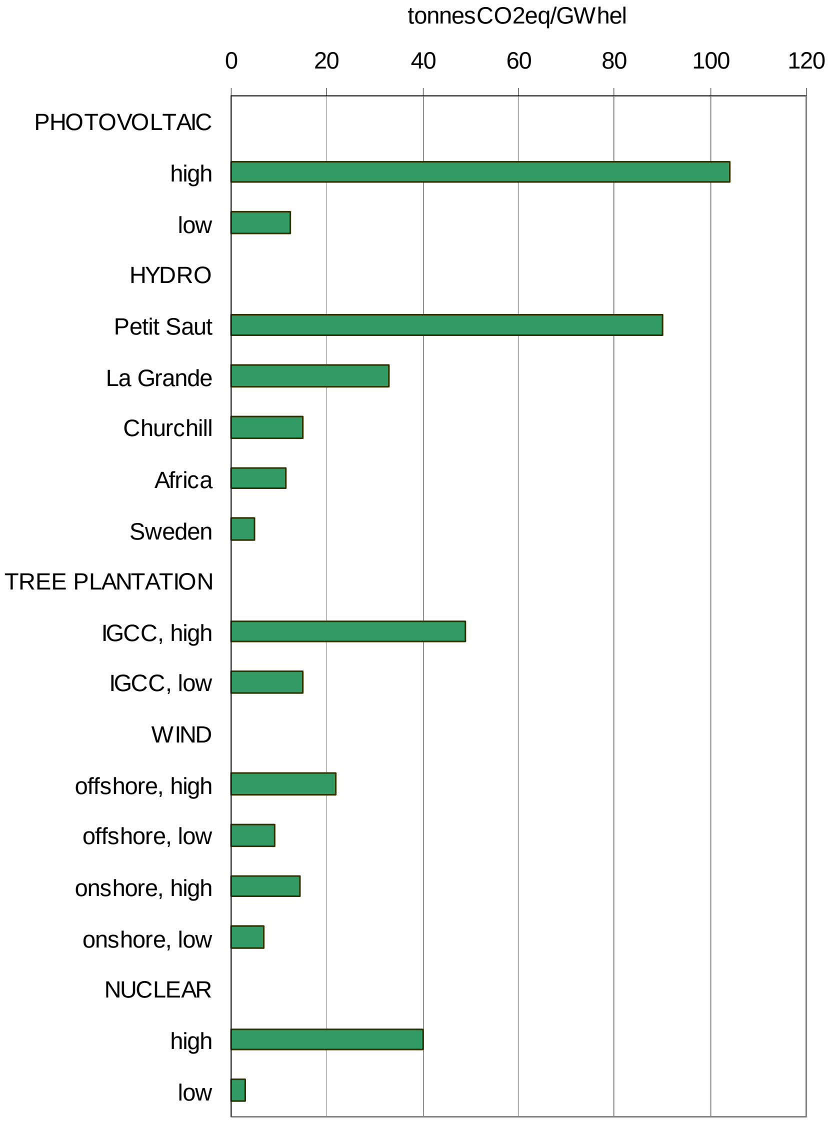

Figure 6.2. Greenhouse gases emissions from renewable and nuclear electricity production systems (tonnes of carbon dioxide equivalent per GWh of electricity generated)

The emissions other than greenhouse gases presented in Tables 6.1 and 6.2 are not shown in graph form because a mere comparison of technologies, such as those in Figures 6.1 and 6.2, is quite difficult for these emissions. Emissions of sulphur dioxide are determined by the sulphur content of the fuel, which varies considerably for lignite, coal and heavy fuel oil. The sulphur content, and possibly other properties of the fuel, affect the choice of control technology and removal efficiency.

6.4. Combined Heat and Power Production Cycles

Table 6.3 is a summary of life cycle emissions for fuel cycles with combined heat and power production (CHP). The emission data has been extracted from ExternE National Implementation Project reports [Refs. 6.9–6.20] and ECLIPSE Project reports [Refs. 6.27–6.31]. For each fuel cycle, the heat produced is used for district heating. The ratio of electricity to district heat produced varies according to the type of energy system. For existing plants, the annual variation of heat load also affects this ratio.

To compare the life cycle emissions of different energy systems with each other, the emissions must be allocated to the electricity and district heat produced. Different allocation schemes have been proposed, but so far there is no generally accepted one. The most common allocation scheme is based on the exergy concept. Exergy is a measure of how much of a quantity of energy can be converted into mechanical work. By definition, electrical energy can be converted into an equal amount of mechanical work. However, only a part of thermal energy can be converted into work. The maximum amount of mechanical energy is determined by the laws of thermodynamics (the Carnot principle). The ratio of mechanical work to thermal energy is given by the Carnot factor $p = 1 – T_0/T$, where T_0 is the ambient temperature and T is the temperature of water fed into the district heating network.

To determine exergy, the formula is as follows: Denote the electrical energy produced as E and the amount of district heat produced as Q. Then the amount of exergy produced by the system is E + pQ. The portion of emissions attributed to electricity production is E/(E + pQ), and that attributed to the production of district heat is pQ/(Q + pQ) times the total emissions.

In practical situations, the starting point is a given demand for electricity and district heat. There are alternative ways to satisfy this demand. Electricity may be produced, for example, by condensing power plants or it may be extracted from the main grid, and heat may be produced, for instance, by central heating boilers. These alternatives each have specific emissions of greenhouse gases and other pollutants.

In Table 6.3, different energy systems for the production of electricity and district heat have been combined on the basis of total annual exergy produced. The total greenhouse gas emissions are expressed as tonnes of CO_2 equivalent per 1 GWh of exergy produced. The total emissions of sulphur dioxide SO_2, nitrogen oxides NOx, non-methane volatile organic compounds (NMVOC) and particles have been expressed as kg/1 GWh of exergy produced. The Carnot factor p ranges from 0.2 to 0.23. For the references where no value for the Carnot factor is given, the value p = 0.23 has been assumed. Figure 6.3 presents a comparison of greenhouse gas emissions of CHP systems divided into direct (stack) and indirect (other stages of the life cycle) emissions.

The coal-fired power plant in Västerås (Sweden) is equipped with flue gas desulphurisation and selective catalytic reduction. The natural gas combined cycle power plant in Linz (Austria) uses selective catalytic reduction, and the one in Hilleröd (Denmark) uses low-NOx burners to control nitrogen oxides emissions.

The first two state-of-the-art natural gas engines shown in Table 6.3 operate in Germany. In both systems, oxidation catalysts have been installed for emission reduction. The third and fourth examples are based on technologies expected to be available around 2005. In these systems, the air ratio of combustion is controlled to make sure that the three-way catalyst runs in optimal condition for emission reduction. In addition, cooled flue gas is re-circulated to reduce the maximum combustion temperature, resulting in low-NOx production. The fifth engine represents the effect of improved technologies expected to be available around 2010.

The first fuel cell in Table 6.3 is based on phosphoric acid (PAFC) and the second on polymer electrolyte (PEFC) technology. Both are natural gas-fired. The four last fuel cells in Table 6.3 are based on solid oxide technology (SOFC). The third and fourth are natural gas-fired. The fourth fuel cell is connected to a micro gas turbine thanks to which the net electrical efficiency is increased from 47-58%. The fifth fuel cell is hydrogen-fired. The hydrogen is produced by electrolysis with electricity from a 1.5 MW onshore wind turbine. The sixth fuel cell is biogas-fuelled. The biogas is assumed to be synthesis gas produced from wood chips. The electricity and heat produced by fuel cell systems refer to the assumed lifetime of 100,000 hours [Ref. 6.30].

Forestry waste consists of residues from tree-felling or waste wood from sawmills. It is combusted either on grate or in a circulating fluidised bed (CFB). The power plant in Norrköping uses selective catalytic reduction to control emissions of nitrogen oxides. In the third and fourth hypothetical Swedish power plants, fuel is dried with steam. The fourth alternative is the combined cycle process based on pressurised fluidised bed gasification (PFBG). The second and third alternatives use selective, non-catalytic reduction to control emissions of nitrogen oxides.

Table 6.3. Combined production of electricity and district heat (per 1 GWh of exergy)

	Capacity	Electricity	Dist. heat	CO2eq	SO2	NOx	NMVOC	particles	Ref.
	MW	GWh/a	GWh/a	t/GWh	kg/GWh	kg/GWh	kg/GWh	kg/GWh	
Coal									
Västerås, FGD, SCR	520	643	1093	880	188	225		215	[6.19]
Natural gas combined cycle									
Linz, SCR	116			551	0,5	333	12		[6.9]
Hilleröd, low-NOx	77	300	370	539	1,8	500		0,02	[6.10]
Natural gas engine									
Germany, stand-alone	5	10,7	16,8	601	307	792	343	39	[6.29]
Germany, indoors	1,3	2,2	4	633	308	820	285	40	[6.29]
Low-NOx	0,9	2	2,3	534	321	287	449	41	[6.29]
Low-NOx	0,9	2	2,8	574	392	344	542	49	[6.29]
Future	0,9	2,1	2,8	553	378	315	522	47	[6.29]
Large fuel cell		GWh/	100 000 h						
PAFC, nat. gas	0,47	20	27	618	313	283	233	50	[6.30]
PEFC, nat. gas	0,4	20	20	592	284	255	226	43	[6.30]
SOFC, nat. gas.	0,43	25	17,6	514	228	220	202	37	[6.30]
SOFC + gas turbine	0,4	29	11	430	188	185	169	31	[6.30]
SOFC, H2, wind	0,48	25	17,6	71	191	144	3	191	[6.30]
SOFC, biogas	0,43	25	17,6	26	107	190	59	54	[6.30]
Forestry waste		GWh/a	GWh/a						
Reuthe, grate	1,2	4,7	29	99	56	1570	170	160	[6.9]
Forssa, CFB	17	56,8	155	93	408	1570		210	[6.11]
Germany, CFB	20	10,8	38,4	20	44	1225	37	31	[6.13]
Fiqueira da Foz, grate	17	127	171	10					[6.17]
Norrköping, CFB, SCR	100	210	552	13	95	475		57	[6.19]
Sweden, CFB	42	30	102	25	111	902	64	58	[6.31]
Sweden, grate	100	91	232	36	139	628	97	34	[6.31]
Sweden, grate+dry	205	98	397	29	139	959	67	24	[6.31]
Sweden, PFBG	119	260	264	17	300	496	44	42	[6.31]

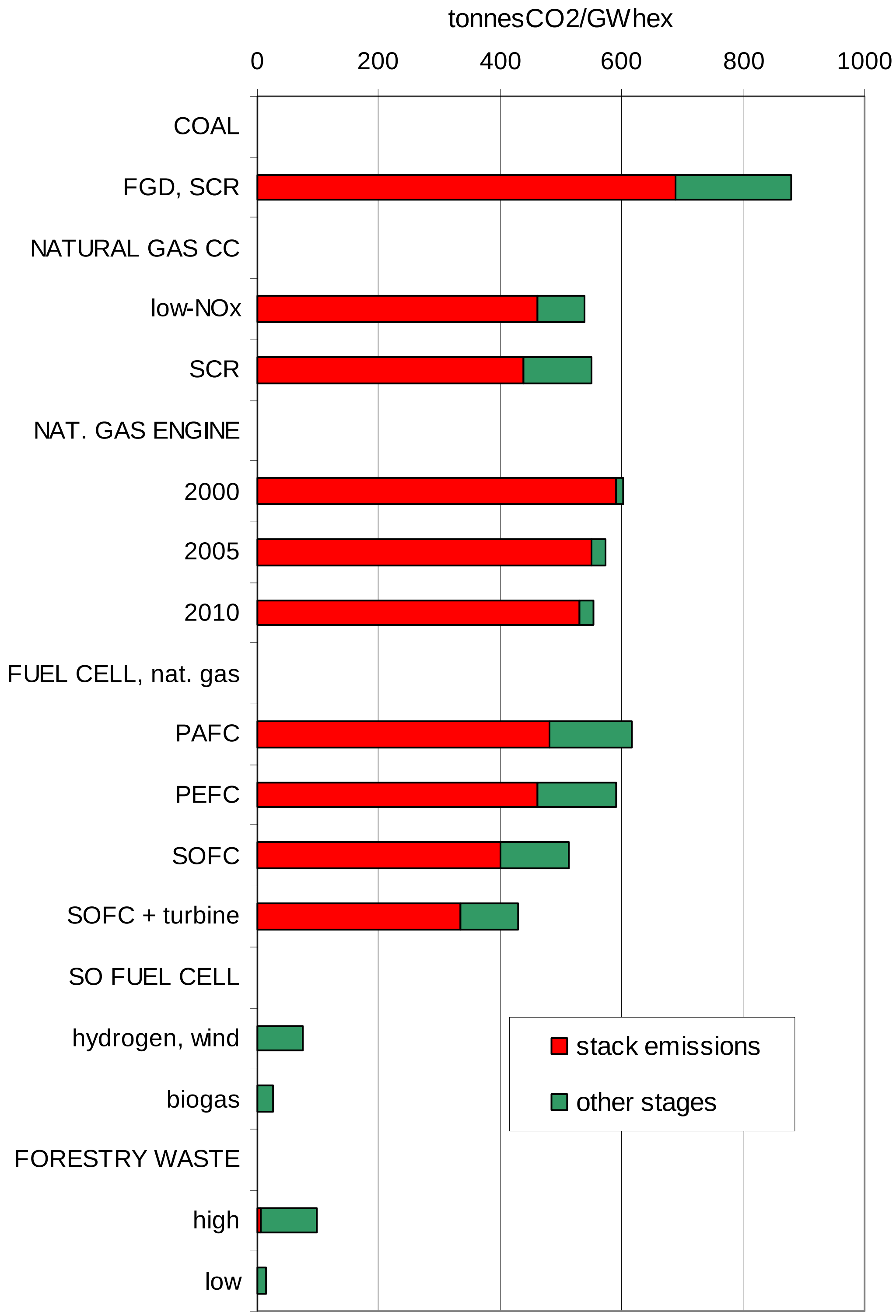

Figure 6.3. Greenhouse gases emissions from alternative heat and electricity production systems (tonnes of carbon dioxide equivalent per GWh of exergy generated)

6.5. Space Heating

Table 6.4 is a summary of life cycle emissions for space heating fuel cycles. The data has been taken from the US study by Delucchi [Ref. 6.39] and the Swiss studies performed at the Paul Scherrer Institute [Refs. 6.40, 6.41]. The heat is produced by stoves burning coal products and by boilers burning light fuel oil, liquefied petroleum gas, natural gas or wood chips. The heat pump operates with electricity produced either by the Swiss mix (61% hydro, 35% nuclear, 3% fossil and 1% renewables) or by a natural gas-fired combined cycle power plant. The electricity fed into the electric heaters is produced at natural gas, fuel oil or coal-fired condensing power plants. Note that Delucchi [Ref. 6.39] uses a set of CO_2 equivalency factors that differs from that specified by the IPCC in 1996.

Figure 6.4 depicts the greenhouse gas emissions of the heating systems in Table 6.4 in graph form. No split into direct and indirect emissions was presented in the original source [Refs. 6.39, 6.40, 6.41].

Table 6.4. Space heat from combustion, heat pump and electricity cycles

	Capacity	CO2eq	SO2	NOx	Ref.
	kWth	t/GWh	kg/GWh	kg/GWh	
Electricity					
natural gas		712			[6.39]
heavy fuel oil		1007			[6.39]
coal		1102			[6.39]
Lignite					
stove, briquet	5-15	700			[6.41]
Coal					
stove, hard coal briquet	5-15	529			[6.41]
stove, hard coal coke	5-15	575			[6.41]
stove, anthracite	5-15	484			[6.41]
Light fuel oil					
boiler	10	369			[6.41]
boiler, condensing	10	342			[6.41]
boiler	100	365			[6.41]
boiler, condensing	100	338	450	330	[6.41]
boiler		357			[6.39]
Liquefied petroleum gas					
boiler, refinery gases		323			[6.39]
boiler, natural gas liquids		298			[6.39]
Natural gas					
boiler, low-NOx	<100	302			[6.41]
boiler, low-NOx, condensing	<100	271	120	180	[6.41]
boiler		263			[6.39]
Heat pump					
ground, hydro+nuclear	10	29	125	60	[6.41]
ground, natural gas CC	10	105			[6.41]
Wood chips					
boiler, softwood	50	23			[6.41]
boiler, softwood	300	21	150	700	[6.41]
boiler, hardwood	50	16			[6.41]
boiler, hardwood	300	14			[6.41]
boiler, sawmill waste	300	10			[6.41]

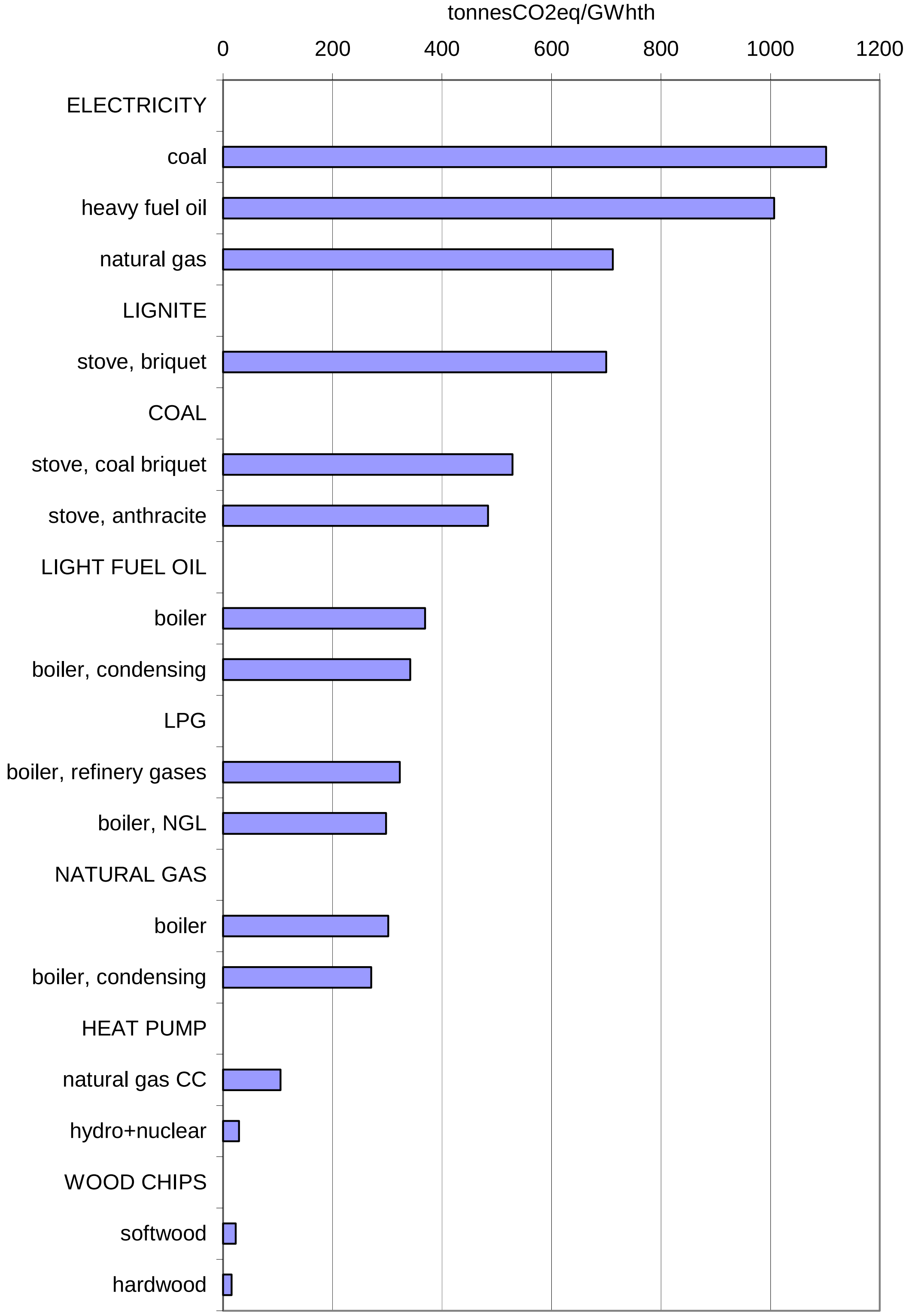

Figure 6.4. Greenhouse gases emissions from alternative space heating systems (tonnes of carbon dioxide equivalent per GWh of heat generated)

6.6. Transportation

Life cycle assessment has been applied to the comparative evaluation of alternative automotive fuels and technologies available in the near future. At present, 99% of the energy consumed in road transportation is based on crude oil. Carbon dioxide emissions result not only from fuel combustion on board the vehicle, but also from fuel extraction, transport, production and distribution. Road traffic is a major source of national carbon dioxide emissions in industrialised countries. Thus it is reasonable to compare alternative fuels and technologies on the basis of emissions of carbon dioxide as g CO_2eq/km.

Alternative fuel chains can involve the use of alternative primary energy sources, innovative fuel production technologies, new automotive fuels or innovative vehicle power-trains. Primary energy sources besides crude oil may be natural gas, biomass, hydro, wind or solar energy. A wide variety of energy carriers can be derived from these sources: petrol, diesel, liquefied petroleum gas, compressed natural gas, liquefied natural gas, methanol, ethanol and hydrogen end electricity. To produce these energy carriers, different production methods can be employed. Furthermore, fuel can be produced centrally at large-scale plants, locally at retail stations or somewhere in between. Fuel may also be converted on board the vehicle. All these options create a wide range of alternative fuel chains [Ref. 6.36].

Since there are so many combinations of fuel power-train, it has been customary to perform the life cycle assessment in two stages. The first stage is called well-to-tank and comprises fuel extraction, transport, production and distribution. The second stage is called tank-to-wheel and comprises conversion of fuel energy into motion of the vehicle. A complete life cycle assessment combines the results of these two stages and is called well-to-wheel.

Most LCAs have considered only light-duty vehicles (for a summary, see, for example, Ref. 6.37), although a few analyses have been performed for heavy-duty vehicles (see Ref. 6.38, for example). Tables 6.5 and 6.6 reproduce the results of two well-to-wheel life cycle analyses performed in Europe for light-duty vehicles.

The GM study [Ref. 6.35] combined fourteen fuels (88 fuel pathways) with 22 vehicle power-trains. The fuels considered were crude oil-based (petrol, diesel and naphtha), natural gas-based (compressed natural gas, diesel and naphtha made with the Fischer-Tropsch process, methanol and hydrogen), biomass-based (methane, Fischer-Tropsch diesel, methanol, ethanol and hydrogen) and electricity-based (hydrogen). Both compressed and liquefied hydrogen were considered. Several alternative methods of hydrogen production were considered. Compressed hydrogen was produced either at a central plant and distributed by pipeline to refuelling stations, or at refuelling stations. Liquefied hydrogen was produced at a central plant and transported by cryogenic road tankers to refuelling stations. Alternatively, compressed or liquefied hydrogen was produced with electricity from the EU electric power mix, natural gas combined cycle power plant or wind turbine.

The vehicle selected for the study was a 2002 production minivan with 1.8-litre petrol internal combustion engine and a 5-speed manual transmission. This vehicle was projected to the 2010 timeframe by introducing an advanced power-train and some anticipated vehicle improvements. In this vehicle, additional power-train technologies were assessed, including:

- advanced internal combustion engine technologies (petrol direct injection, diesel common rail direct injection, natural gas-optimised ignition, hydrogen-optimised ignition) in conjunction with conventional drives;
- more advanced transmissions;
- hybrid drivetrains (engine and electric motor);
- non-hybrid and hybrid fuel cell systems using onboard hydrogen storage and onboard reforming (of petrol, methanol and ethanol).

The Dutch study [Ref. 6.36] compared two primary energy sources: natural gas and crude oil. The crude oil-based fuels were petrol, diesel and liquefied petroleum gas, and the natural gas-based ones were compressed and liquefied natural gas, Fischer-Tropsch diesel, methanol and hydrogen. There were three power-train technologies (internal combustion engine, diesel hybrid and fuel cell).

Table 6.5. Light-duty vehicle transportation using fossil-based fuels (well-to-wheel)

g CO2eq/km	Conventional	Conventional hybrid	Fuel cell non-hybrid	Fuel cell hybrid	Ref.
CRUDE OIL-BASED					
Petrol	217	160			[6.35]
Petrol, direct injection	188	149			[6.35]
Petrol	199		192		[6.36]
Petrol			158	137	[6.35]
Diesel	166	140			[6.35]
Diesel	153	120			[6.36]
Naphtha			152	134	[6.35]
Liquefied petroleum gas	168				[6.36]
NATURAL GAS-BASED					
Compressed NG					
EU natural gas mix	162	127			[6.35]
Russian NG	195	151			[6.35]
from LNG	168	131			[6.35]
Compressed NG	150		129		[6.36]
LNG	163				[6.36]
Fischer-Tropsch, diesel	203	168			[6.35]
Fischer-Tropsch, diesel	181	142			[6.36]
Fischer-Tropsch, naphtha			181	154	[6.35]
Methanol			160	142	[6.35]
Methanol			154		[6.36]
Compr. hydrogen, central					
EU natural gas mix	184	136	103	96	[6.35]
Russian NG	223	164	124	221	[6.35]
Compr. hydrogen, central	231		115		[6.36]
Compr. hydrogen, onsite					
EU natural gas mix	211	156	117	109	[6.35]
Compr. hydrogen, onsite			122		[6.36]
Liquefied hydrogen, central					
EU natural gas mix	253	189	138	131	[6.35]
remote	301	226	165	154	[6.35]
Liquefied hydrogen, central			183		[6.36]

Table 6.6. Light-duty vehicle transportation using biomass- and electricity-based fuels (well-to-wheel)

g CO2eq/km	Conventional	Conventional hybrid	Fuel cell non-hybrid	Fuel cell hybrid	Ref.
BIOMASS-BASED					
Compressed methane					
organic waste	6	6			[6.35]
Fischer-Tropsch, diesel					
residual wood	28	24			[6.35]
Methanol					
residual wood			13	11	[6.35]
Ethanol					
residual straw			29	25	[6.35]
tree plantation			72	65	[6.35]
sugar beet			103	91	[6.35]
Compr. hydrogen, decentral.					
residual wood	17	13	8	8	[6.35]
tree plantation	47	35	25	23	[6.35]
organic waste	4	4	1	0	[6.35]
ELECTRICITY-BASED					
Compr. hydrogen, central					
EU electric power mix	421	312	238	221	[6.35]
wind	3	3	0	0	[6.35]
Compr. hydrogen, onsite					
EU electric power mix	422	309	238	222	[6.35]
natural gas combi	380	280	215	202	[6.35]
wind	3	3	0	0	[6.35]
Liquefied hydrogen, central					
EU electric power mix	486	360	270	252	[6.35]
wind	7	6	2	2	[6.35]

Figure 6.5 represents the greenhouse gases emissions of vehicles with conventional internal combustion engines or fuel cell power-train for selected fuels. The emissions have been split into those from well-to-tank and from tank-to-wheel stages. The emissions from combustion of crude oil and natural gas-based fuel come mainly from vehicle operation (tank-to-wheel stage). The greenhouse gases emissions from the well-to-tank stage of biomass-based fuels are negative, since carbon dioxide is removed from the atmosphere during the growth of the plants, and the carbon is chemically bound to the fuel. During vehicle operation, the carbon is emitted as CO_2, and the well-to-wheel emissions become positive [Ref. 6.35].

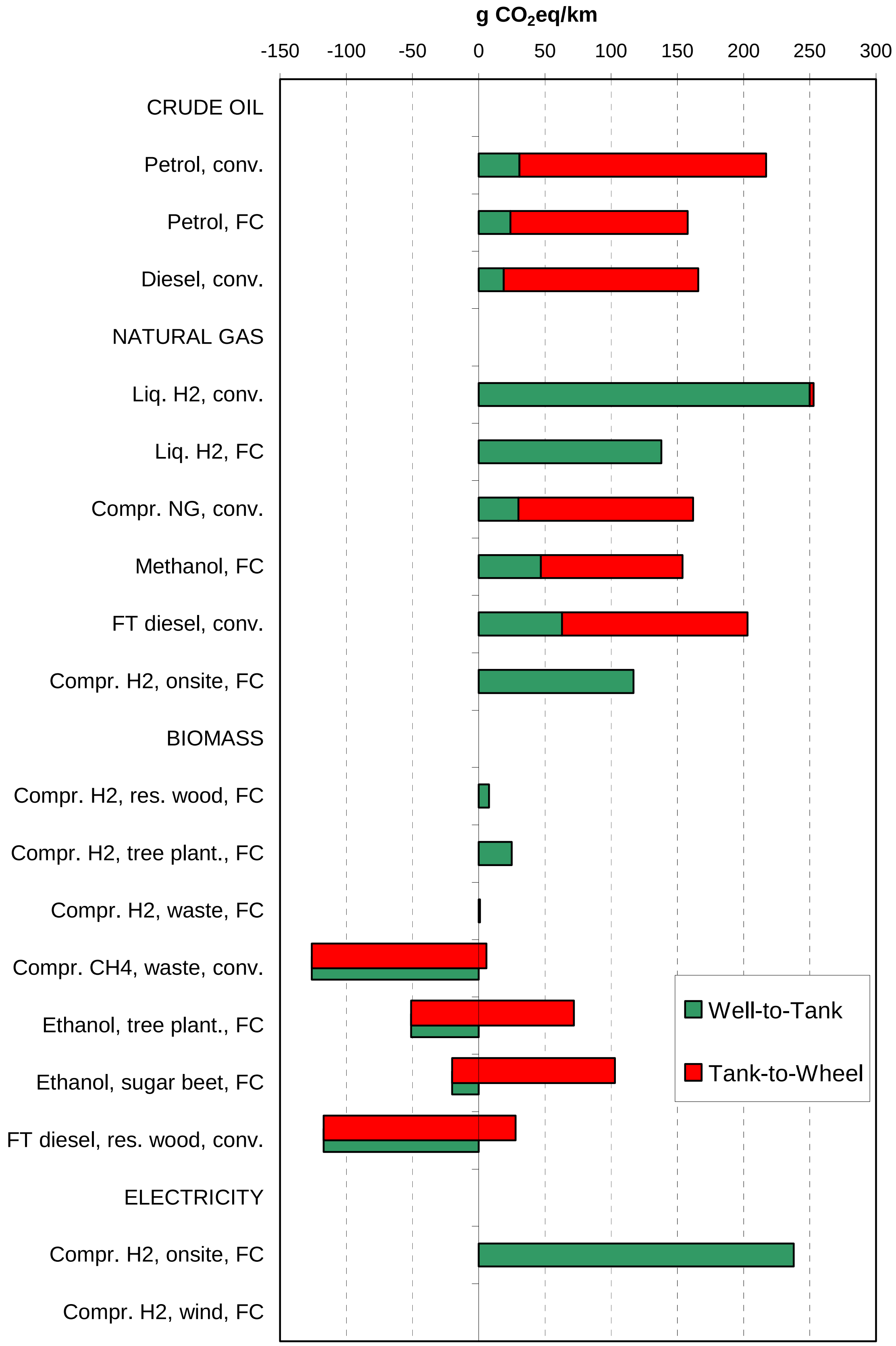

Figure 6.5. Greenhouse gases emission from light-duty vehicles with conventional internal combustion engine or fuel cell power-train for selected fuels [Ref. 6.35]

6.7. Other Effects

Evaluation of emissions from energy production and transportation life cycles has been the principal target of studies because of the direct and indirect impacts on health and environment and the international conventions for emission control. For energy production life cycles, other effects related to rational use of energy, natural resources and land have also been considered. This kind of analysis has been used to compare fossil and renewable energy cycles with each other. Since the renewable energies (particularly solar and wind) are "dilute", more materials and larger land areas are required than for the fossil ones.

One way to compare renewable cycles to fossil cycles is to calculate the so-called life cycle energy payback time. This concept is defined as the time taken by the electricity generation equipment to produce the amount of energy equal to the energy required to build, maintain and fuel the equipment. The amount of fuel energy used in these processes is converted into the corresponding amount of electrical energy, assuming that this fuel is used to generate electricity instead.

Another way to present the results of such an analysis is to calculate the so-called life cycle energy payback ratio. The energy payback ratio (or external energy ratio) is the ratio of the net electrical energy produced over a plant's lifetime to the energy required to build, maintain and fuel the plant over its lifetime, converted to the corresponding amount of electrical energy. The report referred to in Ref. 6.3 presents a summary table of life cycle energy payback ratio studies performed between 1994 and 1999. In Table 6.7, the results for life cycle payback ratio in selected US studies published between 1999 and 2002 are summarised. The studies were performed by the National Renewable Energy Laboratory [Refs. 6.6, 6.7] and the University of Wisconsin [Refs. 6.32, 6.44, 6.45]. All power plants except the one at Cass County are hypothetical. The wind farm with 0.34 MW turbines (Buffalo Ridge Phase I) was an existing one with an actual load factor of 24%. The two other wind farms were under construction, and projected load factors were used [Ref. 6.45].

Table 6.7. Life cycle energy payback time and payback ratio

	Capacity MW	Load factor	Life years	Payback ratio	Ref.
Coal					
USA	1000	75 %	40	11	[6.44]
USA, low-NOx	524	60 %	30	5,1	[6.6]
USA, CuO	425	60 %	30	6,7	[6.6]
Natural gas combined cycle					
USA, SCR	505	80 %	30	2,2	[6.7]
Cass County	620	75 %	40	4,1	[6.32]
Wind					
USA	0,34	24 %	30	14,4	[6.45]
USA	0,75	35 %	25	8,9	[6.45]
USA	0,6	31 %	20	20	[6.45]
Solar photovoltaic					
USA	0,008		30	5,7	[6.32]
Nuclear					
USA	1000	75 %	40	16	[6.44]

The report referred to in Ref. 6.3 also presents a summary table of the land requirements of different electricity generation options. The problem of such comparisons is that the calculated areas are not fully comparable. The area may have other simultaneous uses not related to electricity generation. For example, a hydropower reservoir may also be used for flood control or irrigation and sometimes for fishing and recreation. A tree plantation area may also be used for recreation. Solar photovoltaic modules are usually based on roofs that have no alternative use.

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7. OBSERVATIONS ON VARIOUS PRIMARY ENERGY SOURCES

Questions pertaining to energy accessibility (related to the direct costs of energy), energy availability (related to the security/reliability dimension) and energy acceptability (environmental externalities) form a framework for decision-makers by means of which the relative merits of different options must be gauged. LCA can assist in questions related to environmental impact, but only a subset of these impacts is normally included in an LCA. It can also be argued with reason that some of these externalities cannot be covered by the LCA method – or any other analytical method – but must be dealt with in the political process.

The different energy options differ in the nature and scale of their environmental impacts. Table 7.1 illustrates relative characteristics of various primary energy sources relating to certain key factors which play a vital role in decision-making and which in most cases are covered in LCA studies.

In addition to the results of LCA studies, there are a number of other factors that must be accounted for in decision-making on energy systems. For example, the probability and consequences of hypothetical accidents should be addressed. In the case of nuclear facilities, the safety level can be further improved by introducing additional safety measures and procedures that aim to prevent the initial events and the progression of incidents into accidents which may cause significant releases to the environment. Another way to improve safety is through the mitigation of releases by appropriate in-plant accident management measures. Offsite counter-measures may also be introduced to reduce the consequences. The possibilities for accidents in hydro power systems are very much dependent on local conditions around a particular dam. Other examples are the long-term potential impacts caused by the increased greenhouse gas concentrations in the atmosphere and future impacts brought about by potential releases from nuclear waste repositories. In these cases, the impacts are difficult to compare or aggregate to other types of impacts.

Furthermore, the gradual depletion of primary energy sources is leading to the exploitation of less favourable resources and thus to increased environmental impacts. This may reduce the differences among the considered energy chains in relation to the impact indicators included in the Table 7.1.

Table 7.1. Relative characteristic features of various primary energy sources in view of key factors related to decision-making based on results of LCA-studies

Factors important for decision-making	Combustion based				Nuclear	Hydro	Wind	Solar
	Coal	Oil	Gas	Biomass				
Energy accessibility (related to the direct costs of energy)	F	M	M	M	F	F	D	D
Energy availability (related to the security/reliability dimension)	F	M	M	M	F	F	D	D
Energy acceptability (environmental externalities)	D	D	M	F	F	F	F	F

Relative rankings in the perspective of factors important for decision-making:

- **F** = energy source in **favourable** position
- **M** = energy source in **medium/neutral** position
- **D** = energy source in **disfavoured** position

7.1. Electricity

There are several fuels for and means of producing electricity. Fossil fuels constitute the main source for electricity for the foreseeable future, although the growth of renewables, especially wind, far exceeds the average growth rate. Figure 7.1 illustrates electricity production and projected growth by major generation options in 2001 [Ref. 7.1].

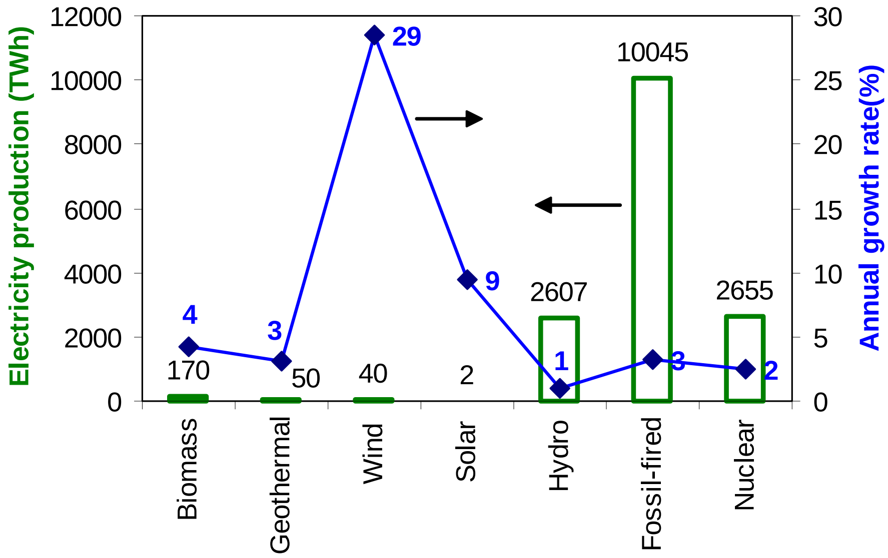

Figure 7.1. The distribution of the global electricity production (15,570 TWh) among different energy sources and the corresponding annual average growth rates during 1993-2001 [Ref. 7.1]

Several technologies exist for converting these energy carriers into electricity. Fuels can be burned on grate, ground into powder and blown as fine dust with air to be ignited in a burner or burned on a bed of hot sand. Solid fuels may be gasified before burning, biofuels and fossil fuels may be mixed together, etc. Each of these requires a different technological solution.

It is evident that, with such a multitude of different fuels and so many technologies for transforming these fuels into electricity, assessing the environmental impacts of all fuel-technology combinations is not an easy task. It is made even more complicated by the fact that the environmental impact of a given plant varies with its environment. The impacts of a plant located far from populated areas are very different from those of a similar plant located in a densely populated area. Again, this may be reflected in the way the emissions of these plants are regulated. The level of accepted environmental impacts may differ in different parts of the world, resulting in unequal levels of emissions. Local geographical and meteorological conditions also have an effect on the level of concentration a given gaseous release will cause.

With electricity production based on conversion of fossil fuels, the main environmental burden originates at the power plant. The contribution of upstream stages – fuel production, transport, etc. – on environmental emissions constitutes at most about 10–15% of the total for most fuel cycles. With the tightening of regulations for power plant emissions, the importance of the environmental burden caused by the upstream stages may grow if the regulation of the emissions at these stages lags.

The environmental burden from hydropower, solar power and wind has a different character. As these systems create practically no emissions during operation, the emissions result from the construction stage. The power production systems themselves occupy or may inundate large land areas or require damming waterways, causing people to be relocated. The visual impacts of these electricity options may be significant but are not easily quantified or assessed.

Since energy in the form of electricity is an important input to many industrial processes, and since there are several alternatives for energy production, many LCAs on electricity production have been carried out at numerous institutes and companies throughout the world.

Normally, LCAs are conducted for a specific purpose. If a comparative study is carried out, the analyst has two or more alternatives to compare. One of these may be the option of not building the plant and instead, importing the electricity. There may be several alternative plant sites.

Caution must be exercised when results of these kinds of studies are put together. The results may not be easily imported to different situations. If the reports are not transparent, the choices the analysts have made cannot be tracked. Some of these choices may be very case-specific, and the use of the results of such studies in different circumstances could lead to wrongly based decisions.

7.2. Impact Categories

The main impacts of electricity production from different production methods are presented in Table 7.2. Some impacts arise during fuel production, others during plant construction and still others during power production.

Table 7.2. The most significant environmental impacts of energy production forms [Ref. 7.2]

Type of impact	**Combustion based**				**Nuclear**	**Hydro**	**Wind**	**Solar**
	Coal	**Oil**	**Gas**	**Biomass**				
Resource depletion	X	X	X		X			
Land use, visual impact	(X)			X		X	X	X
Watercourse regulation						X		
Thermal releases	X	X	X	X	X			
Noise							X	
Radiation					X			
Air quality	X	X	X	X				
Acidification	X	X	X	X				
Eutrophication	X	X	X	X				
Greenhouse effect	X	X	X	X				

7.3. Emissions from Combustion

Several types of materials are emitted from a combustion power system: carbon dioxide, carbon monoxide, hydrocarbons, primary and secondary aerosols, nitrogen oxides, sulphur dioxide and so on. The level and mixture depend on the fuel and the technology used. The emission level is different at different power levels, in steady-state operation and in transients. For meaningful results, a number of decisions must be made about the parameters affecting the study, and these must be clearly spelled out.

Some of the emissions can be estimated or measured with reasonable accuracy, but for some, only rough estimates can be made. Relatively good estimates can be made of CO_2, NOx, SO_2, thermal emissions and solid waste. There are measurements and estimates of total dust and PM10 emissions, but this is less true for the finer fractions, PM2.5, PM1 and nanoparticles.

The impacts of these emissions depend on the location, recipient and scale of the operation. The impacts, for example, of thermal releases into the sea are different from those into an inland water body. The impacts of poor air quality in sparsely populated areas differ from those in urban areas.

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References for Chapter 7

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8. CONCLUSIONS

For a given environmental issue, life cycle assessment comprehensively encompasses all processes and environmental releases beginning with the extraction of raw materials and the production of energy used to create the product through the use and final disposition of the product. LCA extends normal environmental analyses made, for example, for licensing purposes, in its treatment of the whole product life cycle. Thus the emissions originating outside the scope of local, regional and even national regulations are also included.

Conducting an LCA gives a product-centred approach to environmental protection. Specifically, LCA gives information on which stage of a product's life cycle causes the major environmental stress and thus helps actors in the various stages of the product life to share responsibility for reducing the environmental impacts of products. Information from an LCA can help in focussing the efforts to decrease the environmental impacts at the point where these efforts are most effective.

8.1. Results

The main application of LCA to energy production systems is to calculate the emissions of greenhouse gases from the production of unit amounts of electricity, heat or (in combined heat and power production) a combination (based on the exergy principle) of both. In this way, the alternative systems may be ranked according to their respective emissions of greenhouse gases. This ranking can be seen in Figure 6.1. The advantage of analysing full life cycles as opposed to using only emission factors is that renewable and nuclear systems with no direct (stack) emissions can be compared with systems based on fossil fuel combustion. The same applies to space heating and transportation.

With electricity production based on conversion of fossil fuels, the main environmental burden originates at the power plant. The contribution of upstream stages – fuel production, transport, etc. – on environmental emissions constitutes at most about 10–15% of the total emissions for most fuel cycles.

Since all the coal-fired power plants reviewed in the reports included in this study are quite new or hypothetical, they have effective control technologies for sulphur dioxide, nitrogen oxides and particles emissions. Emissions of sulphur dioxide are determined by the sulphur content of fuel, which varies quite widely for lignite, coal and heavy fuel oil. The sulphur content, and possibly other properties of the fuel, affect the choices of control technology and removal efficiency.

A common feature of the life cycles of renewable energy sources and nuclear power is that the emissions of greenhouse gases and other atmospheric pollutants arise from other stages of the life cycle than power generation. These stages are raw material extraction, component manufacture, fuel and material transportation and construction and dismantling of facilities. The emissions from these stages depend, among other factors, on the national mix of electric power production. In countries where most of the electricity is produced from fossil fuel combustion (e.g., USA, 61%), the emissions are greater than in countries using fewer fossil fuels in power production (e.g., Switzerland, 3%).

Greenhouse gases (carbon dioxide and methane) are emitted from hydroelectric reservoirs due to the natural degradation of flooded vegetation and soil by microbes. Actual emissions vary considerably between individual schemes, depending on the flooded area, vegetation type, soil type and temperature. In addition, the emissions vary with time. As a result, average emission values are difficult to estimate.

In these evaluations, renewable fuels and sources and nuclear compare favourably. Using new, advanced fossil technologies with higher efficiencies, the environmental performance of fossil fuel use can be improved significantly.

In heating applications, direct use of fuels compares favourably with electric heating based on the same fuels. In combined heat and power production, the efficiency of fuel use is similar to that of direct conversion to heat. The CHP applications are advantageous if there is a synchronous demand for heat and electric power.

In transportation applications, GHG emissions produced by different options of fossil fuel use vary roughly within a factor of two, with the emissions of fuel cell applications being at the lower end. The use of biomass-based fuels results in emissions that are approximately one order of magnitude lower than the emissions of fossil fuels. In cases where electricity is needed for the conversion process, the assumptions regarding the source of electricity dictate the results.

8.2. Use of the Method

Adding life cycle assessment to the decision-making process provides an understanding of the human health and environmental impacts not traditionally considered when selecting a produce or process. This valuable information provide a way to account for the full impacts of decisions, especially those that occur outside the site, that are directly influenced by the selection of a product or process.

Performing a complete LCA requires significant resources. Usually, at least part of the data needed is taken from generic data or another analysis. The LCA practitioner must keep the scope and aim of the study clearly in mind and avoid taking shortcuts where these might compromise the objective. Knowledge of both the process to be studied and the LCA method is needed.

Factors limiting the applicability of LCA

The limits to LCA applicability are due mainly to:

- uncertainties about the results;
- incomplete scope (some impacts are not covered);
- static analysis (technological progress is not be reflected); and
- site-specific character of the method.

Uncertainties. Uncertainties about the results create a challenge to using those results in policymaking. Since results are site-specific, it is not easy to draw generic conclusions from LCA studies. First, there is a generalised lack of methodological consistency across different sources. Although the International Organization for Standardisation (ISO) has issued a series of standards (ISO 14040 to 14043) that lay down the basic concepts and general procedures for performing an LCA, these standards are still very general and require ad hoc interpretation when they are to be applied to the assessment of energy systems. This lack of clear and specific guidelines is reflected in many available LCA reports, which also lack harmonisation and transparency regarding their methodological assumptions (choice of system boundaries, allocation procedures, type of emissions to trace, etc.).

As a consequence, a significant amount of LCI data currently available is misused because the scope of the original LCA study often does not match the requirements of other users. This situation can seriously limit the usability of LCI data for energy system analysis and modelling.

Scope limitations. The aggregated nature of LCA, encompassing an entire chain of activities taking place in various jurisdictions, limits its relevance for policymaking. Since the scope of LCA does not cover security of supply, ecosystem integrity, biodiversity or social impacts, the approach is not comprehensive enough for measuring the sustainability of an energy system.

There is a substantial interface between LCA and the economics of resource depletion, and the question of whether current economic decisions correctly reflect resource depletion has not yet answered.

Perhaps the most important issue in LCA is the question of time and discounting. This is particularly critical in discussing the greenhouse gas emission problem, since the damage caused by global warming will occur mainly in a rather distant future and will vary with time; thus it cannot be definitively assessed today.

Many impacts not covered. Furthermore, LCA focuses on what can be readily analysed, but it is not very helpful for criteria which cannot be easily quantified. Differences in social value systems between countries are not reflected. It is uncertain whether a value can be placed on aesthetics or other qualitative externalities. There is research, some of it already incorporated in LCA, that does attempt to quantify such externalities, e.g., through willingness to pay to avoid them. However, biological diversity impacts are much harder to define since we do not know what they are, how to measure them, how they are affected by different power generation or transportation fuelling options or how to measure the changes in biodiversity caused by those impacts.

In most of the studies carried out, emissions from combustion (SO_2, NOx, particles and greenhouse gases) have been taken into account. As far as the energy sources studied are concerned, greenhouse gas emissions would appear to carry relatively great weight. This is partly a logical consequence of the fact that the studies have primarily covered new power plants where attention has been paid to the reduction of sulphur, nitrogen and particle emissions.

Issues pertaining to biodiversity and non-renewable natural resources have not been examined as extensively as the emissions referred to above. Environmental impact scoring systems relating to the use of land and the associated biodiversity also appear somewhat complicated and difficult to interpret. However, even on the basis of the sample calculations, it is clear that these issues may have significant influence on environmental impact scoring. In this way, the insufficient consideration of biodiversity and natural resources essentially impairs the credibility of the assessment methods.

The methods are not comprehensive; for instance, for a host of issues, the methods are not complete enough to be applied to the comparison of all energy sources. It is currently not possible to use these methods for assessing issues such as the risks of power production, scenic values or harnessing of rivers. The problem in converting the environmental impacts to a common scale is the insufficiency of information available on one hand and the dependence on subjective values on the other hand. In addition, it is not evident that the research results are transferable to another place or time.

Limited temporally and spatially. Technology developments that may significantly change life cycle impacts are not taken into account, since the assessment is static and does not reflect dynamic system evolution. Publicly available LCA databases on energy systems often do not include up-to-date, transparent data on new, decentralised renewable power generation systems.

Given the ever-increasing importance that these technologies are expected to assume in the future, this must be seen as a serious shortcoming. Furthermore, the few data currently available are often very general and do not account for the fact that the performance of these systems changes significantly as a function of the geographic and climate conditions under which they operate.

Another aspect seriously limiting the applicability of LCI data for energy modelling, planning and policymaking purposes is that many databases have been developed without the option of future updates. The rapid technological development that pervades today's energy sector is rendering many of these databases obsolete. Hence many important policy decisions and modelling results risk being based on data that – in spite of their apparent robustness – are often inaccurate or outdated.

As a consequence, a significant amount of LCI data currently available is misused because the scope of the original LCA study often does not match the requirements of other users. This situation seriously limits the usability of LCI data for energy system analysis and modelling.

LCI for decision support relies on relevant stressors only. In most cases, when using LCA for comparing different options, only a few stressors prove to be relevant. Relevance may be defined in many ways and depends on the goal of the study. LCIs and databases that are used for many different types of decision support lack one, single goal definition, and therefore, the key question remains: What is “relevant”?

Concluding remarks. Adding LCA to the decision-making process provides an understanding of human health and environmental impacts not traditionally considered when selecting a product or process. This valuable information provides a way to account for the full impacts of decisions, especially those that occur outside the site, that are directly influenced by the selection of a product or process.

Using the results of someone else's LCA can be risky. If the assumptions and choices made are not spelled out clearly, there is a danger of being misguided. The results of LCAs tend to outlive their applicability.

It is important to remember that LCA is a tool to better inform decision-makers and should be included with other decision criteria, such as cost and performance, to make a well-balanced decision.

8.3. Some Possible Areas for Future Research

Some possible areas for future research include:

- assessment of externalities such as security and diversity of supply;
- further investigations in the field of discount rates applicable in the very long term and the value of statistical life;
- incorporation of dynamics, technological progress in LCA;
- energy efficiency of the production chain;
- evaluation of energy policy measures with LCA;
- establishment of a database containing information on externality assessment and the way it is being used.

Finally, it must be remembered that "politics will decide" how and to what extent environmental impacts are ultimately incorporated into economic decisions; politicians are not making the best of all possible decisions in the best of all possible worlds.

ANNEX A: STUDY GROUP MEMBERS AND INVITED EXPERTS

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