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Planning of sustainable energy distribution systems
Part III: A Life Cycle Assessment Perspective

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TECHNICAL REPORT

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Planning of sustainable energy distribution systems
Part III: A Life Cycle Assessment Perspective

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RESULT (summary)

This study provides an introduction to Life Cycle Assessment (LCA) in the context of energy planning, and tries to point out the major differences between emission accounting and a broader LCA perspective. LCA is a holistic approach accounting for all environmental impacts occurring from the system's "cradle" to the "grave", together with all related activities throughout the lifetime of the system. The study presents a broad range of different LCA studies, thus providing a starting point for further studies of LCA of energy systems. The LCA perspective is found to be useful and necessary for sound environmental planning of energy systems, aiming at socio-economic optimal energy systems.

The main conclusions are as follows: For most energy system utilising a fuel, the fuel chain is of great importance. This is the case for sources such as; coal, lignite, natural gas, biomass and oil. The building/demolishing etc. from these energy systems are seldom of great importance. The total Green House Gas (GHG) emissions are for coal around 1000 g CO_2 eq. / kWh, for CCGT 400 g CO_2 eq. / kWh. For renewable technologies, the building phase is often more dominant, being the cause of the major environmental impact. This is the case for solar energy, wind power, hydro power etc. All renewable energies are mostly below 100 g CO_2 eq. / kWh, many below 20 g CO_2 eq. / kWh, with exception for Photo Voltaic (PV), which has more emissions due to energy demanding wafers, which are important components. The PV examples from this study indicates GHG emissions in the range of 100 – 280 g CO_2 eq. / kWh, which is rather high from an energy source seen as renewable. This is however, totally dependent of where the PV plant is situated. Transport of biomass and other fuels is possible without severely increasing the overall environmental impact, as long as the distance is within limits, and done with proper transportation mode. Construction of electricity grids or district heating grids etc. is of less importance in an LCA perspective, the most important part being the losses in the grids, which has to be compensated by increased generation up-stream. This extra generation yields the major part of the environmental impact caused by the distribution grids.

KEYWORDS

SELECTED BY AUTHOR(S)		
	LCA - Life cycle assessment	Energy system planning
	Environmental impact	CO_2-emissions

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1 INTRODUCTION

This report represents part III of the results from the R&D project SEDS – Sustainable energy distribution systems: Planning methods and models' for the project period 2002 – 2007. The main partners within SEDS have been:

- Department of Electric Power Engineering, Norwegian University of Science and Technology (NTNU)
- Department. of Energy and Process Engineering, NTNU
- Department of Energy Systems, SINTEF Energy Research
- Department of Energy Processess, SINTEF Energy Research

The project has been funded by the Research Council of Norway, StatoilHydro, Statkraft alliance (Statkraft SF, Trondheim Energi, BKK), Lyse Energi and Hafslund Nett, while Norwegian Water Resources and Energy Directorate (NVE) has been a co-operating partner. Our international partners have been University of Porto and INESC Porto in Portugal, Helsinki University of Technology and VTT in Finland as well as Argonne National Laboratory in USA and Swiss Federal Institute of Technology (ETH) in Switzerland.

The main objectives of the SEDS project, as stated in the original project plan have been the two following:

1. Develop methods and models that allow several energy sources and carriers to be optimally integrated with the existing electric power system.
   Particular emphasis is placed on distribution systems and integration of distributed energy sources, from a technical, economic and environmental point of view.
2. Develop a scientific knowledge base built on a consistent framework of terminology and concepts for mixed energy systems, in the field of planning methods and models.
   This will be a cornerstone for the curriculum 'Energy and environment' at NTNU.

Mixed energy distribution systems are illustrated in Figure 1. A mixed energy distribution system means (in this context) a local energy system with different energy carriers (electricity, district heating, natural gas, hydrogen) and a mix of distributed energy sources and end-uses.

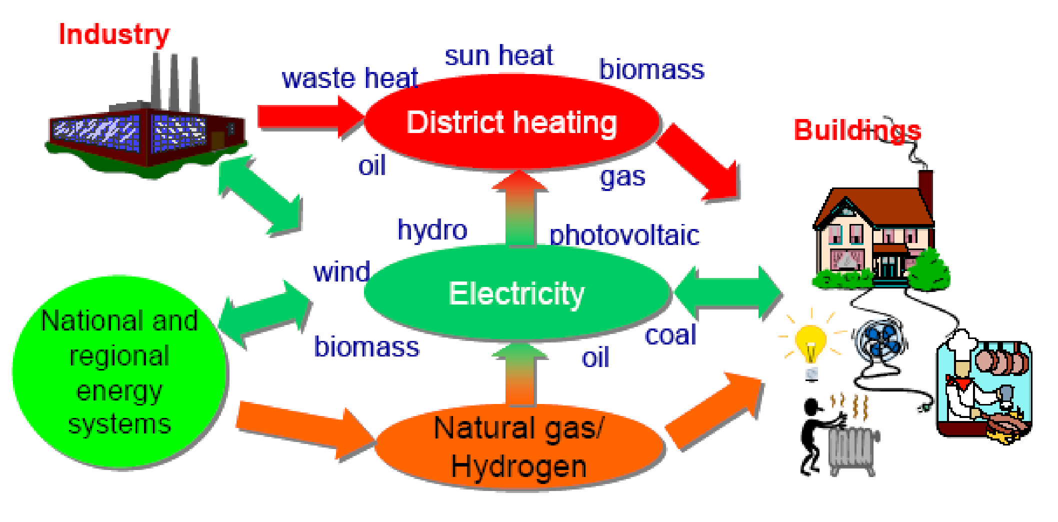


Figure 1 A mixed energy distribution system.

Thus, it is the scientific based methods and models for planning mixed energy distribution systems which are focused in the SEDS project. The term sustainable in the project name should be interpreted in this context. Sustainability relates to all aspects of the recommended planning objective: Economy, quality, security, safety, reputation, contractual aspects and environment. Hence, different energy distribution system alternatives should be characterized with respect to all these objectives, and the planning process should clearly quantify and make these parameters visible and understandable to decision makers and stakeholders, enabling the decision makers to choose sustainable system solutions.

The first objective has been realized through PhD-studies within the following three areas:

- Load and customer modelling of combined end-use (heating, cooling, electricity)
- Quality and reliability of supply in mixed energy systems
- Multiple criteria decision methods for planning of mixed energy distribution systems

In addition an initial study has been performed focusing on environmental impacts using a life cycle assessment (LCA) perspective in planning of local energy systems.

The project has also funded a post doctoral fellowship in multi-criteria decision aid and risk based methodology, and a tutorial given by our partners at University of Porto about risk analysis and multi-criteria decision making.

The second objective has been grouped in two parts:

- Development of a consistent planning framework for mixed energy distribution systems (terminology, concepts, socio-economic principles, general methodology etc)
- Development of a software toolbox environment (web-site) for decision support, visualization and demonstration of methodologies and technologies

For this part SEDS has co-operated with the eTransport project at SINTEF Energy Research [1], where a new tool for planning of energy systems is developed, considering several energy carriers and technologies for transmission and conversion.

The main products from the SEDS project are[2]:

- Technical reports: "Planning of sustainable energy distribution systems" in four parts
- Web-site for energy planning methods and tools[3]
- Three PhD candidates
- Publications in international journals and conference papers
- Presentations at workshops and seminars
- Numerous student project reports and Master theses

The SEDS results constitute a scientific knowledge base for the curriculum Energy and environment at NTNU as well as for energy distribution companies, energy authorities like NVE and governmental agencies like Enova and other stakeholders interested in local energy planning.

[1] eTransport-report: Energy 32 (2007), Elsevier
[2] SEDS results are presented and described in the reports "Planning of sustainable energy distribution systems": TR A6556, TR A6557, TR A6558, TR A6560, NTNU/SINTEF Energy Research 2007
[3] http://www.energy.sintef.no/prosjekt/EnergyPlanningToolbox/

2 OVERVIEW

This review presents and comments existing Life Cycle Assessment (LCA) analysis of stationary energy systems. LCA is a holistic approach that captures most (all) interactions between the analysed system and its environment. A complete LCA of an energy system documents all of the mass and energy flows, during construction, operation and disposal. It is therefore called a Life Cycle Assessment, since the whole life from “cradle” to “grave” is analysed. The main contribution compared to traditional emission accounting is therefore the holistic view. It is often a focus on the amount of emissions exhausted through the power plant stack, but seldom an assessment of the whole system, necessary for delivering the demanded energy service. One assesses not only the system and it’s emission but also the upstream activities, and the production and demolition phases of related equipment. The LCA thus introduces two new important dimensions of analysis of an energy system; energy flow activities from extraction of fuel to utilisation in e.g. a power plant, together with the up and downstream processes related to any process associated with the energy service.

In the context of SEDS it is important to analyse the importance of these two dimensions, to find out whether the additional information is crucial for the overall environmental impact. It is important to be aware of the limitations of a traditional emission accounting analysis, which only counts for operational (stack) emissions. Different environmental loads occur at different phases of the energy system’s life cycle. Examples where traditional emission accounting fails are e.g. (1) the burning of biomass if it is transported long distance by truck and/or need considerably amounts of fertilizer, or (2) the installation of a Photo Voltaic (PV) panel when more energy is used during production of the PV panel than will ever be produced during its lifetime. These two examples are banal, but show how only operational emission accounting can produce false answers. In strive for sustainable energy systems; LCA is a powerful tool to assess different options. By analysing energy systems with LCA, there are two major areas of interest:

- Detection of the most harming processes located in the energy system being analysed, serving as basis for system optimizing.
- Comparison between different energy system options in order to make a well informed decision.

Most LCAs executed on energy systems are concerned either with the electricity production itself or e.g. district heating. The combination of these carriers is seldom analysed.

2.1 GOAL AND SCOPE OF THE REPORT

The scope of this report is to present LCA methodology in the context of energy planning with multiple energy carriers. Further to sketch the parts of an energy system that requires attention when one wants to apply an LCA perspective into energy planning. An important question to answer regards the use of LCA versus traditional emission accounting, where the latter requires far less work. The goal is to demonstrate the importance of an LCA perspective when one is trying to find optimal energy systems. Further to provide the important initial information input required to bear an LCA-perspective in mind during energy planning.

2.2 CONTENT OF THE REPORT

Chapter 3 is presenting LCA methodology in the context of energy system planning. Chapter 4 is a literature study which emphasizes case studies and executed energy system LCAs. The section includes also a literature table over SEDS relevant LCA literature, facilitating the search for and introduction of LCA-literature. Chapter 5 tries to point out where the attention should be directed when one wants to apply an LCA-perspective into energy planning and provides some generic energy system LCA data comparing the environmental performance of different energy technologies. This chapter also demonstrates the need of an LCA-perspective when one wants to implement an optimal energy system, accounting for major environmental impacts. Chapter 6 underpins Chapter 5 by demonstrating in a small case, the difference between using an LCA-perspective and traditional emissions accounting.

3 PRESENTATION OF LCA

Every energy system has a ‘‘life,’’ starting with the design/development of the energy system, followed by resource extraction, production (production of materials, as well as manufacturing/provision of the energy system), use, and finally end-of-life activities (collection/sorting, reuse, recycling, waste disposal). All activities, or processes, in a product’s life result in environmental impacts due to consumption of resources, emissions of substances into the natural environment, and other environmental exchanges (e.g., radiation, land use etc.).

3.1 LCA AS PLANNING TOOL AND USE IN PRACTICE

The generation of environmental loads occurs mainly during the “use-phase” of an energy system but is determined by the planning and decisions made in the first phase. This is exemplified in Figure 2, where a simplified scheme of the product-life concept is presented. The dark grey area indicates the importance of decisions made at a certain point where parts of the environmental impact from the whole life cycle is determined, and how this phase might be itself without much environmental impact. However, the decisions taken in this phase often determines much of the environmental impact generated during the products life cycle. This is rather obvious, but emphasises the need for planning in order to create sustainable energy systems. A decision-maker deciding whether to use heavy oil or biomass as fuel does not herself have much impact, but the decisions made has considerably impact over the whole life cycle of the energy system.

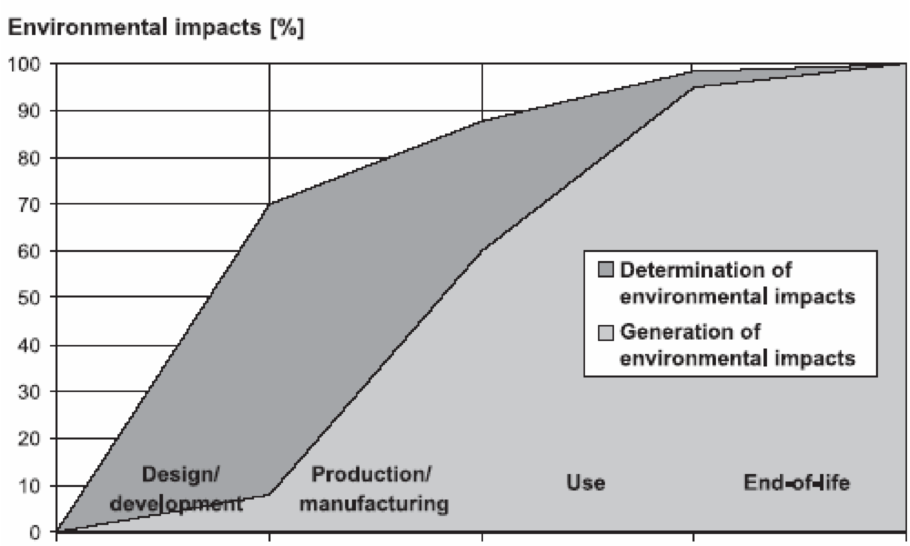


Figure 2 Generalized representation of the (pre)determination and the generation of environmental impacts in a product’s life cycle (Rebitzer et.al. 2004).

The environmental impact of e.g. a heating system is mostly generated through the use of it, but the determination of the impact was done during planning, as fuel source etc. for the heating system was chosen. Careful design and planning of the energy system is thus a necessity for a more sustainable oriented energy system.

3.1.1 Short presentation of LCA-history

The LCA-methodology has originated from different locations and institutions, the history has some variations depending on who is explaining. The seventies were characterised by oil-crisis and related energy debate. Many places the first LCA in this context, but the first LCA concerned waste management and was actually conducted by the Coca Cola company, who was considering manufacturing beverage cans (Baumann & Tillman 2004). Plastic bottles, refillable glass bottles and disposable containers were among the alternatives. The study was conducted by the Midwest Research Institute and under the name: "Resource and Environmental Profile Analysis". The LCA concept (however with different appellation) was not well known before the 1990s. Most activity was concerning waste management. The LCA work was conducted continuously but without surfacing to the public debate. This changed during the eighties as several environmental disasters struck; chemical accident in Bhopal (India), meltdown in Chernobyl and severe oil spill from the boat Exxon Valdez. Environmental concerns gained more interest as did LCA as methodology, and again related to waste problems, as landfill space was scarce and related packaging issues attained attention. This sparked a new area of methodological discussion and development, which harmonized the different "schools" and finalized into the first ISO standard in 1997.

3.1.2 Increasing interest in LCA

The massive increase in interest for LCA can be reflected through the numbers of articles in academic press, as shown in Figure 3.

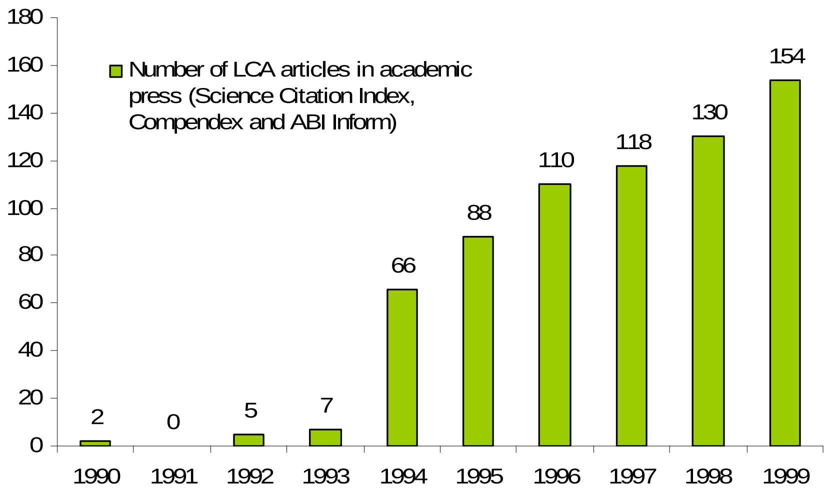


Figure 3 Number of LCA articles in academic press [Baumann & Tillman 2004].

The methodology now called LCA was undertaken under many names. The meaning of "LCA"; "Life Cycle Analysis" or "Life Cycle Assessment" was discussed on a conference in 1991, and the latter was chosen to reflect that there are also subjective elements in an LCA.

3.1.3 The ISO standard for LCA

The ISO 14040 standard series tries to introduce some common guidelines for system boundary selection and a general LCA framework. The different standards are listed below:

International Standard ISO 14040 (1997) on principles and framework
International Standard ISO 14041 (1998) on goal and scope definition and inventory analysis
International Standard ISO 14042 (2000) on life cycle impact assessment
International Standard ISO 14043 (2000) on life cycle interpretation

These standards are generally accepted as providing a consensus of a framework for LCA. They do not provide detailed methodology guideline, which are found elsewhere as e.g. in Consoli et.al. (1993) or Guinée et.al. (2002).

3.1.4 Environmental product declaration, EPD

An environmental product declaration, EPD, is defined as "quantified environmental data for a product with pre-set categories of parameters based on the ISO 14040 series of standards, but not excluding additional environmental information" (EPD 2007). The intent of an EPD is to provide the basis for a fair comparison of products and services based on their inherent environmental performance. EPDs can reflect the continuous environmental improvement of products and services over time and are able to communicate and add up relevant environmental information along a product's supply chain.

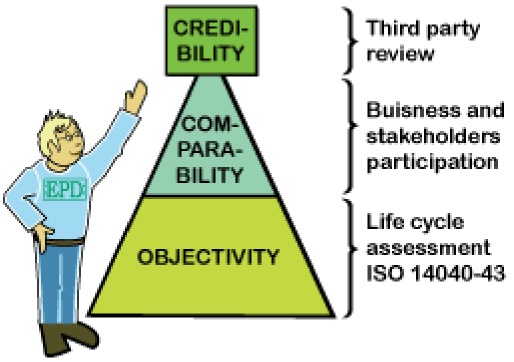


Figure 4 The key characteristics of en EPD [EPD 2006].

As Figure 4 tries to explain: The EPD is based on objective data through the use of standard LCA methodology, comparability through usage of similar assumptions for different products, and credibility through third party review. Vattenfall has declared some of their energy products, and they are found at the EPD website (EPD 2007). The EPD system boundary for the electricity is shown in Figure 5 below:

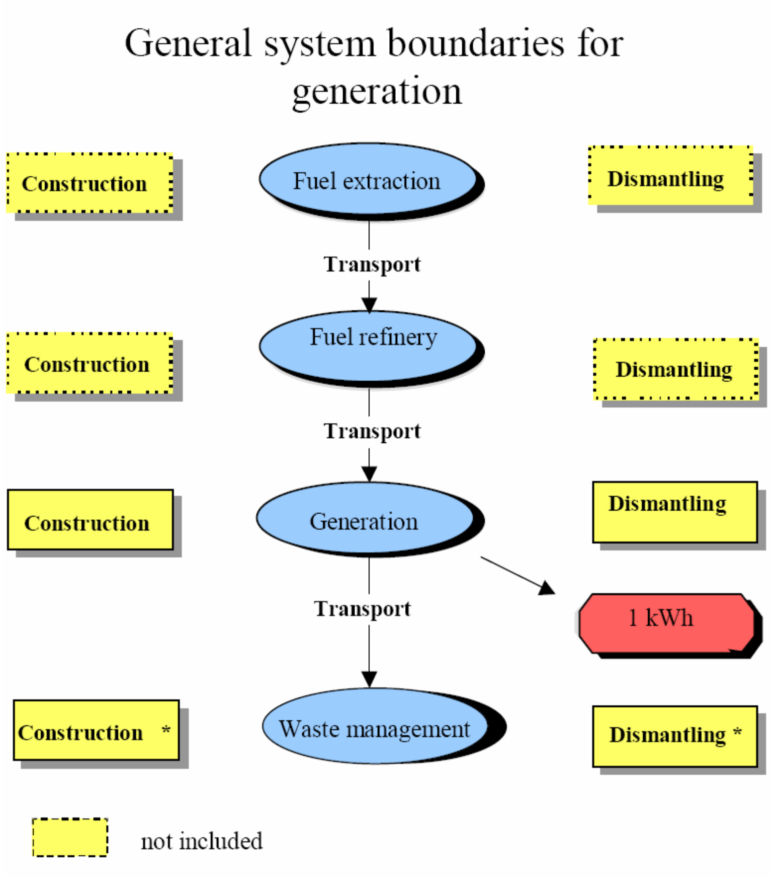


Figure 5 System boundaries suggested in the "Product-specific requirements" (PSR) for preparing an environmental product declaration (EPD) for Electricity and District Heat Generation" (Swedish EM Council 2004).

*Only to be included in the case of directly fuel-related waste, e.g. radioactive waste.

The functional unit is 1 kWh heat or electricity distributed to customer. The distribution comes therefore in addition to what is shown in Figure 5. The use of system boundaries and functional unit is explained in chapter 3.2. One hydro power plant in Norway (Trollheim) so far has an EPD, and the EPD is found as attachment 1 (EPD-Norge 2007).

3.2 LCA METHODOLOGY

A life cycle assessment consists of mainly three phases as shown in Figure 6; "Goal and scope definition", "Inventory analysis" and "Impact assessment". One phase called "Interpretation" interacts with all stages of an LCA. If different energy system alternatives are compared, they might score ambiguous among different indicators. An interpretation is therefore necessary at all stages as not only the impact assessment is important to decision makers (economy, social issues etc.) The process of LCA and included steps are explained further in Rebitzer et.al. (2004) and Pennington et.al. (2004). This section is mainly based upon the mentioned papers.

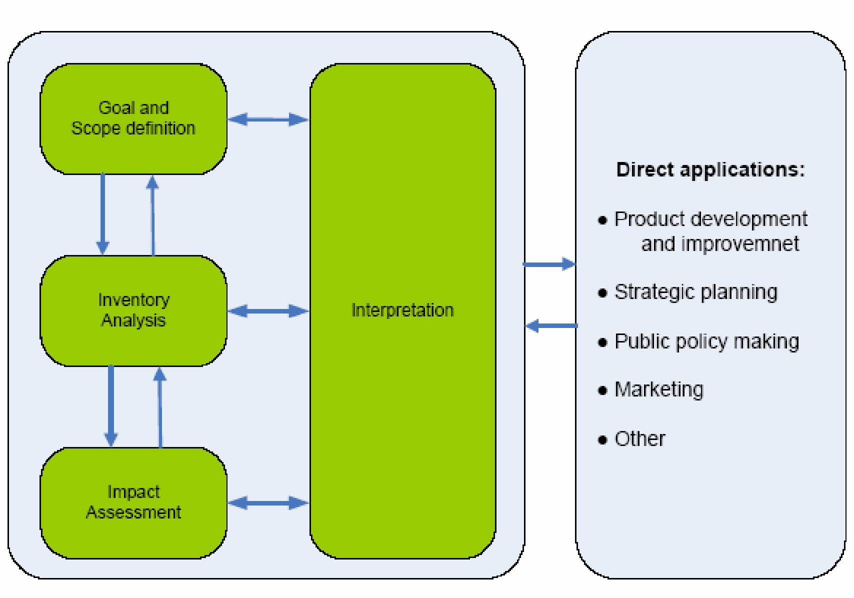


Figure 6 Phases and applications of an LCA (Rebitzer et.al. 2004).

A last step of an LCA that is not shown in Figure 6 is the "data quality analysis", which is highly recommended but is receiving little attention in current practice (Rebitzer et.al. 2004).

The ISO 14043 is presenting the procedure for interpretation of the obtained LCA data. The intention of the procedure is to give a clear presentation of the results. This part includes analyzing the results and deriving conclusions and recommendations.

3.2.1 Goal and scope definition

The goal and scope definition of an LCA provides a description of the product system in terms of the system boundaries and a functional unit. The functional unit is the object of analysis but is not necessarily just a quantity of material. For energy system it could be the energy service such as 1 MJ heat at 25 °C in a room, transport from A to B, one kWh electricity delivered at customer or 1 m^3 of water vapour at 1 bar and 120 °C.

The choices and assumptions made during system modelling, especially with respect to the system boundaries and what processes to include within these boundaries, are often decisive for the result of an LCA study. For comparison between different energy systems it is therefore highly important to define comparable system boundaries. The literature is expanding in the field of bound definitions, for more details see e.g. *Critical review; System boundary Selection in Life-Cycle Inventories Using Hybrid Approaches*, Suh et.al. (2004). The paper presents many aspects of LCA and boundary selection. May et.al. (2003) presents a system boundary diagram for fossil energy sources that exemplifies how boundaries can be established see Figure 7.

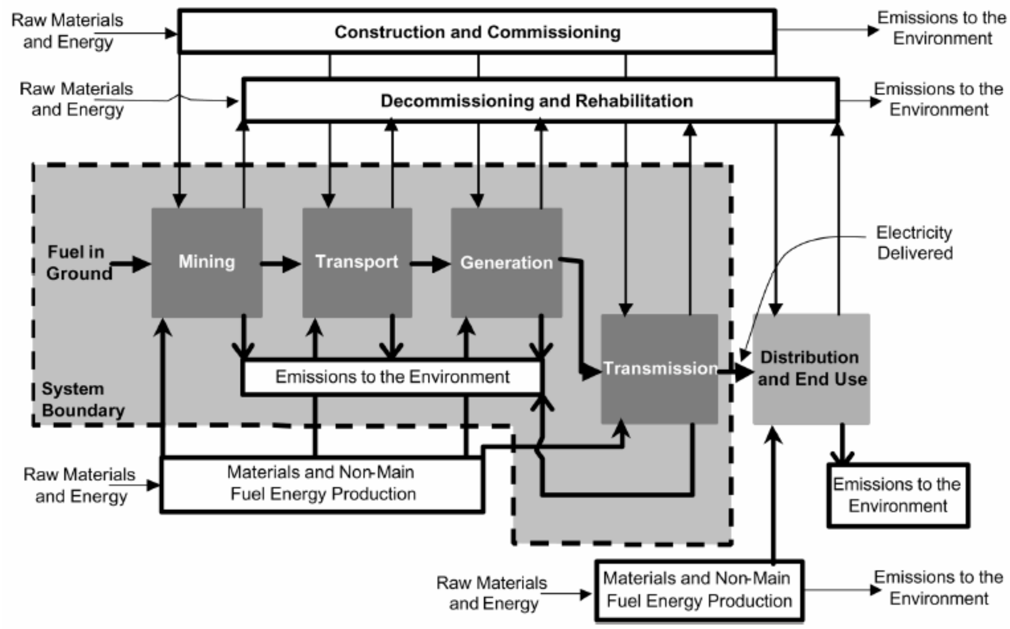


Figure 7 System boundary for fossil power generation (May et.al. 2003).

The shaded areas are included in the model. Construction and decommission is thus excluded in this assessment since several detailed investigations have shown that the contributions from these phases are minor in comparison with operational aspects over the whole lifetime. This assumption is valid only for fossil power plants, as the construction phase of a renewable power plant often is the main emission contributor.

Deciding where the system boundary is, and which cut-off criteria to utilise is an important part of an LCA, and is thus further elaborated in Chapter 3.2.3.2.

3.2.2 Inventory analysis

Life cycle inventory (LCI), is a methodology for estimating the consumption of resources and the quantities of waste flows and emissions caused by or otherwise attributable to a product's life cycle. The quantification of resources and waste is complicated as these are likely to occur at different places, at different times and over different time periods. Wastes might be stored in unstable locations where the consequences have a considerable delay (landfill, nuclear waste, ocean deep water storage, geological storage etc.).

Other difficulties arise from units producing more than one product. Because the up and down stream processes have to be partitioned between the products. A simple example related to energy systems is heat supply, let say the functional unit is 1 MJ of heat; how to compare district heating with a CHP solution, where the electricity from the latter alternative is not a part of the functional unit. The ISO standard suggests three consecutive steps, briefly presented here: The first option is to include the co-product in the functional unit, implying that the system can be easily expanded, which implies for the heat example that a unit of heat and electricity is chosen as functional unit. The second option is to theoretically separate the exchanges "in a way which reflects the underlying physical relationships between them, i.e., they shall reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.'' This could be to use e.g. energy or exergy quantity. The third option is to use "other relationships" than those physical possible. This is further emphasized by the only example provided, namely, that of the economic value of the products, which can be seen as the ultimate cause for the existence of the process. Economic value is, thus far, the only causal relationship that has been found to fit this last step of the ISO procedure. The different options for allocation is further elaborated in Chapter 3.2.3.3 – 3.2.3.5.

There are two major ways of doing the LCI (life cycle inventory); process LCI and input/output (I/O) LCI. I/O models have their origin in economical models, where the product system consists of supply chains. The analysis is a more aggregated approach and is not suitable to analyze e.g. material selection within one industry. The nature of the I/O model serves better for problems that are more general and overall. The impacts of a new telecom technology or introduction of a new energy carrier to a larger energy system are two examples. The I/O analysis uses e.g. the national production of concrete and finds the related emissions and environmental loads from the national concrete industry. The result is an average figure of the impact which is more general than a process LCA, and not adapted to local conditions. The I/O results are therefore better suited to describe a general case than a highly site-specific analysis. If one wants to determine e.g. the impacts of different cement ingredients an I/O analysis is not suited. A process LCA will often have system boundary issues which influence the results. In a response to this critique, a hybrid between I/O and process LCA has been developed. The combination tries to utilize the best from both models. The combined model is often referred to as "hybrid LCA". The I/O analysis is used to give information regarding typical input/output categories (steel, concrete etc.) and the process LCA approach is applied to the remaining main products. However, the hybrid LCA requires insight to decide which processes are well represented through I/O and which are not. The hybrid LCA is regarded to represent the LCA development frontier, and will thus be explained in more detailed in a subsequent chapter.

Data collection and compilation are often the most time and work consuming steps in an LCA. But many processes are similar country and region-wide, it has therefore evolved a range of databases that are of high quality and very useful for practitioners of LCA. Common processes might be e.g. cement or electricity production in Nordic countries, road transport or steel production. Also LCA software is highly useful, and is often used in combination with one or more databases. These tools reduce the work load related to an LCA considerably, and help to coordinate different LCA methodologies.

For future scenarios of LCA performance, dynamic LCA is an important aspect, where future changes in the subsystems are also addressed. Pehnt puts it this way (Pehnt 2006):

> *Future development will enable a further reduction of environmental impacts of renewable energy systems. Different factors are responsible for this development, such as progress with respect to technical parameters of energy converters, in particular, improved efficiency; emissions characteristics; increased lifetime, etc.*

The principle is shown in Figure 8.

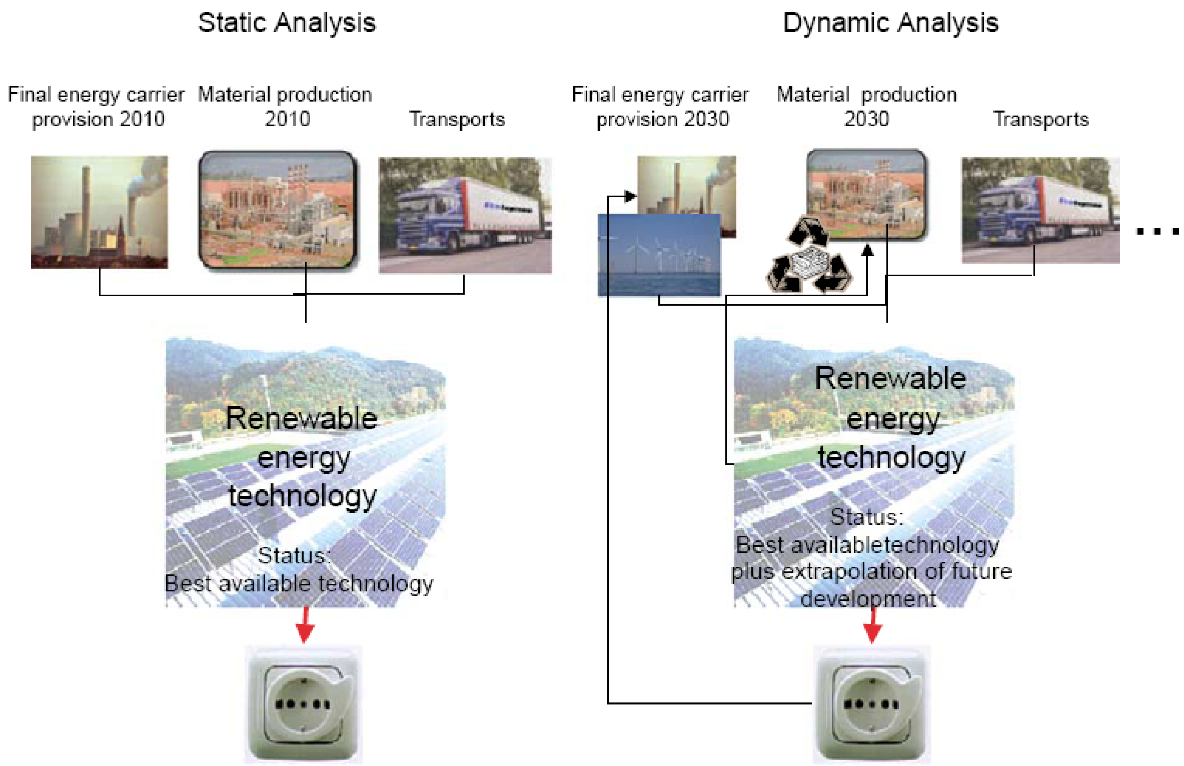


Figure 8 Principle of dynamic LCA.

As the scope of the study is extended, the higher the risk for false predictions rises, especially with regard to feed-back loops, where changes may occur exponentially. Dynamic LCA should be undertaken with precautions.

3.2.3 Impact assessment

The impact assessment analyses the quantitative results from the inventory analysis, and structures the results. The guidelines for life cycle impact assessment (LCIA) are described in the ISO standard 14042 and are divided in the following three steps:

1. Selection of impact categories
2. Classification
3. Characterization

Life cycle impact assessment (LCIA) provides indicators and the basis for analysing the potential contributions of the resource extractions and waste/emissions in an inventory to a number of potential impacts. The result of the LCIA is an evaluation of a product life cycle, on a functional unit basis, in terms of several impacts categories (such as climate change, toxicological stress, noise, acidification, land use, etc.) and, in some cases, in an aggregated way such as years of human life lost or aggregated through different valuation and weighting methodologies, thus concluding the LCIA with one parameter. The range of indicators gives an impression of the complexity of LCA results and the amount of information that may result from a comprehensive LCA. Central to the LCIA (life cycle impact assessment) is the classification process where the inventory data are summarized in "classes". The most common are briefly presented below (mainly based upon Baumann et.al page: 145-157):

Resource use	Resource depletion is one of the most debated topics. Different ways of viewing resource use as an environmental problem results in different approaches. Some may say resource use is a problem in it self, while other argues that limited resources are a societal problem and focus more on the resource extraction than the resource use itself. Grouping in renewable and non-renewable or biotic and abiotic is common.
Land use	Land use is another debated topic, central issues included in this category are among others; occupancy of land area, change in land use, change in biodiversity, and change in life supporting functions. Most of these impacts are difficult to measure and quantify, further is there a lack of knowledge and data on the influence of land use on the environment.
Global warming	Global warming may cause a wide range of changes, but this category represents the amount of GHGs (Green House Gases) emitted using their respective global warming potential (CO_2 equivalents). Since the GHGs have different lifespan in the atmosphere, GWPs (Global Warming Potential) have been calculated for different time horizons
Ozone depletion	Ozone (O_3) is a harmful pollutant in the lower atmosphere, but is essential in the upper atmosphere were the ozone screens out more than 99 % of the ultraviolet radiation. The ozone depletion refers to the thinning of this layer caused by e.g. halons or CFCs
Toxicity	Toxity is another complicated indicator, much because it includes a wide range of pollutants, ranging from organic solvents, heavy metals to pesticides. All of them having different toxic impact. The category is often divided into human toxicity and eco-toxicity.
Photo-oxidant formation	These are secondary pollutants formed in the lower atmosphere from NO_x and hydrocarbons in the presence of sunlight. Photochemical smog is a better known notion and is cause of health problems such as irritation to respiratory systems and damage to vegetation.
Acidification	Major acidifying pollutants are: SO_2, NO_x, HCl and NH_3. Acid rain is a well known problem frequently on the agenda since the 1980s, but acid deposition occurs also through snow, fog and dew. The common characteristic is the formation of H^+ ions. The impact is therefore often measured in H^+-equivalents.
Eutrophication	The term covers all change in biological productivity, from nutrients, degradeable organic pollution to waste heat which all affect productivity. nitrogen and phosphorus are the main nutrients. Eutrophication potentials are often expressed as PO_4^{3-} -equivalents.

The environmental impact is thus categorised and grouped into aggregated measures. The most common are shown in Figure 9 below, where focus in this study is only global warming. This selection is made due to limited time resources. A more comprehensive study, demonstrating how different technologies perform over the whole set of impact categories, and the ambiguous results one might obtain would be interesting. Global warming is chosen since it is one of the greatest threats to the global ecology, and the energy industry is a major emitter of GHGs.

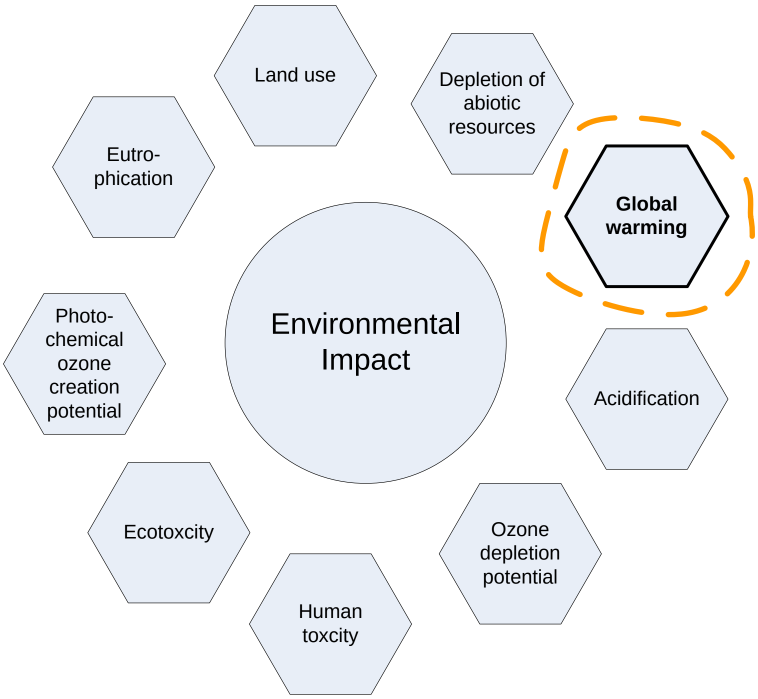


Figure 9 Common environmental impact categories.

The classification provides an overview of the environmental impact from the studied system, but when different options are compared one often want to aggregate the impact into one overall indicator i.e. a single score as shown as “index” in . The concept of LCI and LCIA is illustrated in Figure 10, where the inventory first is classified, and then the impact category is calculated and compared to reference values in order to measure the different impacts. The results are then grouped and possibly also weighted into one index.

The Institute of Environmental Sciences, in the Netherlands, has downloadable characterisation factors available, together with other useful LCA information (CML-IE 2007).

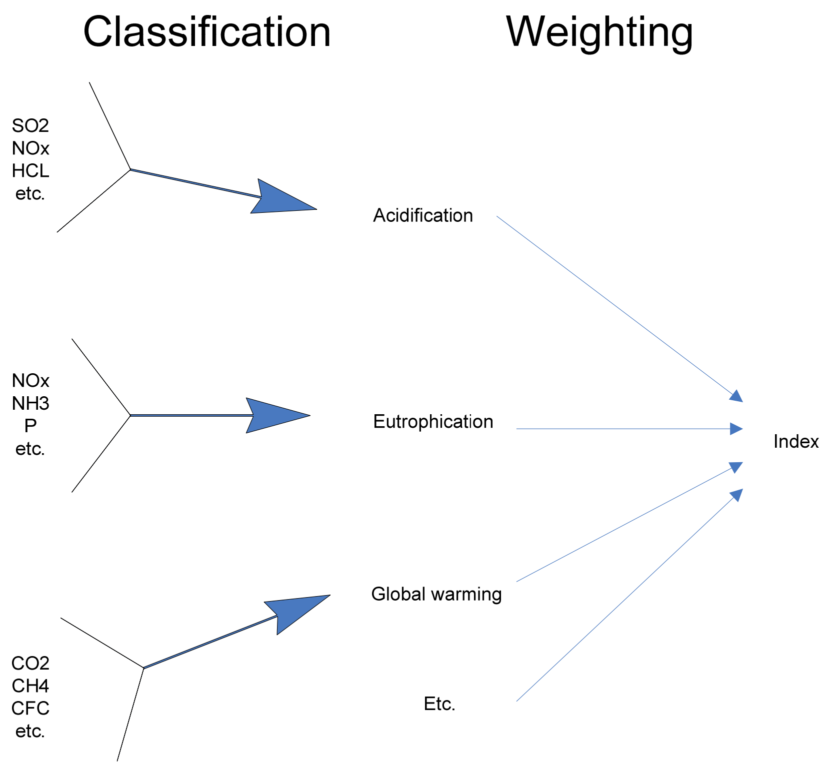


Figure 10 Illustrative overview of LCIA, where the inventory is classified and the impact is aggregated (from Baumann et.al. 2004).

The shift from environmental impact categories to a single score is a shift from scientific fairly precise data towards value-laden subjective judgements. However, a decision maker needs a single score to evaluate the results from an LCA, and further aggregation into a single score is often a necessity in order to make a decision. As one can imagine, it is not trivial to compare the consequences of eutrophication with the consequences of ozone depletion. The use of weighting is therefore subject to value-laden decisions; each weighting method reflects different social values and preferences, which can be quite inhomogeneous. Examples are shown in Table 1.

Examples for aggregated measures are:

Ecopoints	(Björk, Rasmuson 2002)
NETS: Numerical Eco-load Total Standard	(Kato, Widiyanto 2005)
EcoTax02	(Eriksson et.al. *In press*)
Eco-indicator 99	‘ ’
EPS 2000	“
Environmental Themes - short	(Baumann et.al. 2004)

The relative harm from different substances is compared against CO_2 in Table 1 (Baumann et.al. 2004).

Table 1 Comparison of the relative harm of selected environmental loads (relative to CO_2 in three LCIA methods (Baumann et.al. 2004).

	Ecoindicator 99	Environmental Themes - short	EPS
CO_2	1	1	1
NO_x	416	356	2.32
SO_2	737	218	0.524
PAH	4 842 195	177 477	6 952
Hg (air)	482 211	4 252 253	2 521

Table 1 indicates clearly how inconsistent the LCIA methods are, as the emission of e.g. SO_2 is 1400 "worse" following the Ecoindicator'99 compared to EPS (relative to each valuation of the harm from CO_2). To emphasize the difference an example from Bengtsson (2000) is shown, where a polyethylene envelope is analysed.

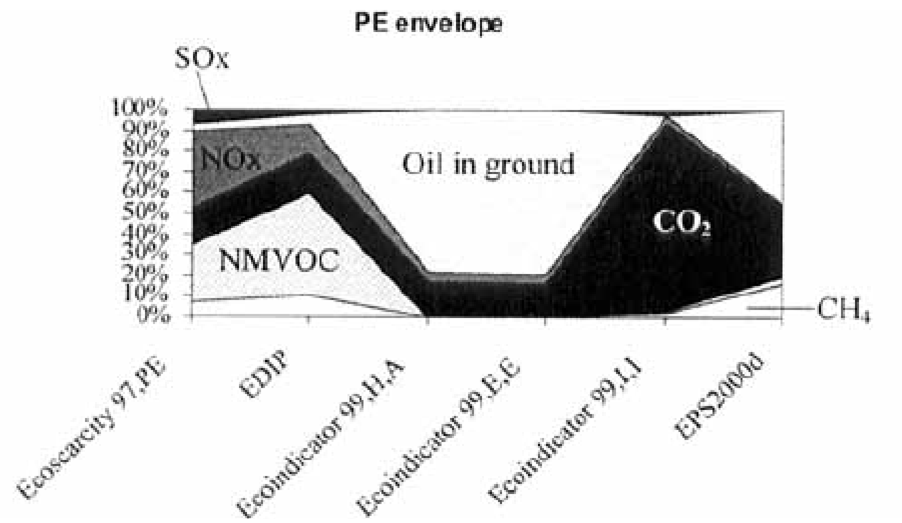


Figure 11 Relative contribution to the aggregated impact weight from various inventory results of a polyethylene envelope (Bengtsson 2000).

This reflects the complexity of environmental problems and the diverging view humans have on nature. Some key areas to illustrate are e.g. ecosystems, are they self-regulating robust systems or fragile systems based upon a sensitive balance? Are humans a culture being or mere a nature being and are we evolving?

Two main classes of weighting single score frameworks exist (Bengtsson 2000):

- **Distance to target**
  The underlying principle for these is simple: The quotient between the current levels of emissions in a geographical area (often a country) and the level that is considered critical (target level) indicates how severe a certain kind of emission is. A critical element in this class of methods is the target levels and how these are determined. A criticism raised against distance-to-target methods based on public policy goals is that policy targets may be of different dignity and that the mere distance-to-target ratio therefore is not a good indicator of which emissions are the most severe. Ecoscarcity and EDIP are examples of "distance to target" models.

- **Damage modelling**
  The damage modelling has different ways of assessing the damage. Eco-indicator uses a board of LCA experts to do the weighting. The EDIP assess the society's willingness to pay for avoidance, and thus derive a weighting from the "willingness to pay". Ecoindicator'99 is described in some detail here (Bengtsson 2000). The Ecoindicator'99 method was developed as a respond to a need for aggregated environmental data (single score). A first version was made in 95 (ecoindicator 95), and then updated and extended in 99 with a focus on European conditions. Average European data are used to calculate the extent to which human and ecosystem health are threatened and affected, analysing the seriousness of the damage. Three different cultural views can be applied for the final weighting; egalitarian, hierarchist and individualist. The latter operates with a short timeframe and applies no "precautionary principle", the first one on the other hand applies a long term view and uses the "precautionary principle" consistently. The hierarchist view is in between and reflects the view of recognised political and scientific bodies.

The 'distance to target methods', the Ecoscarcity 97 and the EDIP methods, have a relatively even contribution to the overall weight from the most regulated emissions. The damage-oriented methods, the Eco-indicator and the EPS2000d methods have more focus on issues of great future significance, i.e. the global warming and depletion of fossil resources. More information about weighting is available e.g. Bengtsson (2000) and Baumann (2004).

The divergence in results from using different weighting-indicators emphasizes the need of using more than one during aggregation, and the persons involved in LCA practice should be aware of the multitude of evaluation approaches, what principles they are based on and what information they convey (Bengtsson 2000). By solving the problem of too many environmental impact groups, one created another, namely to choose which weighting method, as there is no certain method that describes the world more "correctly" than another. Bengtsson (2000) states:
"if the idea was to find one best method, (…) we do not see this as the goal for methods development in the field of weighting – different methods can shed light on the decision situation from different angles and contribute with different kinds of information to decision-making processes."

3.2.3.1 Change-oriented LCA and attributional LCA

There are two ways of performing the impact analysis:

- To describe a product system and its environmental exchanges (attributional LCA, descriptive LCA) or;
- To describe how the environmental exchanges of the system can be expected to change as a result of actions taken in the system (consequential LCA, change oriented).

An attributional LCA provides the set of total resource and waste flows that are “attributed” to deliver the amount of the functional unit. A consequential LCA, in contrast, is an estimate of the system-wide change in pollution and resource use caused by the functional unit. For e.g. electricity production one would compare the results from the analysis with the marginal (substituted) electricity produced in that specific region or country. One may then obtain negative impacts if the analysed system has less impact than the existing one. The consequential LCA is related to its surrounding environment and requires insight into how the functional unit affects and influences its environment. Another term to distinguish the two is “change-oriented” LCA and “attributional” LCA (Baumann 2004).

3.2.3.2 Cut-off arrangement

A major challenge in every LCA study is to determine when enough is enough. This relates to the fact that during execution of an LCA, one does not know the total environmental impact, it is thus difficult to determine what is significant and not. However, through literature it is possible to have a clue of which processes that are more dominant than others. In the scope of SEDS and practical use of an LCA perspective to non-LCA practitioners it is even more important to determine what processes that are most important. The method would have to be precise enough to include the dominant processes in the product life cycle and at the same time be simple enough to be applied by several actors. In finding the appropriate cut-off one is faced with the challenge of defining what processes and stressors to include in the life cycle inventory (LCI) study in order to get an adequate description of the environmental load of a product. The objective is to find the trade-off between precision and complexity in going from a complete LCI to a condensed definition of processes and stressors to be included. There exist methodologies to assess this challenge analytically and quantitatively. A definition of a “cut off” criteria is often useful, and can be as simple as a percentage limit; each contribution lower than x % is not accounted for. Another way to solve this is the use of structural path analysis (SPA) to identify and rank the most important chain-of-events with respect to various impacts. It is important to remember that a single process can show a high degree of impact as a result of several paths leading to the same process. This is the advantage of SPA, since the method allows analysis of the process network paths that is contributing to the environmental impacts. When the network is found, “pruning” removes branches which are not significant. This is exemplified in the Figure 12 below:

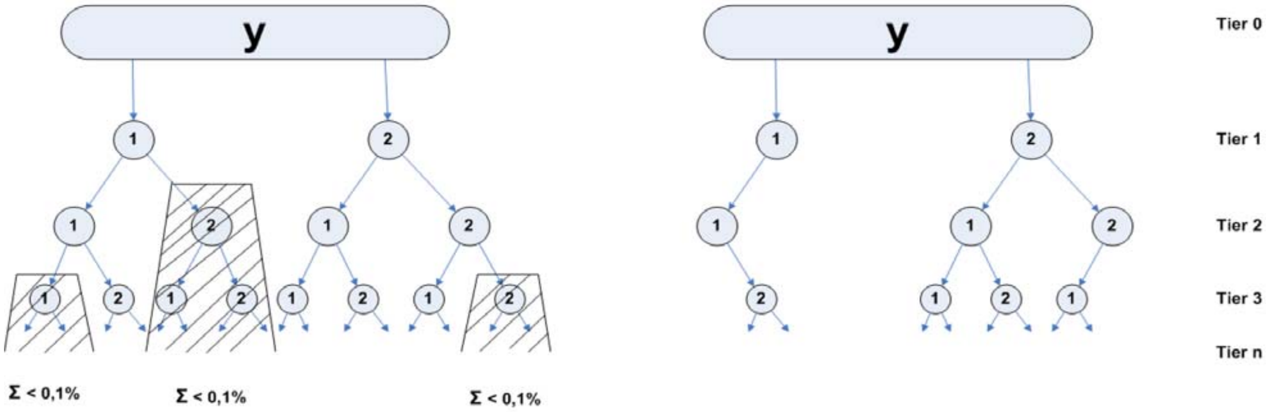


Figure 12 Branches pruned when sum are lower than 0,1 percent and y is the functional unit (Sundseth 2006).

An example of an SPA (Structural Path Analysis) from an alpine hydropower station is shown below in Figure 13, where abiotic depletion is the indicator (fossil resource use):

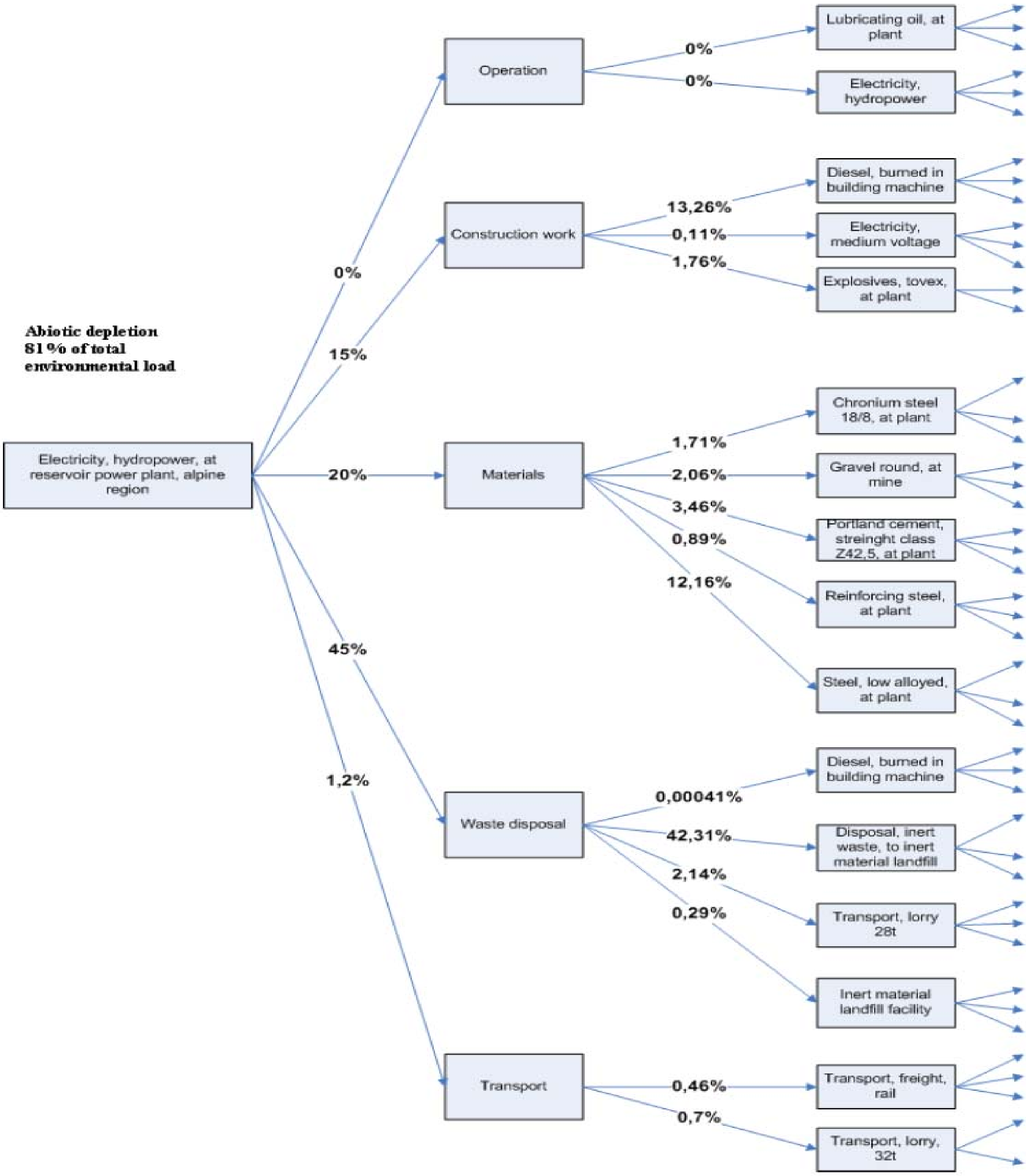


Figure 13 An example of abiotic depletion process-tree for hydro power (Sundseth 2006).

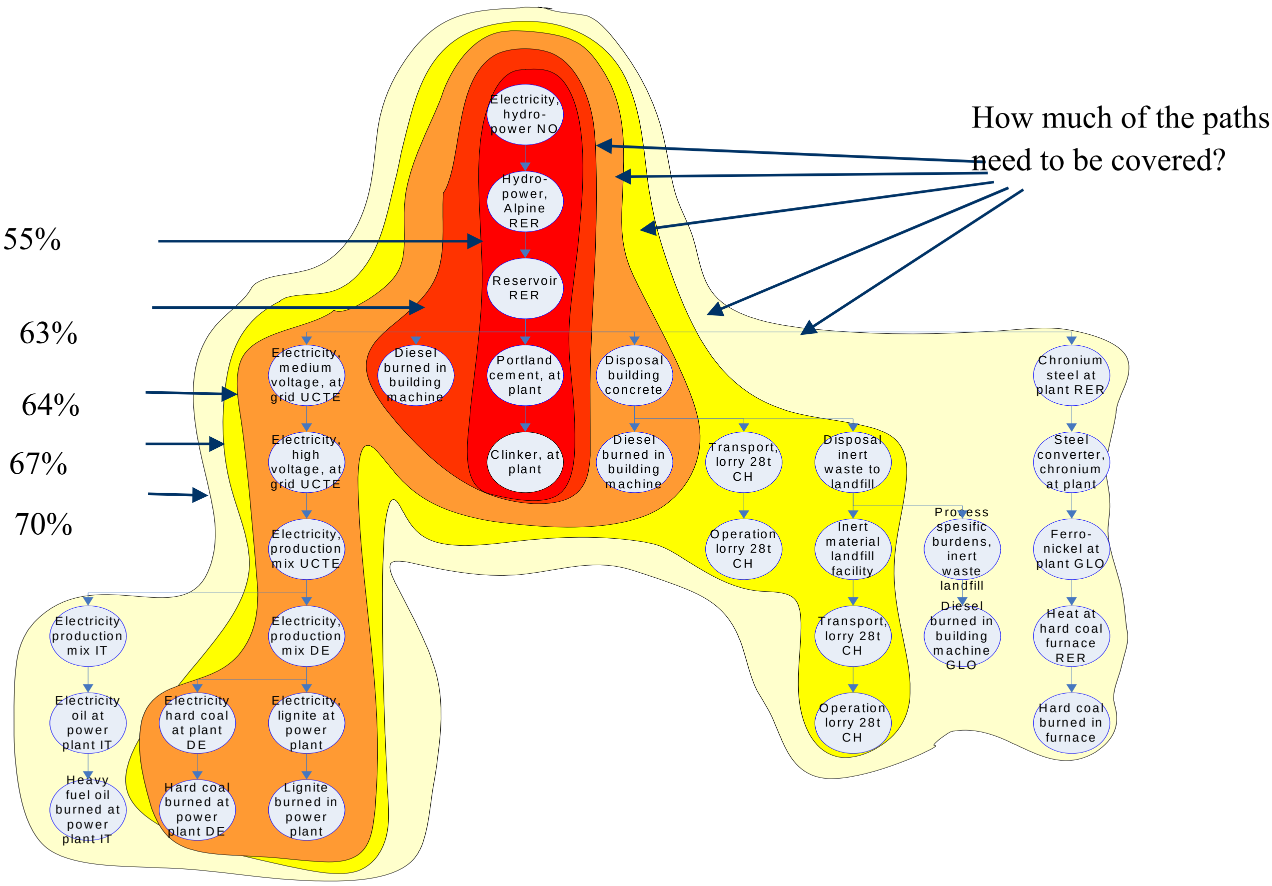


Figure 14 Example of applied SPA to hydropower station (global warming) (Sundseth 2006).

As more details are included, the analysis is more comprehensive, simultaneously demanding heavier work load and more data input.

3.2.3.3 Allocation

The combination of heat and electricity through multiple energy carriers complicates the definition of functional unit, as the energy quality[4] of the carriers is different. 1 MJ heat is not comparable with 1 MJ of electricity. The choice of allocation method has impact on the results, as e.g. the products from a CHP have higher numerical value counted as energy units than as exergy units. The environmental impact is thus divided between different quantities of product. Here is allocation with exergy and the “alternative production method” presented.

3.2.3.4 Allocation with Exergy

In order to be able to compare different forms of energy, a measure of the quality of the energy concerned is required. Exergy is a way of describing "energy with quality". Exergy is thus a measure of the part of energy that can be made available in the form of useful work. The

[4] Quality in this case means “share of work” (thermodynamical definition) and thus not quality in the sense of power supply quality (interruptions, frequency etc.)

definition of exergy assumes that mechanical work – or electrical energy - has the exergy component 1. Energy of this type represents pure exergy. Environmental impact may thus be allocated on a physical basis as amount of exergy on the heat and electricity or other energy carriers.

The exergy content of a quantity of heat Q, that is available at a temperature T, in an ambient temperature of T_0, is:

$$E = Q\left(1 - \frac{T_0}{T}\right) \qquad T = t + 273 \; [K]$$

Allocation in accordance with exergy content means that heat production may only bear that part of the environmental load that corresponds to the exergy content of the heat produced in relation to total net exergy. The remaining environmental load is allocated to electricity generation. An example makes it clear:

Let’s say one has a CHP producing 1 MWh of electricity and 3 MWh of heat at 120 °C, resulting in 5 ton CO_2. How much of the CO_2 is to be allocated to the heat production? We assume ambient temperature at 273 K, total exergy production is thus:

$$E = E(electricity) + E(heat) = 1 + 3\left(1 - \frac{273}{393}\right) = 1 + 3(0.305) = 1.92\,MWh$$

CO_2 emissions allocated to 3 MWh heat is thus: 2.40 ton, and to 1 MWh of electricity it is 2.60 ton CO_2, i.e. almost the same amount, even though the production of heat is three times the amount of electricity. The exergy allocation method allocated most of the environmental impact to electricity since the exergy content of heat at lower temperatures (100 – 200 °C) is small. The method reflects physical relations but not necessary the society’s needs and how humans value the difference between heat and electricity.

3.2.3.5 Allocation based on the alternative production method (adopted from Setterwall 2004)

This allocation method was originally developed by the Finnish District Heating Association as a proposal for a new and uniform reporting method for production statistics relating to CHP plants in Europe (Setterwall 2004). This allocation method is based on distributing the gain relating to heat production, in the form of improved fuel utilisation, between the two products electricity and heat in proportion to the individual fuel requirement of electricity generation and heat production respectively (single-output plants). The distribution of environmental impact between electricity and heat is carried out on the basis of the percentage relationship between the quantity of fuel required for electricity generation and heat production respectively in the alternative single-output production plants, as shown in Figure 15 below.

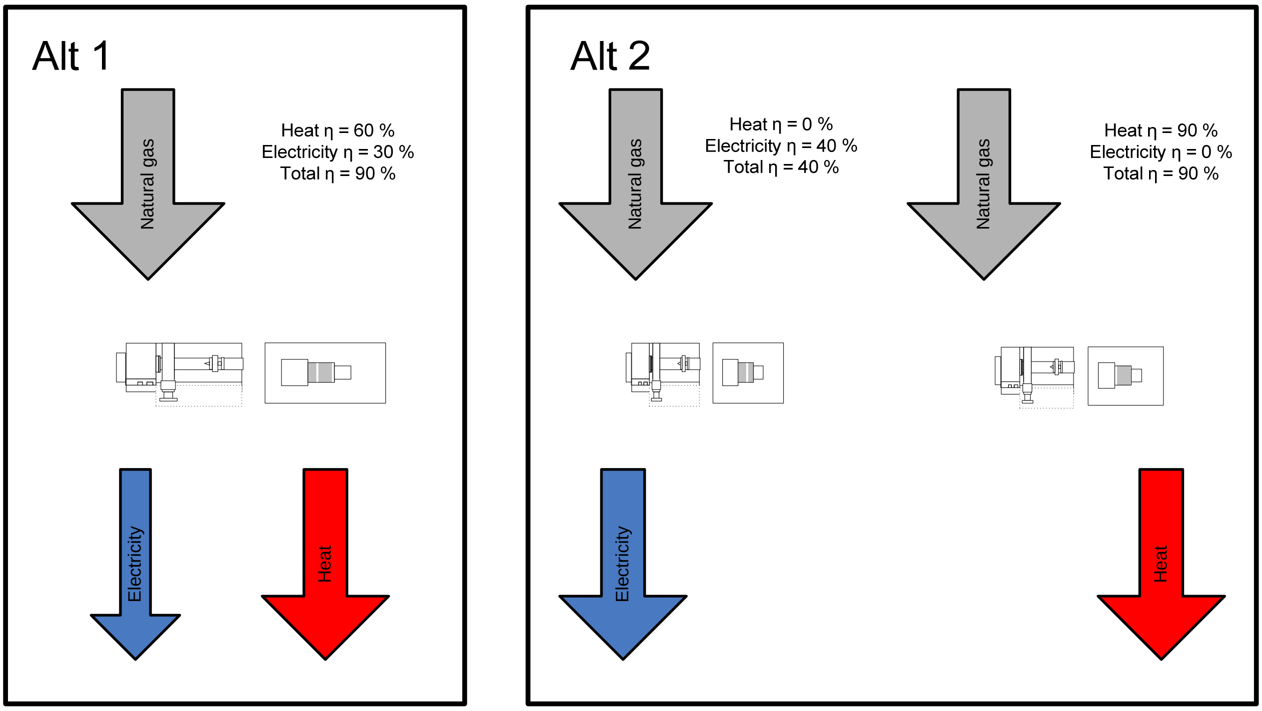


Figure 15 Allocation based on alternative production method.

With alternative 1 one get from 100 units of natural gas 45 units of electricity and 40 units of heat. With the alternative 2 one has to use more natural gas to obtain the same amounts.

Fuel consumption in alternative electricity generation 30/0.4 = 75
Fuel consumption in alternative heat production 60/0.9 = 67

Total fuel consumption in alternative 2 producing the same amounts of heat and electricity: 142

Allocate to electricity:	75/142 => 53 %
Allocate to heat:	67/142 => 47 %

The selection of parameters for the alternative production plants has a direct effect on how environmental impact should be distributed. There are different approaches with regard to the selection of plant data, (above all efficiency) for alternative production:

- Plant data that corresponds to the mean for existing plants.
- Plant data for the best possible plant performance irrespective of the type of fuel.
- Plant data for the best possible plant performance for the same type of technology and fuel as the studied plant.
- Plant data based on the recalculation of the studied plant's steam data solely in relation to electricity generation and heat production respectively.

3.3 HYBRID LCA

The hybrid LCA combines the traditional LCA, called “process LCA” and economic input/output (I/O) analysis. The two are first shortly presented, before the combination of them, the hybrid LCA is explained. The overall methodology is similar, but the technique of compiling the life cycle inventory differs considerably. The data sources are economic national accounts instead of unit process data and have thus much lower level of detail. The aggregated level in I/O analysis has the advantage of easy accessible data, which also includes all interrelations between different sectors, but much of the individual differences within a sector are lost through the aggregation.

Process LCA is the most used and known type of LCA. It analyses the processes included within the system boundary, trying to capture all processes with substantial environmental impact. The main challenges are the boundary definition and data collection, as opposed to I/O LCA where no real system boundary is drawn.

The hybrid approach combines the advantages of both traditions; the less data-intensive and more aggregated data for the background system (less important) and the process approach applied to the main system components, thus enabling efficient resource allocation, as minor processes are given less attention, but are not cut off. At the same time the main system components are thoroughly analysed.

3.3.1 Input/Output model analysis

The I/O analysis is a top-down technique that uses sectoral monetary transaction matrixes describing complex interlinks between different sectors in the national economy. These data are regularly compiled as part of national statistics and thus easily accessible. Another advantage is the possible inclusion of related processes, such as the need for support services or overheads i.e. sales department, lunch rooms, management etc. which are needed as input to a product system. These processes are mainly deliberately excluded in process LCA, as their contribution relative to the complexity of compiling the inventory is often low. The use of economic I/O analysis with environmental data was first done by Wassily Leontief in 1970 (Pan et.al. 2001). Leontief advanced the understanding of interconnections in economics considerably and even received the Nobel Prize for his contributions. The I/O concept mainly deals with society analysis, where one wants to know what might be the consequences of e.g. reducing the military budget or putting a tax on carbon emissions, on employment patterns in different sectors in various regions.

3.3.2 An Input/Output model example

The I/O concept is most easily explained through a simple example, based on Watkins (2006). Let us examine a highly hypothetic example. Suppose there are only two industries producing coal and steel. Coal is required to produce steel and some amount of steel in the form of tools is required to produce coal. Suppose the input requirements per ton output of the two products are:

Table 2 Input requirements for producing one ton of coal or steel.

Industry	Coal	Steel
Coal	0	3
Steel	0.1	0

The table should be read as follows: To produce one tonne of coal you need 0.1 ton of steel and to produce one ton of steel you need 3 ton coal. The chain starts to develop as you need additional amount of coal to produce the 0.1 ton of steel needed to produce the desired ton of coal. Let us try to produce one ton of steel, the question is then: What total amount do we need of coal and steel to produce 1 ton of steel?

This may be written as a geometric series:

$$Ton_{coal} = 3 + 3\cdot(3\cdot 0.1) + 3\cdot(3\cdot 0.1)(3\cdot 0.1)....+3\cdot 0.3^n \longrightarrow \quad [1]$$

$$Ton_{steel} = 1 + 1\cdot(3\cdot 0.1) + 1\cdot(3\cdot 0.1)(3\cdot 0.1)....+1\cdot 0.3^n \longrightarrow \quad [2]$$

$$Coal: \sum_{1}^{n\to\infty} 3\cdot 0.1^n \xrightarrow{geom.} 3\cdot\sum_{k=1}^{n\to\infty} q^{k-1} = 3\cdot\left(\frac{1-q^n}{1-q}\right) = 3\cdot\left(\frac{1}{1-0.3}\right) = 4.286 \quad [3]$$

$$Steel: \sum_{1}^{n\to\infty} 1\cdot 0.1^n \xrightarrow{geom.} 1\cdot\sum_{k=1}^{n\to\infty} q^{k-1} = 1\cdot\left(\frac{1-q^n}{1-q}\right) = 1\cdot\left(\frac{1}{1-0.3}\right) = 1.429 \quad [4]$$

Series 1 and 2 can be followed easily by adding consequently the required amounts of coal and steel to produce one ton of steel. They both form a geometric series, which sum is easily found for q < 0. To produce one ton of steel output, one needs 4.286 ton coal and 1.429 ton steel.

Another way of writing Table 2 is in matrix form, where the needed intermediate inputs are denoted **A** and the desired amounts of coal and steel are d_1 and d_2. The levels of used coal and steel are x_1 and x_2:

$$A = \begin{bmatrix} A_{1,1} & A_{1,2} \\ A_{2,1} & A_{2,2} \end{bmatrix} = \begin{bmatrix} 0 & 3 \\ 0.1 & 0 \end{bmatrix} \qquad x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \qquad d = \begin{bmatrix} d_1 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

We then have a simple matrix equation indicating the relation; the final demand; **d** added to the intermediate output **Ax** gives the total usage of coal and steel:

$$Ax + d = x \qquad [5]$$

$$\begin{bmatrix} A_{1,1} & A_{1,2} \\ A_{2,1} & A_{2,2} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} d_1 \\ d_2 \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$\begin{bmatrix} 0 & 3 \\ 0.1 & 0 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$\left.\begin{matrix} 3x_2 + 0 = x_1 \\ 0.1x_1 + 1 = x_2 \end{matrix}\right\} \xrightarrow{simple \quad a\lg ebra}$$

$$x_1 = 4.286$$
$$x_2 = 1.429$$

The results yield the same amounts as found with the geometric series. A third way of obtaining the needed amounts of coal and steel is by matrix calculation. Let us return to equation 5, which we rearrange with simple matrix computation:

$$Ax + d = x$$
$$x - Ax = d$$
$$x(I - A) = d \qquad I = n \times n \;\; unit\, matrix$$
$$x = (I - A)^{-1} d$$

The $(I\text{-}A)^{-1}$ matrix is called the "Leontief inverse" after Wassily Leontief. The calculation of the Leontief inverse is shortly shown below for the coal and steel example.

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = (I - A)^{-1} d = \begin{bmatrix} 1-0 & 0-3 \\ 0-0.1 & 1-0 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \frac{1}{\det(I - A)} \begin{bmatrix} 1 & 3 \\ 0.1 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \frac{1}{0.7} \begin{bmatrix} 0 & 3 \\ 0 & 1 \end{bmatrix}$$

$$x_1 = 1.429 \cdot 3 = 4.286$$
$$x_2 = 1.429$$

The Leontief inverse thus yields the same result as the geometric series and the algebra solution. The Leontief inverse is the main tool to examine large input/output tables with the help of suitable software. The Leontief inverse allows one to examine systems with many thousands interrelated processes. The combination of the process matrix and environmental impact intensities matrix yields the environmental impact. The matrix **E** contains all environmental burdens arising from one economic unit of industrial activity, the burdens are then given by:

$$e = E^T \cdot x$$

The matrix **e** contains the inventory set of emissions and raw material input from a demand **d**. Impact assessment can be performed by multiplying **e** with a characterisation matrix **C** that contains the impact factors, resulting in an impact matrix **b**.

$$b = C \cdot e$$

The matrix **b** contains impact categories such as global warming potential, acidification etc. The I/O approach makes it possible to calculate total environmental burdens arising from a demand of a sector activity without applying any system boundaries or cut-off procedures. The main disadvantage is the high level of aggregation, which does not differentiate whether one purchase a luxury car or a small hybrid car.

An environmental I/O LCA consists of the following three main stages (Rebitzer et.al. 2004):

- Creation of a direct requirements matrix from economic data, generally from make and use tables from national accounts
- Linkage of data for environmental exchanges (e.g., pollutant releases and resource consumption flows) to the direct requirements matrix, called **x** in the example above. The linkage matrix is the matrix **E** in the example above
- Calculation of a cradle-to-gate inventory (up to the finished/sold product) using the direct requirements matrix and environmental exchange data. Which means finding the coefficients in matrix **A**

3.3.3 Concluding comments to I/O analysis

The above example demonstrates the powerful “Wassily inverse” which easily sums the environmental impact from a system and it’s related interactions.

The I/O economics concept presented here also has relevance for different LCA software, where one chooses processes from a database, and the resulting environmental impact is calculated with help of Leontief inverse.

Hybrid LCA utilises process LCA for the most relevant parts and applies I/O analysis for assessing the processes of secondary importance. As seen above is this to find the optimum between two extremes:

- Only process LCA; every process chain has to be followed to the bottom, which implies endless amount of work
- Only I/O environmental analysis; being too coarse to really present the present system with adequate detail.

As one knows; thousand of separate processes yielding 0.01 % of total environmental impact combined, still yield 10 % of total impact and is thus highly relevant. The hybrid LCA approach tries to find the trade-off between alternative a and b, described above.

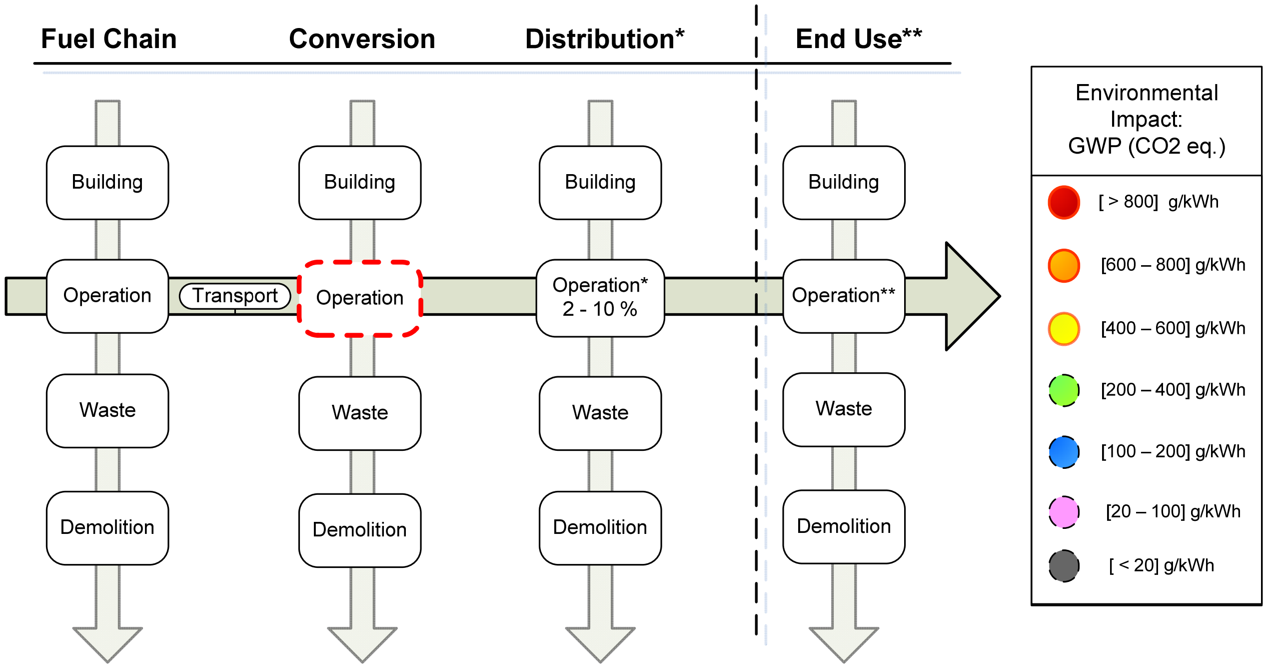
There are many references to I/O analysis in the literature. A good overview is given by e.g. Suh et.al. 2004.

4 PRESENTATION OF LCA LITERATURE RELEVANT TO LOCAL ENERGY PLANNING

4.1 MOTIVATION AND INTRODUCTION

The literature review aims at presenting some of the major LCA studies of energy systems that are available. This overview gives an impression of what an LCA could entail, and what results, both quantitative and qualitative may be the outcome of an LCA study. The latter helps to formulate some general observations concerning the environmental impact from different energy technologies. This is important in order to determine possible cut-offs in performing an LCA. A relevant question is e.g. how much do the construction phase matter for a fossil fuel power plant, when analysed over the whole life cycle? Is the environmental impact during construction negligible compared to 20 years of operation? This and other questions are important to form a framework for practical use of LCA relevant to local energy planning. The summary only presents some results from the actual report or paper; just enough to give an impression of main content and enable the reader to decide which reports or papers should be studied further.

LCA at a glance is presented below in Figure 16 to demonstrate the LCA concept as opposed to traditional emissions reporting (based on Persson et.al. 2005). The direct emissions from the operation of the energy conversion (power plant, boiler etc.) are often accounted for when environmental impact from an energy system is analysed. These are marked with red in Figure 16. Reasons for this limited perspective may be: Firstly; a more comprehensive accounting requires much resources and knowledge, and secondly: The main environmental impacts from an energy system utilizing a fuel are often related to the operation phase of the energy conversion. An LCA takes all related processes into account, presenting a more holistic environmental accounting.



*The distribution phase contributes through energy losses, i.e. dependent of voltage level and distance to demand
**End-use is highly important for the LCA result, but exoghenous to the SEDS project

Figure 16 The holistic LCA perspective on an energy system (based on Persson et.al. 2005), with the life cycle of the energy product horizontally and the life cycles of the sub-processes are represented vertically.

A more specific overview of main elements in an energy system LCA is provided in Figure 17, where the construction and demolition phase, together with fuel provision and auxiliary elements are shown.

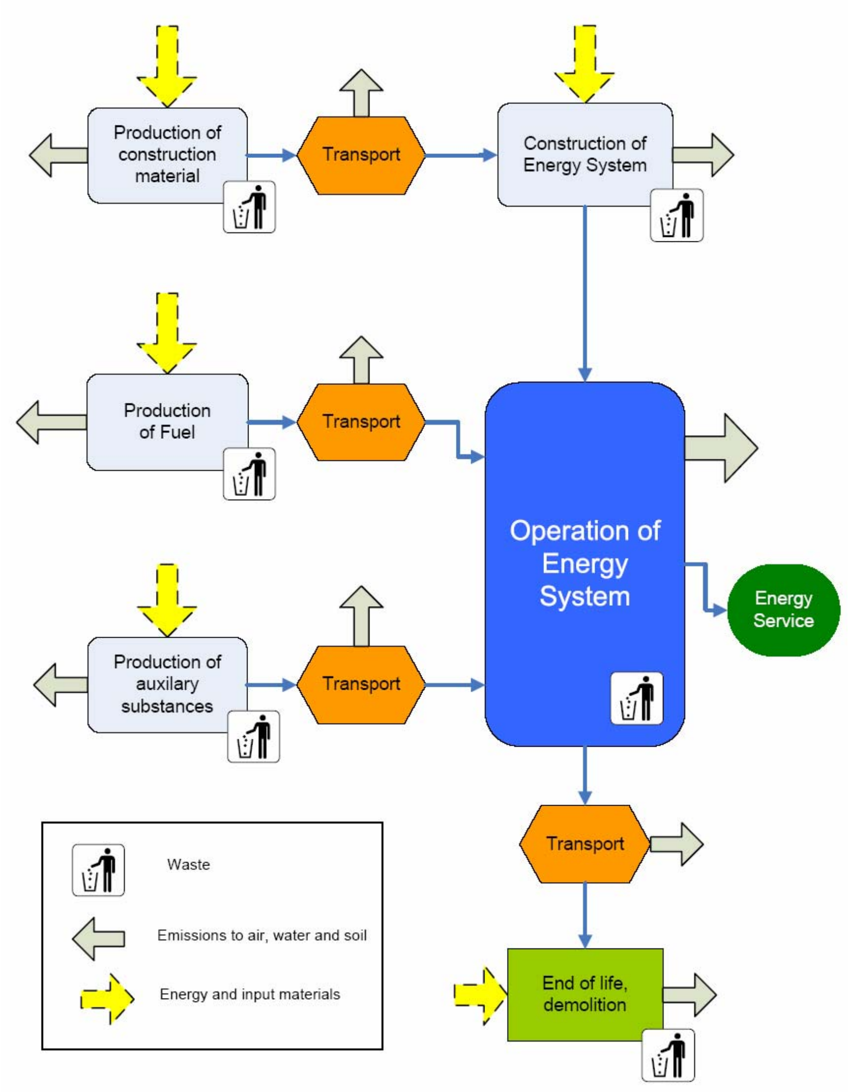


Figure 17 Illustration of life cycle scope of energy systems (based on Setterwall et.al. 2004).

The life cycle of an energy system comprises the following main elements (based on Setterwall et.al. 2004):

- Fuel preparation incl. exploration, extraction and transport)
- Building of energy system incl. roads, housing manufacture of tools etc.
- Operation of energy system incl. maintenance, handling of fuel residues etc.
- End of life incl. disposal, transport, recycling etc.
- Production of auxiliary substances and materials incl. reinvestments etc.

The reading of the following short presentations of relevant literature may be more rewarding with the Figure 16 and Figure 17 kept in mind.

4.1.1 Structure of chapter

The summary is structured as follows: First are some LCA-studies from the Nordic countries presented followed by international studies, where also relevant EU projects are presented. At the end some observations and final remarks are stated, together with a more comprehensive table of LCA-literature relevant to SEDS. The literature table is meant to ease the introduction into energy system LCA-literature, and could be a starting point for someone interested in energy systems and LCA-literature.

4.2 NORDIC LCAS

4.2.1 Swedish electricity

Dethlefson et.al. present an LCA of the electricity produced by Vattenfall. The main report is not accessible (aggregated results available at the Vattenfall webpage, (Vattenfall 2006)), but a summary is available on "World Energy Councils" web-pages. The report focuses on GWP (Global Warming Potential), represented by emissions of CO_2, N_2O, CH_4 and SF_6, from energy technologies present and available in Sweden and with Swedish conditions. This implies e.g. that the enrichment of uranium takes place in either Netherlands or France. The CO_2 emissions from different types of Swedish power plants are shown in Figure 18.

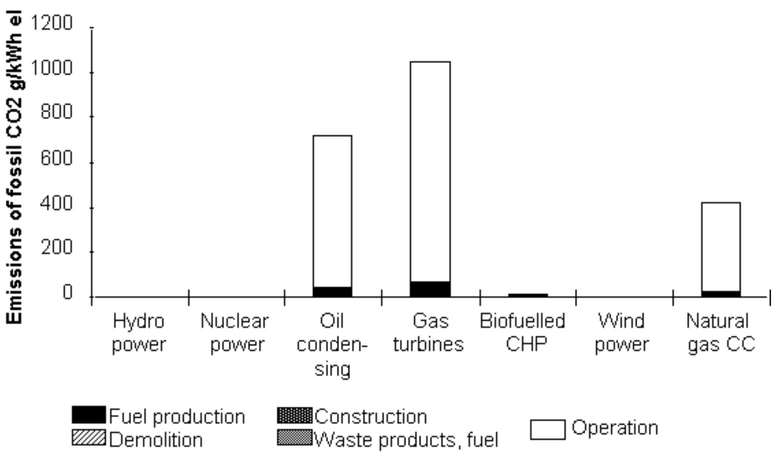


Figure 18 Emissions of CO_2 from different types of power plants in Sweden.

It is evident from Figure 18 that most emissions occur in the operational phase of the power plants life cycle. The emissions from nuclear, wind and hydro are not visible as their emissions are much smaller. Vattenfall also analysed the energy required to build power-lines, which is shown in Figure 19.

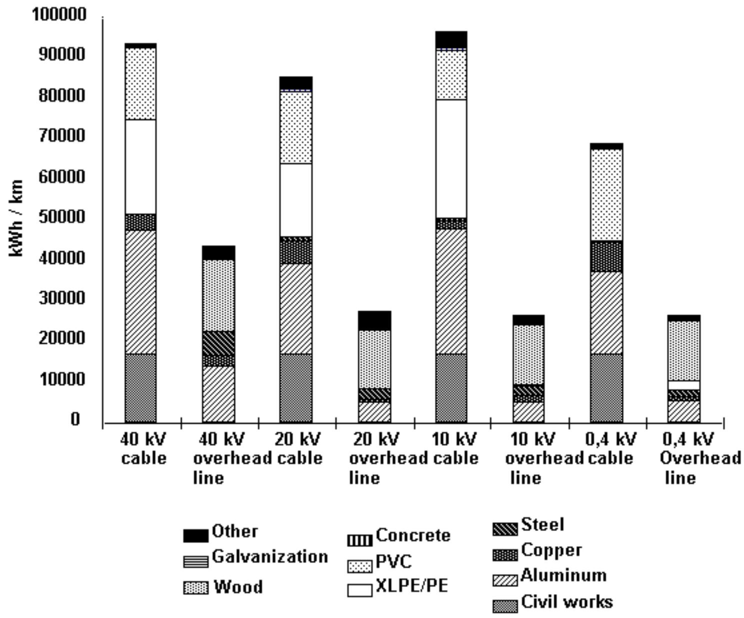


Figure 19 Energy required for building one km of cable or overhead line.
(The legend is read from lower right corner and upwards.)

The construction of cables requires considerably much more energy than overhead line, as seen in Figure 19, but has advantages as less required maintenance, lower risk of failure and no visual disturbance. A total LCA would also include these parameters. The energy used in building power lines depends heavily on the relative amount of recycled materials used. With the energy used in construction and data from maintenance of power transmission, it is possible to determine the CO_2-equivalent emissions from distributing one kWh of electricity. The electricity is supplied at the central grid, the emissions thus increase along with lower voltage level as shown in Figure 20:

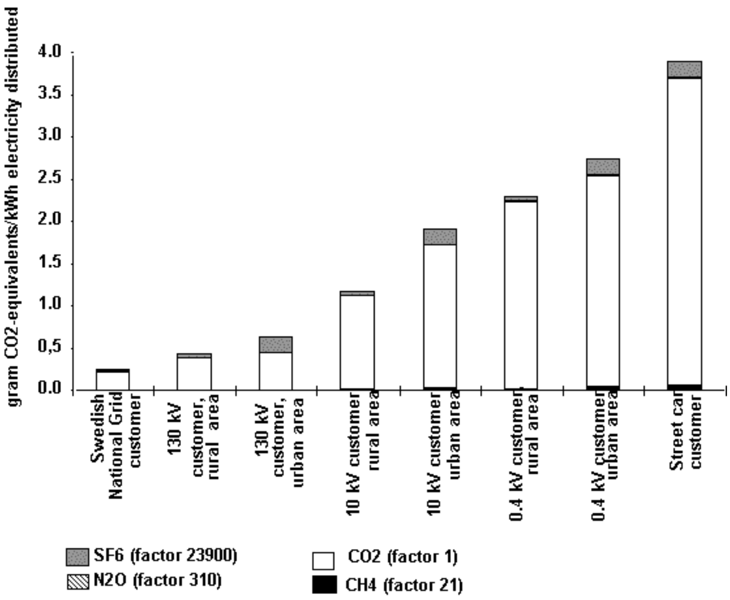


Figure 20 Emissions from distributing one kWh of electricity to different voltage levels.

The electricity delivered at household level has a longer transport distance, as most electricity production is centralised, and thus has higher losses than consumers connected to higher voltage levels. The total emissions from delivering Vattenfall electricity (mainly hydro and nuclear) is then calculated separating the different energy technologies and their respective stages of the life cycle. As seen in Figure 21, the construction phase has most of the emissions since hydropower and nuclear power emits limited amounts of GHG (Green House Gases) during operation.

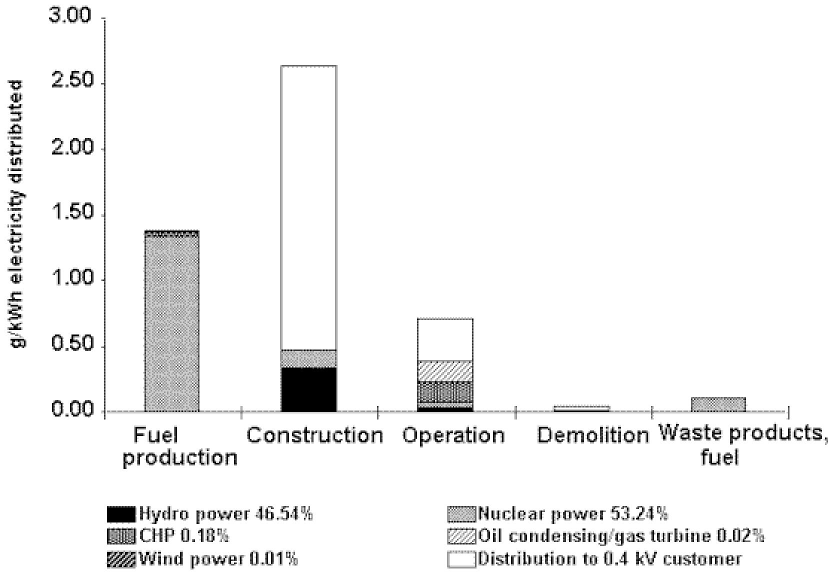


Figure 21 Emissions of CO_2-equvalents in connection with production and distribution of 1 kWh of Vattenfall electricity (mainly hydro and nuclear) to a customer on the 400 V-level.

The Vattenfall study emphasizes the need for powerful tools such as LCA to assess the whole life cycle of energy technologies. The study is limited to only one type of impact, GWP, and does not evaluate impacts such as: acidification, radiation, solid waste, air pollution, water pollution or ozone layer. Vattenfall continues to update its LCA data on the electricity they produce (Vattenfall 2006d). A summary of their results is available at their webpage. Some of the main figures are presented here. Figure 22 presents CO_2 emissions from producing and distributing 1 kWh of electricity, generated by different technologies.

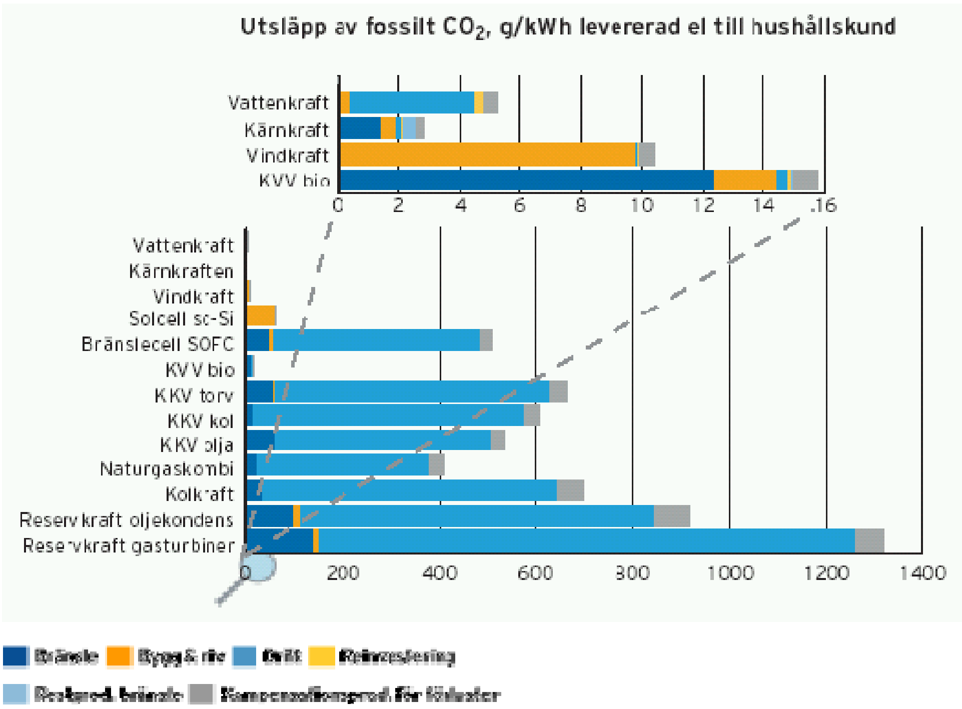


Figure 22 Emissions of CO_2 from electricity production and transmission to households for different generation technologies [g/kWh] (Vattenfall 2006d).

It is clear from Figure 22 that building and demolition is not contributing significantly to CO_2 emissions as long as the power plant is fuelled by fossil fuel. Upstream activities are more important, often contributing to more than 10 % of the total life cycle emissions. Building and demolition is contributing with a much larger part for the renewable and nuclear technologies as these avoid most of the operational emissions connected with fossil fuel use. It is evident from Figure 22 that CO_2 emissions from hydropower is negligible compared to coal and gas power plants (the CO_2 emissions from hydro power mostly relates to lost biomass in the flooded areas). For a simplified LCA this information is essential, as it provides reasons for great cut-offs and accompanying decrease of workload. The same is observed for NO_X, SO_2 and particle emissions (not shown here). The use of copper is another indicator presented in the Vattenfall study and shows opposite characteristics compared to NO_X, SO_2, CO_2 and particles emissions. The impact is mainly during building and the impact from renewable technologies is in general larger than for fossil based generation technologies as seen in Figure 23. The use of copper is shown in order to emphasize the width and complexity of LCA results, e.g. for GHG emissions the operation phase is dominant and coal is performing worst, for the use of copper is building phase dominant and the solar cells are performing worst.

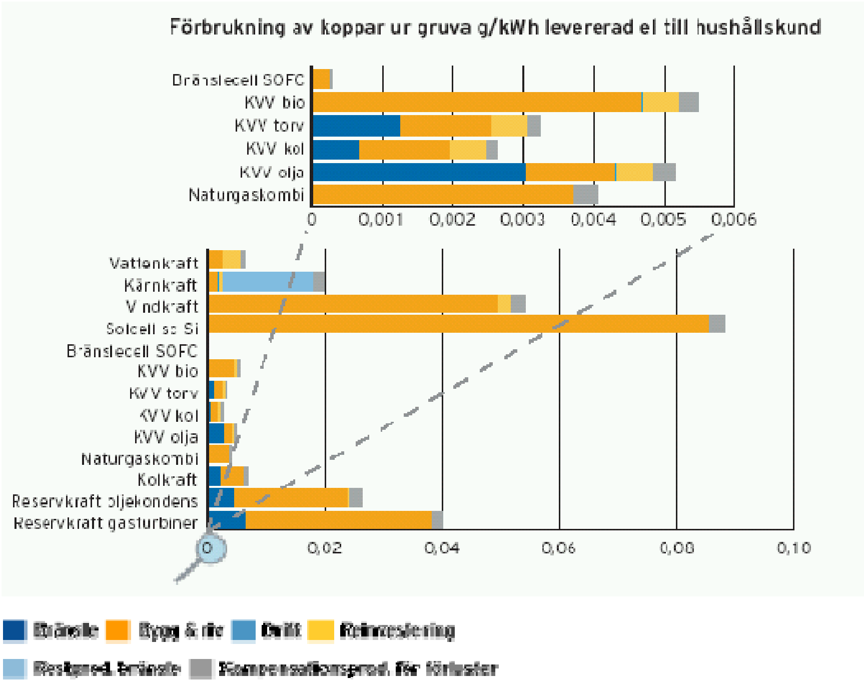


Figure 23 The use of copper in [g/kWh] for different generation technologies.

Vattenfall also presents performance indicators for the amount of radioactive waste, which yields poorly (as expected) for nuclear electricity generation. The final challenge for the user of the Vattenfall study is to determine the relative importance between nuclear waste production, CO_2 emissions and the use of copper etc. This weighting decision is difficult and often relies on personal preferences and subjective decisions as explained in Chapter 3.2.

4.2.2 Swedish heat and electricity

Vattenfall has recently started with "certified Environmental Product Declaration" (EPD®) for its generation and distribution of heat and electricity. These data are highly relevant, as LCA methodology is applied and the declaration contains detailed environmental information. The main environmental impacts are reported as the example below from a CHP at Uppsala (Vattenfall 2006a). The results are divided between "fuel", "construction", "operation" and "distribution" as seen in Figure 24.

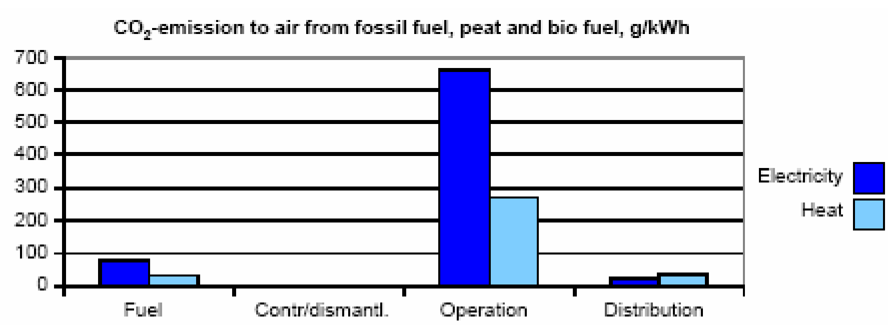


Figure 24 CO_2 emissions from the CHP at Uppsala per kWh heat and electricity (Vattenfall 2006a).

The “construction/dismantling” phase is not significant for CO_2 emissions. Peat is not CO_2 neutral, which increases the emissions during operation considerably. Notice that also the DH (District Heating) grid is included in the “construction/dismantling” phase, which implies that the production of the pipes is insignificant. More EPD reports are available at the official webpage (Environdec 2006), which is one of the most relevant literature sources for SEDS and the applied LCA perspective. A dominance analysis of the CHP is shown below, where one can clearly see how the fuel production and operation is dominant for most impact catergories.

Table 3 Contributions to the studied environmental impact categories from the various life cycle stages (Vattenfall 2006a).

Electricity	**Fuel production**	**Construction, reinvestment, dismantling**	**Operation**	**Distribution**	**Total prodution stage incl. generation and distribution**
Greenhouse gases	12%	0%	**85%**	3 %	100%
Ozone-depleting substances	**79%**	1%	17%	**3%**	100%
Acidifying substances	23%	1%	**73%**	3%	100%
Hydrocarbons contributing to the formation of ground-level ozone	**79%**	1%	18%	**3%**	100%
Eutrophying substances	33%	0%	**64%**	3 %	100%
Heat	**Fuel production**	**Construction, reinvestment, dismantling**	**Operation**	**Distribution**	**Total production incl. generation and distribution**
Greenhouse gases	10%	0%	**79%**	11%	100%
Ozone-depleting substances	**73%**	0%	16%	11%	100%
Acidifying substances	20%	0%	**68%**	11%	100%
Hydrocarbons contributing to the formation of ground-level ozone	**68%**	0%	17%	15%	100%
Eutrophying substances	28%	0%	**56 %**	16%	100%

4.2.3 Swedish production of district heating pipes

An LCA report concerning production of district heating pipes (Fröhling M. et.al. 2002), analyses the production of four different types of pipes. The main conclusion is that the production of the input-materials contributes the most to the environmental load, thus manufacturing of the pipes contributes less than production of the steel and plastic and other materials used as input-materials. However should the material use never jeopardise the insulation capacity of the pipes, as the heat losses during its lifetime is the most important factor considered the whole lifetime.

The emissions are as follows, for production of the four different types of pipes:

Table 4 Major results from the Fröhling M. et.al. study of production of district heating pipes.

kg / pipe	DN500 Single	DN100 Single	DN25 Single	DN25 Twin
Length of pipe [m]	16	12	12	12
CO_2	4000	360	82	150
NO_x	12	1,1	0,31	0,49
SO_x	10	0,93	0,29	0,44
COD	1,5	0,16	0,04	0,07

4.2.4 Swedish biomass utilised in CHP

An LCA comparison between processed biomass and raw biomass for usage in CHP is undertaken by “Värmeforsk” (Värmeforsk, LCA-analysis) . The report is detailed and includes description of methodology and input-data. The data may be used for transport and combustion of biomass. The report is in Swedish language and offers a good introduction to LCA. It is emphasized to communicate the underlying thinking and assumptions.

4.2.5 Danish heat and electricity

Denmark has also started with declaration of its electricity, but on a more aggregated level than the Swedish declaration, adding up all generation capacity in east and west of Denmark.
The main responsible energy distributor “Energinet” is obliged through law to deliver an environmental report every year. The report delivers an aggregated declaration of the electricity produced in west and east of Denmark. Losses in electricity grid and natural gas grid are reported, but not included in the aggregated declaration results (Energinet 2006). The Danish power sector (Energi E2, Elsam, Elkraft System) has undergone an LCA analysis of the heat and power produced and distributed in Denmark. The study presents aggregated numbers for 1 kWh of el and heat delivered to the customer. Despite the high aggregation level of result-reporting, the study is detailed and entails numerous of SEDS relevant information. The report is not freely available, but can be sent (Troels Duhn 2006). The results are often presented as milli-person-equivalent (mPE), which is a normalisation based on average society-emissions per person. For local impacts is the Danish 1990 data used. Global impacts are normalized with global 1990 data (reference for Danish LCA report).

The Danish LCA operates with 12 indicators of environmental impact; Ash/clinker, radioactive waste, dangerous waste, volume of waste, persistent toxicity, eco-toxicity, human toxicity, eutrophication, photochemical ozone 2/ozone 1, acidification, ozone depleting, greenhouse gases. Some power producing technologies are reported in Figure 25 with some of the indicators. The unit is milli-person-equivalents, the Danish coal plant thus emit 0.065 of a person equivalent of CO_2 (8.7 ton 1990), which implies 566 gram CO_2 / kWh electricity and heat combined.

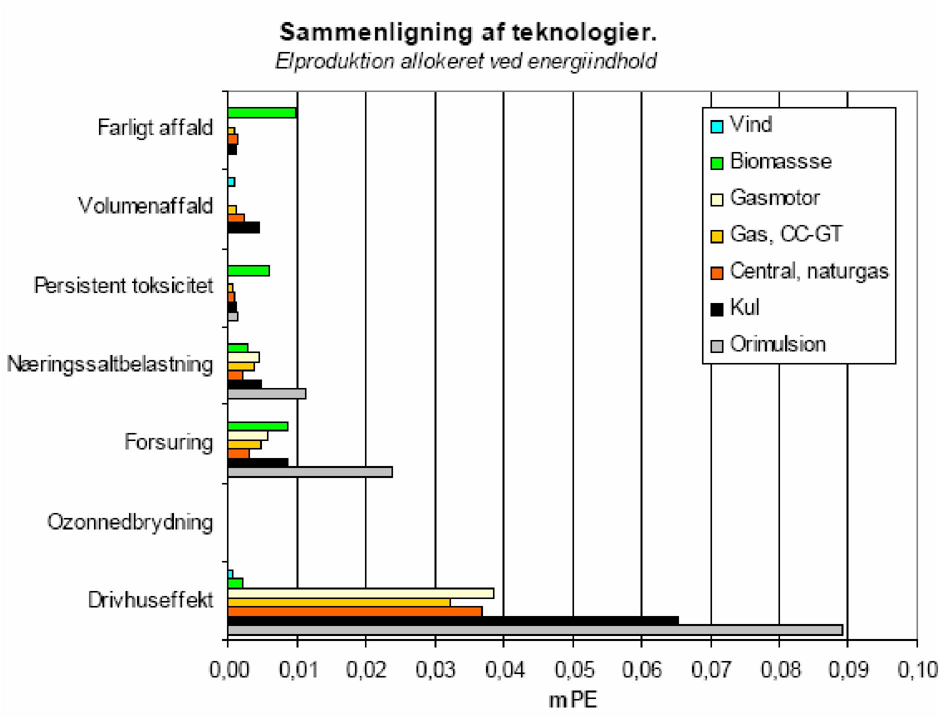


Figure 25 Comparison of technologies, impact measured as milli-person-equivalents.

It is clear how orimulsion is performing worst in most indicator-classes, with biomass being the heaviest polluter in regard of dangerous waste and persistent toxicity. This figure exemplifies the danger of using "energy content" (meaning heat and electricity) as functional unit, as orimulsion emit less CO_2 than coal, but produces less energy (high portion of electricity). The coal power plants producing mostly heat thus appear to have less environmental impact. By using exergy instead this problem is avoided, however creating a new one since exergy is more reflecting a physical relation rather than human preferences for energy services.

To valuate the different indicators against each other demands a weighting methodology, this depends on personal preferences i.e. how to value acidification versus global warming. The consumed electricity in Denmark is shown in Figure 26, where the life cycle impact is divided between; "operation", "fuel", "building/demolition" and "transport"

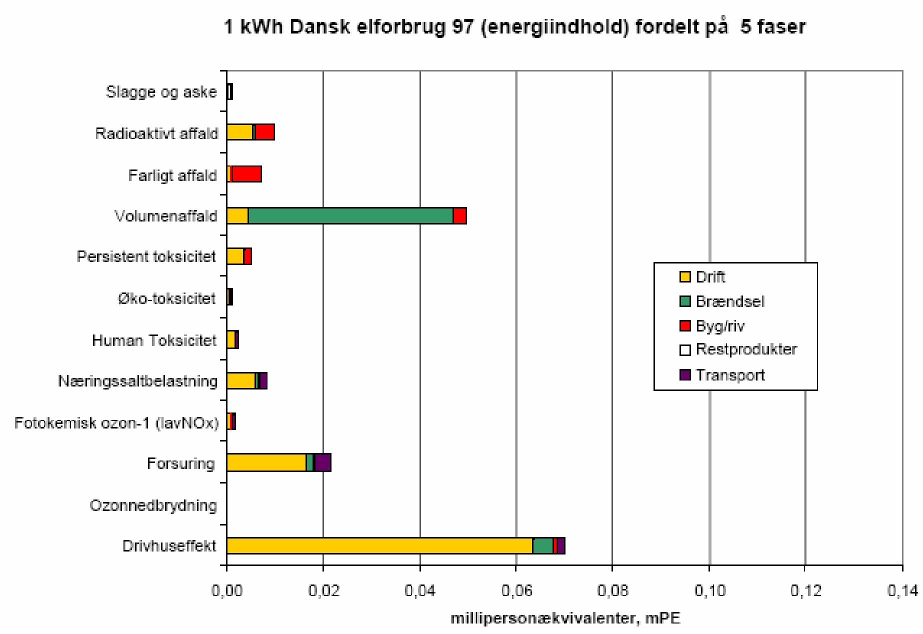


Figure 26 Impact from consumption of 1 kWh electricity, divided on five phases of the life cycle.

It is evident how “operation” is the major contributor to most of the impact-indicators, with exception for “dangerous waste” and “volume of waste”. The “building/disposal phase” is hardly present except for “radioactive waste”, “dangerous waste” and persistent toxicity. A short summary of the Danish LCA study of CHP power plants is available on internet (Duhn et.al. 2002).

4.2.6 Norwegian gas power plant

One Norwegian study performed by “Østlandsforskning” (Magnussen K. et.al.) analyses a gas fired combined cycle power plant, based in Norway and using Norwegian gas as fuel. The report analyses energy use, NO_x, SO_2, Cr (chromium) and CO_2 emissions. All indicators except chromium have main environmental impact during operation; this is exemplified with CO_2 emissions in Figure 27. Construction and demolition is too small to be visible in the figure.

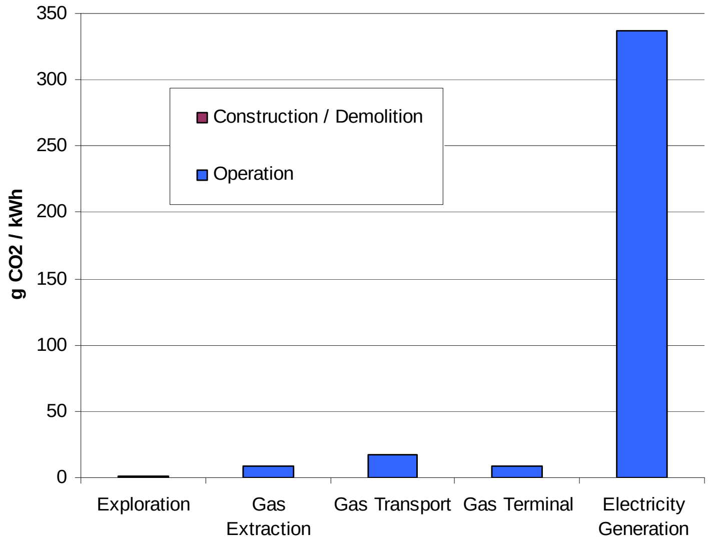


Figure 27 Carbon dioxide emissions along the whole energy chain.

The report from “Østlandsforskning” presents LCA methodology in great details and provides an introduction to LCA. The report is written for non-practitioners of LCA and is thus easy reading.

4.2.7 Norwegian hydropower

“Østlandsforskning” (Vold M.et.al.) has also performed an LCA on Norwegian hydropower, with a detailed case study of Jostedalen hydro power plant, which is seen as a typical Norwegian modern hydro power plant placed in the mountains. The study is from 1996 and analyses 1 kWh delivered to random customer in Norway. Building and maintenance of power plant and transmission grid is included. A wide range of impacts are analysed, impacts which are not included are commented and assessed. Different weighting procedures are tested and compared, showing how different methodologies return quite different answers. The total emissions from transmission grid and power plant including dam and tunnels amount to around 4 g of CO_2 per kWh as shown in Figure 28.

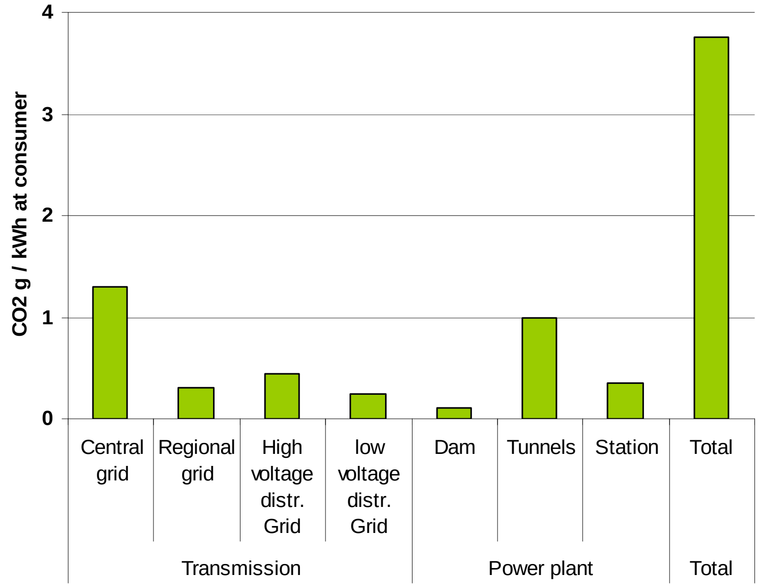


Figure 28 CO_2 emissions from hydro power distributed among the main elements.

The results for the transmission grid are relatively similar to the Swedish study, which is reasonable as both grids have many similarities (climate, country size, customer density, technology, use pattern etc.). The study examines a wide range of impacts quantitatively, among the most important and significant are: CO_2, SO_2, NO_X, fluoride, particles, fossil energy use and copper use. Other impacts such as changed water flow, visual disturbance, conditions for fish etc. are treated qualitatively. The ISO standard has emerged after this study was undertaken (1996), but the analysis seems to be of reasonable quality according to LCA standards of today. The CO_2 emissions mainly occur from the production of cables and pylons (transmission) and from the transportation of boulders from tunnels etc. A reservoir situated at lower altitudes with more surrounding fauna would probably emit more CO_2 as fauna is being flooded.

4.3 INTERNATIONAL LCA STUDIES

It is a considerable international literature concerning life cycle approaches to energy systems. First is some major EU projects commented before more general literature is presented.

4.3.1 EU projects

Two EU projects are relevant to describe inventories and externalities of European power production that is Eclipse and ExternE respectively. ECLIPSE (**E**nvironmental and e**C**ological **L**ife cycle **I**nventories for present and future **P**ower **S**ystems in **E**urope) describes and analyses 100 possible configurations of five main emerging technologies for distributed power generation, i.e. photovoltaics (PV), wind, biomass, small combined cogeneration systems (CHP), and fuel cells. The results are given in a life-cycle inventory (LCI) database, containing both the overall results in terms of resource consumption and emissions (the focus is on airborne emissions) over the whole life cycle and detailed information on unit processes. The database is supposedly updated and available at internet (ECLIPSE 2007). Here is an example of a 420 kW engine-based CHP plant. Notice the different units at the axis.

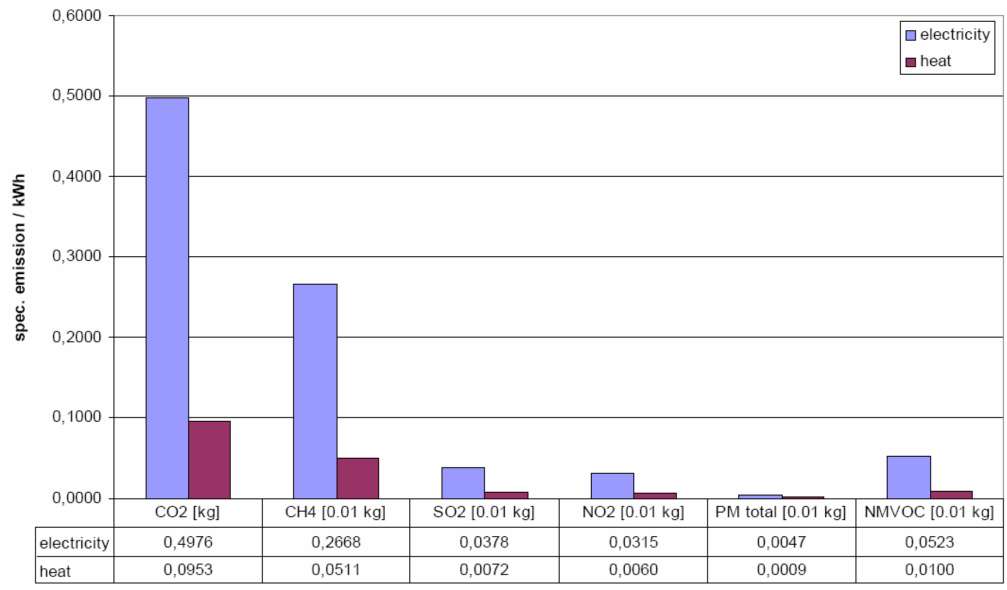


Figure 29 420 kW engine-based CHP from the ECLIPSE inventory.

The ECLIPSE project only provides inventories to new energy technologies, and thus not the valuing and weighting steps of a total LCA. Perhaps more important is the sensitivity analysis, showing which processes are most important, as shown in Figure 30 below:

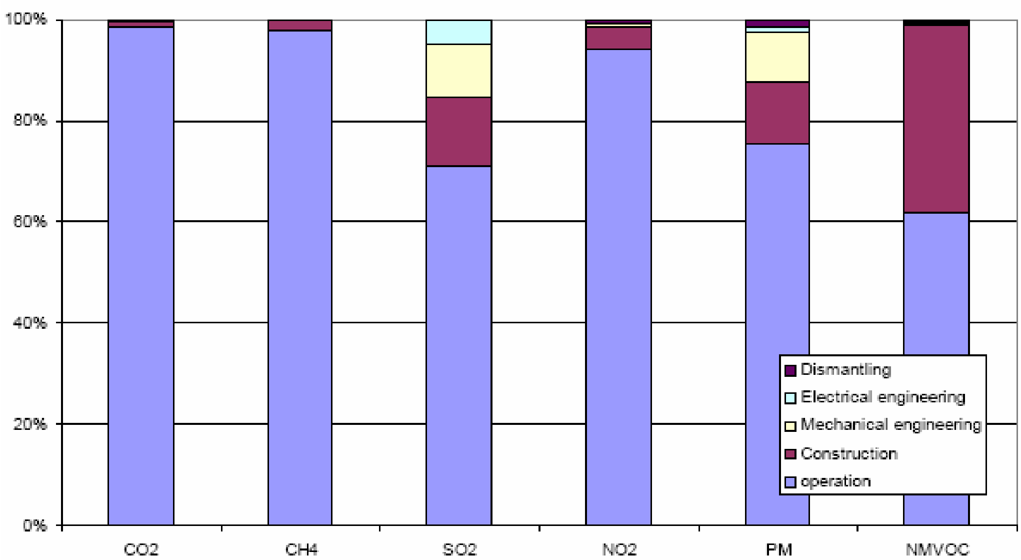
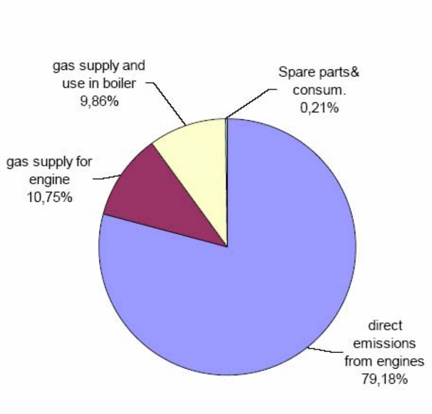
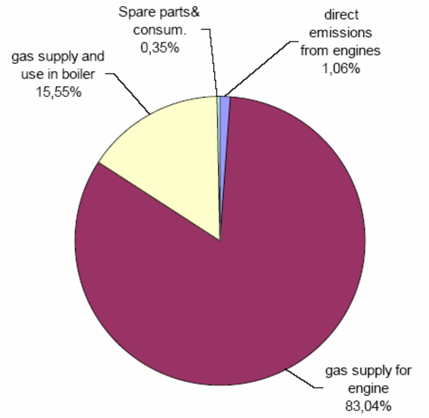


Figure 30 Life cycle stages where emissions occur.

The "operation" phase is dominating for most emissions, and needs thus a closer analysis. Below is the operation phase divided into its sub-processes for CO_2 emissions and NO_2 emissions respectively:





It is clear how direct emissions from the engine is dominant for the CO_2 emissions but that gas supply is the most important life cycle stage for the emissions of NO_2.

A related project is the ExternE project which has been going on for 15 years since 1991. The objective of the ExternE-Project series is the quantification of external costs arising from the use of energy. External costs express monetary evaluated damages or risks to the environment, human beings and material. The evaluation is based on a life cycle inventory analysis of a particular technology in the present or the near future. Some cost parameters are given in Table 5 (Rainer 2005).

Table 5 Monetary values of some health consequences (Rainer 2005).

Health end-point	Recommended central unit values in € price year 2000
Value of a prevented Fatality	1,000,000
Year of Life Lost	50,000 / year lost
Hospital admissions	2,000 / admission
Emergency Room Visit for respiratory illness	670 / visit
General Practicioner visits:	
Asthma	53 / consultation
Lower respiratory symptoms	75 / consultation
Respiratory symptoms in asthmatics:	
Adults	130 / event
Children	280 / event
Respiratory medication use – adults and children	1 / day
Restricted activity days	130 / day
Cough day	38 / day
Symptom day	38 / day
Work loss day	82 / day
Minor restricted activity day	38 / day
Chronic bronchitis	190,000 / case

As one can see from Table 5, a year of life lost is valued to 50 000 €. Global warming is another consequence which is hard (if not impossible) to value. ExternE has used different values, from 2.4 € / ton CO_2 in 2000 and 19 € / ton CO_2 in 2005 (Dr. Ari 2005). These costs add up to the external cost of each analysed technology. For electricity these are shown in Figure 31.

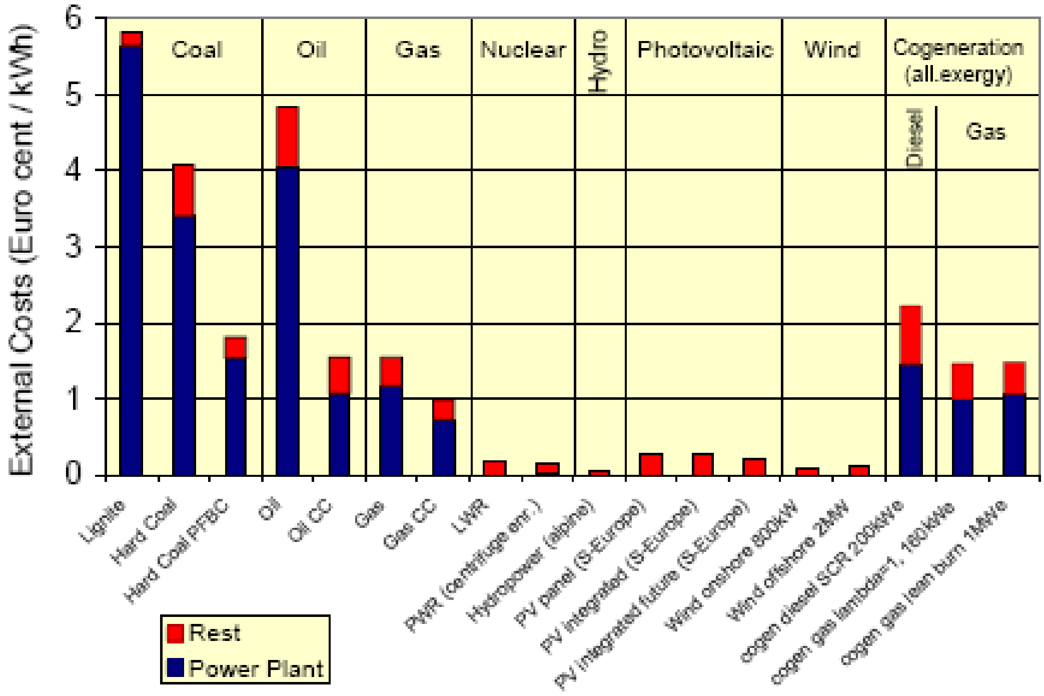


Figure 31 External cost to some Western European power plants.

Where “power plant” refers to the operation of the energy conversion plant, and the term “Rest” refers to all other phases of the life cycle. As expected; the renewable power plants emit zero or almost zero emission during operation, but have some environmental burdens during the rest of the life cycle. The fossil based technologies have high external cost related to the operation of the plant caused mainly by CO_2 emissions. A coal plant emits around 1 kg CO_2 per kWh (Stene 2006), thus with a cost set at 19 € per tonne, the CO_2 emissions accounts for 1.9 €cents out of the total ca. 4 €cents (as seen in Figure 31 above).

The list of included impacts is shown in Table 6 (Rainer 2005):

Table 6 Impacts considered by the ExternE prosject.

Impact Cat.	Pollutant / Burden	Effects
Human Health mortality	PM_{10} SO_2, O_3	Reduction in life expectancy due to short and long time exposure
	Benzene, BaP, 1,3-butad., Diesel part.	Reduction in life expectancy due to short time exposure Reduction in life expectancy due to long time exposure
	Noise	Reduction in life expectancy due to long time exposure
	Accident risk	Fatality risk from traffic and workplace accidents
Human Health morbidity	PM_{10}, O_3, SO_2	Respiratory hospital admissions
	PM_{10}, O_3	Restricted activity days
	PM_{10}, CO	Congestive heart failure
	Benzene, BaP, 1,3-butad., Diesel part.	Cancer risk (non-fatal)
	PM_{10}	Cerebrovascular hospital admissions, cases of chronic bronchitis, cases of chronic cough in children, cough in asthmatics, lower respiratory symptoms
	O_3	Asthma attacks, symptom days
	Noise	Myocardial infarction, angina pectoris, hypertension, sleep disturbance
	Accident risk	Risk of injuries from traffic and workplace accidents

Impact Category	Pollutant / Burden	Effects
Building Material	SO_2, Acid deposition	Ageing of galvanised steel, limestone, mortar, sand-stone, paint, rendering, and zinc for utilitarian buildings
	Combustion particles	Soiling of buildings
Crops	SO_2	Yield change for wheat, barley, rye, oats, potato, sugar beet
	O_3	Yield change for wheat, barley, rye, oats, potato, rice, tobacco, sunflower seed
	Acid deposition	Increased need for liming
	N, S	Fertilising effects
Global Warming	CO_2, CH_4, N_2O	World-wide effects on mortality, morbidity, coastal impacts, agriculture, energy demand, and economic impacts due to temperature change and sea level rise
Amenity losses	Noise	Amenity losses due to noise exposure
Ecosystems	SO_2, NO_x, NH_3	Eutrophication, Acidification

The ExternE project impact assessment does not include (Rainer 2005):

- Visual intrusion
- Biodiversity losses (eutrophicationand acidification), however new method developed within the NEEDS project
- Biodiversity loss (local, however included in Environmental Impact Study)
- Risk of nuclear proliferation and terrorism
- Risk aversion resp. treatment of Damocles risks

The ExternE project is followed up through the NEEDS project (**N**ew **E**nergy **E**xternalities **D**evelopments for **S**ustainability) which is continued throughout 2008. The objective of NEEDS is: "*…to evaluate the full costs and benefits (i.e. direct + external) of energy policies and of future energy systems...*" (NEEDS 2007). The LCA methodology is central to accomplish this objective and is even brought forward through the development of dynamic LCA. The project refines and develops the externalities methodology already set up in the ExternE project, through an ambitious attempt to develop, implement and test an original framework of analysis to assess the long term sustainability of energy technology options and policies.

4.3.2 Other international LCA literature

Gagnon L. et.al (2002) presents a summary of comparative studies on the environmental impacts of electricity generation. The study is highly generic because it presents a general overview of environmental impacts that can be “normally” expected. Many technologies are highly site specific, and generic data might be misleading. This is however in some degree captured by the inclusion of the value range found in international literature.

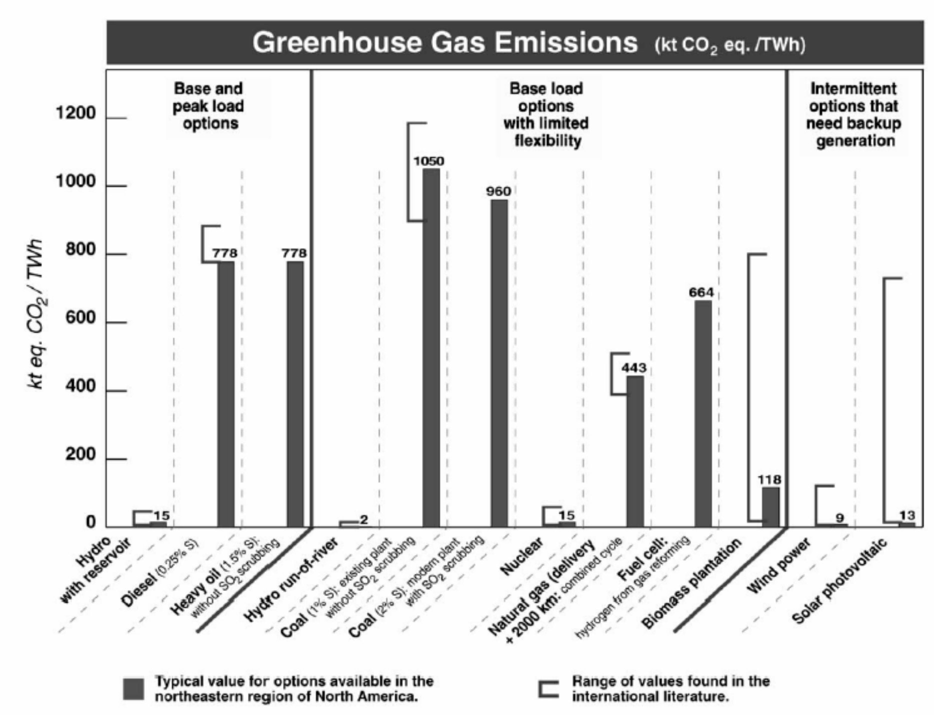


Figure 32 GHG emissions from different energy technologies.

The Global Warming Potential (GWP) varies considerably among the different alternatives, with coal as the worst. Many of the technologies have quite a range of results, with biomass and solar photovoltaic as the most extreme. The wide range of results stems probably mainly from different assumptions and system boundaries as well as site specific characteristics. A classification between flexible, less-flexible and intermittent options is made since the service delivered from a nuclear power plant is not the same as from wind power, since the latter is dependent on the wind conditions. A fair comparison can be obtained by including back-up power in such a way that the availability is the same.

For energy systems the energy payback ratio is of special interest since the service supplied is energy and one does not want to use more energy on the facility and transport etc. than what one provides the customer. This was one of the major criticisms against PV, as the energy demand for producing the solar panels exceeded the amount of energy ever to be supplied from the solar panel itself. The same criticism has been raised against wind power.

One obvious advantage with the energy payback ratio is that one keeps the energy as commodity and not as e.g. GWP (Global Warming Potential), thus avoiding the question of e.g. the aluminium source (the GWP results might vary greatly between aluminium produced from hydropower vs. coal power). Figure 33 shows some energy payback ratios. A value of e.g. 5 mean that 5 times the energy used to build, maintain and fuel the generation equipment is produced. A project with value close to one should thus not be realised.

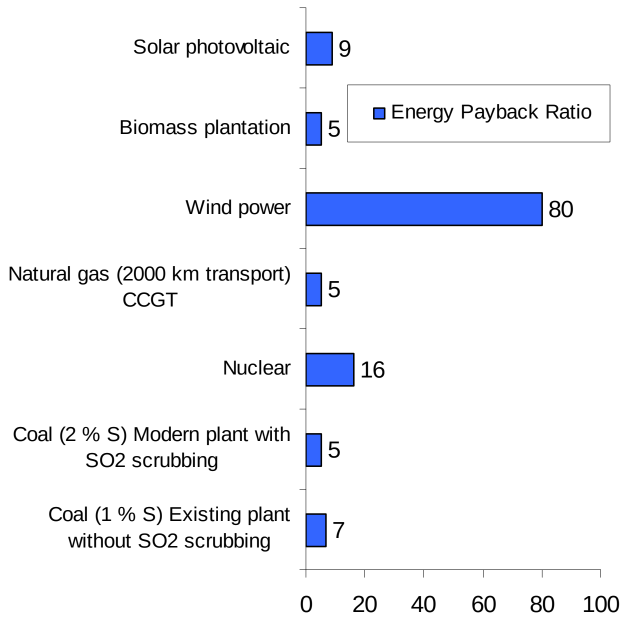


Figure 33 Energy payback ratio [Energy output / input] for some common electricity generation options (Gagnon L. et.al. 2005).

If one include the energy in the fuel as energy input: it is clear that none of the fossil options will achieve an energy payback ratio higher than 1, as all of them have efficiency lower than 100 %.

Another paper comparing different options for electricity production is Pehnt (2006). He argues that a dynamic life cycle assessment of renewable energies will allow improved technologies and practices in the future, thus lowering the environmental impact. The renewable energies turn out even more favourable with such an approach, since much of the input materials and energy is assumed to also be renewable. PV wafers today are produced with e.g. coal power, but in 2030, the PV wafers are produced by e.g. wind power, thus lowering the environmental impact of wafer production. The paper has a comparison of renewable energies and average German electricity mix and heat mix in 2010. The values are normalised to the average value.
The factors used for normalisation are given in Table 7.

Table 7 Normalisation factors used by Pehnt (2006).

		Electricity mix 2010 per kW h_{el}	Heat mix 2010 per MJ_{th}
Iron ore	g	2.6	0.2
(Finite) energy resources	MJ	8.91	1.23
Global warming	g CO_2 equiv.	566	81.5
Acidification	mg SO_2 equiv.	1083	115
Eutrophication	mg PO_4^{3-} equiv.	59.9	7.7

The comparison is given in Figure 34. The technologies perform differently among the different impact categories. The iron ore requirements are often higher than for the average (fossil) German energy mix.

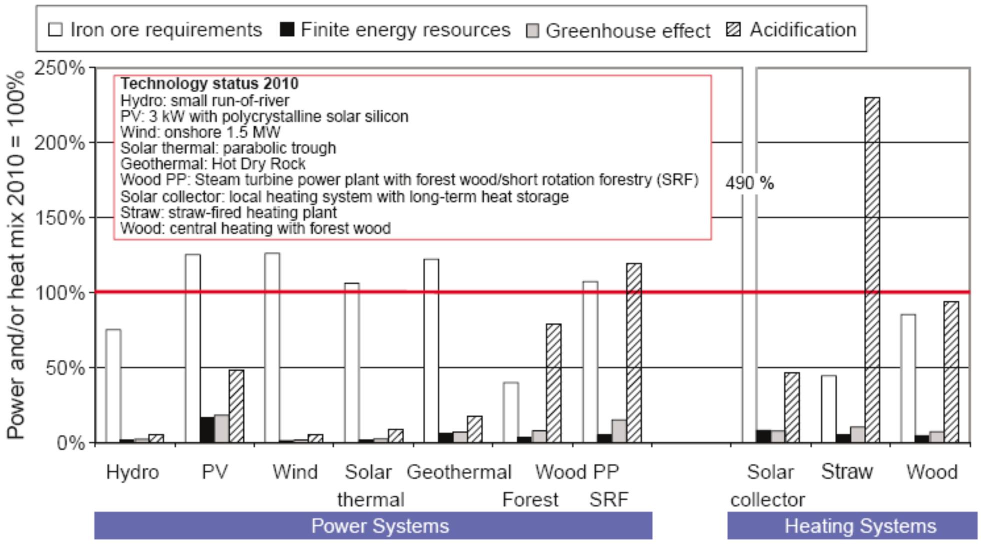


Figure 34 Normalized LCA data for selected renewable energy systems for selected impact categories.

The results leave it up to the decision maker to value the different impact categories up against each other. Environmental impacts which differ considerably in consequences related to time, place and type e.g. is acidification typically more local than global warming, and does not have the long time horizon connected to climate change. To compare the two is not an easy task. Some authors suggest different types of aggregated indicators to handle these issues. The next paper suggest one, called NETS" (Numerical Eco-load Total Standard).

A paper introducing an aggregated performance indicator, comparing different options for electricity production is Kato et.al (2005). The paper uses a numerical indicator "NETS" (Numerical Eco-load Total Standard) to quantify different environmental loads with one unit. The indicator is not trivial but uses a kind of relative impact, which is compared to the maximum tolerable value. The emissions are thus compared to the maximum level of tolerable emissions. Every person has 100 NETS, which implies that a total NETS global value of 600 billion (6 billion people) is the maximum value our earth can bear. In the case of global warming and CO_2 emissions is the IPCC (Intergovernmental Panel on Climate Change) stabilization goal at 450 ppm in 2100 used. The critical limit P and environmental load standard value ELM [NETS/ton CO_2] are then calculated as:

$$P_{CO_2}^{GW} = 2.07 \cdot 10^{12}\ Ton, \qquad ELM_{CO_2}^{GW} = 0.29\, NETS\,/\,Ton$$

The NETS indicator value is thus 600 billion when the critical limit P is reached. Different other environmental impacts are calculated using the same framework. The critical maximum value is inevitable an important parameter in these calculations and is found in sources that should be objective. This allows a complete quantitative evaluation of the various environmental loads in the new units (NETS). The main impact categories are:

- Solid waste
- Air pollution
- Water pollution
- Ozone layer
- Global warming
- Acidification
- Natural resources
- Fossil fuels

The use of scarce fossil resources is heavily penalized with this scheme, which is seen in Figure 35.

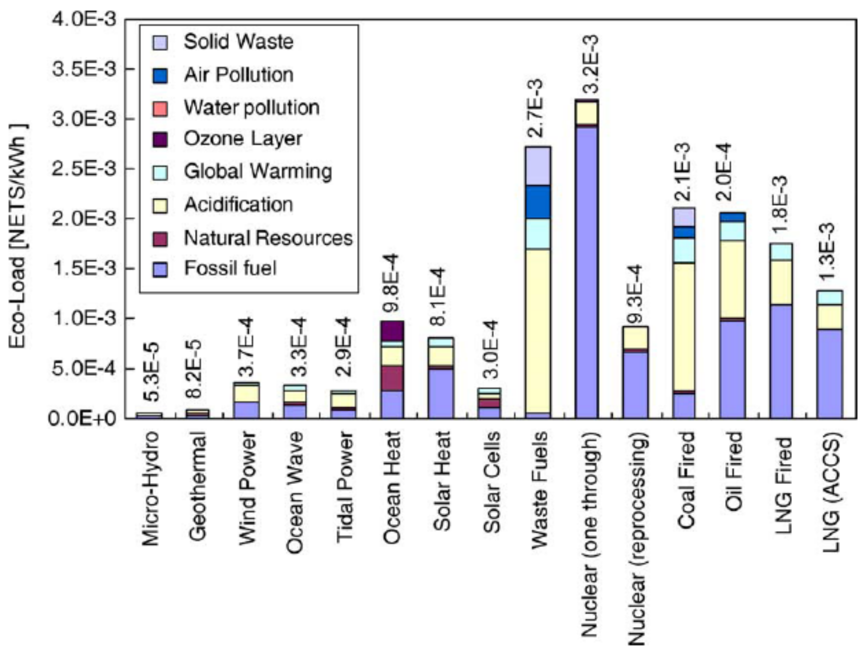


Figure 35   The total environmental load and its causes for different types of power plants.

Especially the "nuclear once through" receives considerable amounts of NETS because of its plentiful use of scarce resources. The reprocessing variant has markedly lower impact. The final question that remains with the NETS scheme is whether one can compare the use of uranium with emissions of green-house gases. The idea of comparison of different environmental loads in an objective framework is interesting, but the practical use may be questioned. The "objectiveness" might be questioned as well, as it is a subjective matter to decide the critical level of CO_2, or critical level of acidification. Kato (2005) argues that the use of internationally recognised limits can be considered as reference, thus consolidating an objective weighting.

The Ecoinvent database (www.ecoinvent.ch) is a comprehensive source for inventory data. It consists of more than 2500 different processes where energy systems amount to half of these. Unfortunately the Ecoinvent database is licensed, and is therefore not public accessible. Some papers from the Ecoinvent webpage are distributed freely, but most are limited to members only. Dones R., et.al. presents different energy chains and compares GHG emissions from their life cycle. The figures shown below indicate the range for European power plants. The values are divided between fossil and not fossil technologies as their result range differ considerably. The range is shown for each technology, with also the average value indicated.

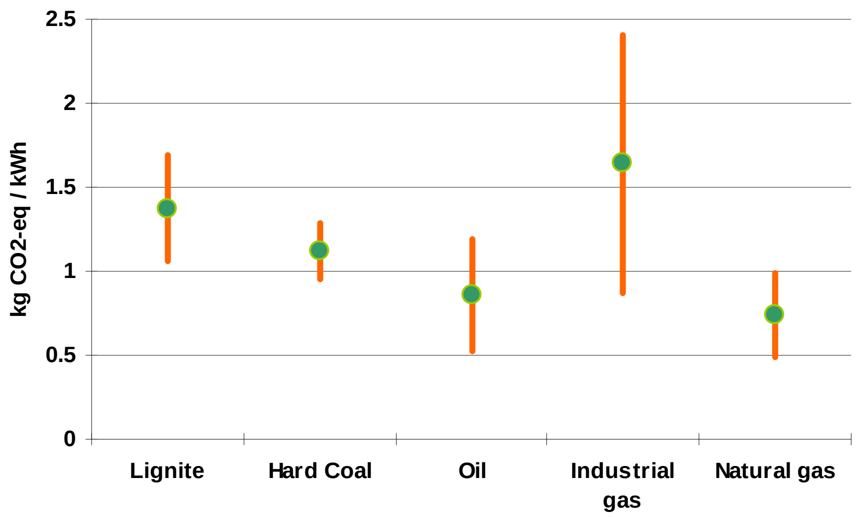


Figure 36 Ranges of GHG emissions from fossil power plants.

The non-fossil alternatives are given below. Notice the different axis in Figure 36 and Figure 37. The hydropower has emissions two order of magnitude lower than coal.

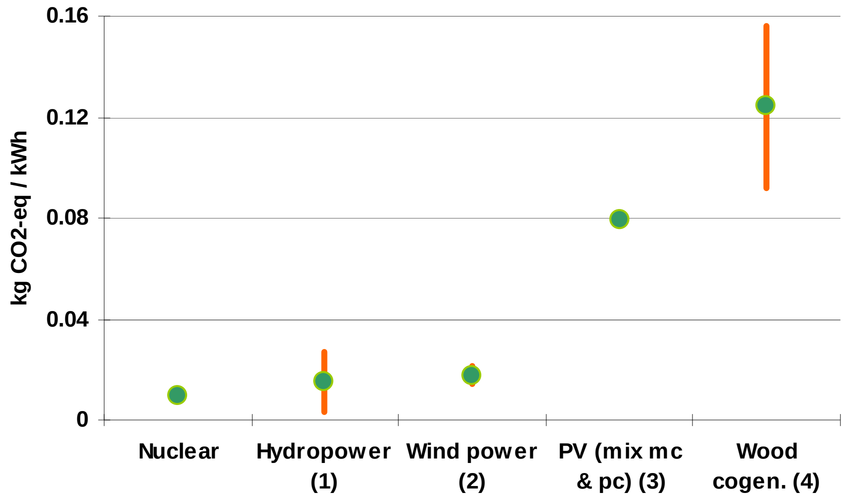


Figure 37 Ranges of GHG emissions from renewable and nuclear power plants[5].

The values shown in Figure 36 and Figure 37 include upstream activities. These account approximately for 10 % of the total emission for hard coal, slightly more than 10 % for the oil chain and about 20 % for the conventional natural gas systems. The Ecoinvent also contains LCA based GHG emissions for European countries regarding supply and production mix. Norway is in the lower range with 0,010 kg CO_2-equiv./ kWh.

Several papers are written based on the Ecoinvent database. Dones R et.al. (2005) analyses the inventories of nuclear and natural gas energy systems. Jungbluth N et.al. (2004) analyses the emerging photovoltaic technology and wind power.

May et.al. presents fossil power plants and related energy chains in Australia. The study includes extraction, transport, generation and transmission. Construction and decommissioning is not included as shown in Figure 38, where shaded areas represent inclusion.

[5] (1) The hydropower is a combination of run-off and reservoir. (2) The windpower has its maximum emission range from wind conditions in Switzerland and lowest from Western Europe. (3) Solar conditions as in Switzerland. (4) The wood cogeneration is calculated with exergy allocation and has 6400 kWth and 400 kWe as capacity. The upper range is with SNCR (selective non-catalytic reduction) filter and the lower without.

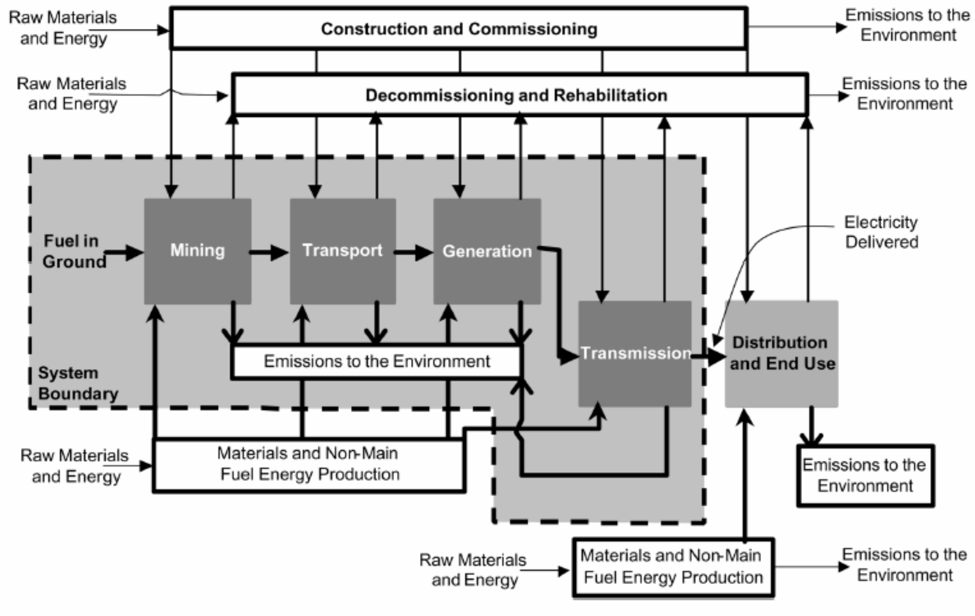


Figure 38 System boundary for fossil power generation.

The exclusion of the construction and demolition phase from the analysis is justified with reference to several detailed studies showing their minor contribution compared to the operational phase. This conclusion is only valid for fossil power plants as renewable power plants often have minimal emissions during operation. For SEDS this conclusion is very useful and interesting towards performing LCA on energy systems, as it represents a considerable cut-off and simplifies the data collection (inventory analysis) and analysis phase (impact assessment) considerably.

Some results from the analysis are shown in Figure 39, where only GHG reported in the study is shown. The different chains are explained in Table 8.

Table 8 Abbreviations used in Figure 39.

ST-BrC	Steam turbine fuelled with brown coal
ST-BlC	Steam turbine fuelled with black coal
OCGT-NG	Open cycle gas turbine fired with natural gas
OCGT-LNG	Open cycle gas turbine fired with liquefied natural gas
CCGT-NG	Combined cycle gas turbine fired with natural gas
CCGT-LNG	Combined cycle gas turbine fired with liquefied natural gas

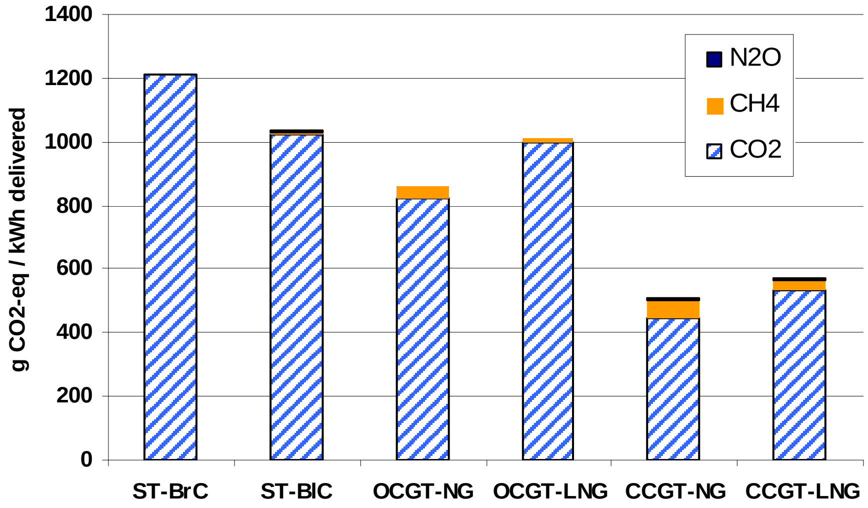


Figure 39 Global warming potential for N_2O, CH_4 and CO_2 for a selection of energy chains.

The CO_2 emissions are clearly the main contributor to global warming among the reported GHG. The warming potential factors for N_2O, CH_4 and CO_2 are taken from IPCC (2001).

The relative importance of the subsystems mining, transport generation and transmission is further analysed. The generation phase is most important, contributing for 72 – 97 % out of the GWP from the whole energy chain. The differences are shown in Figure 40.

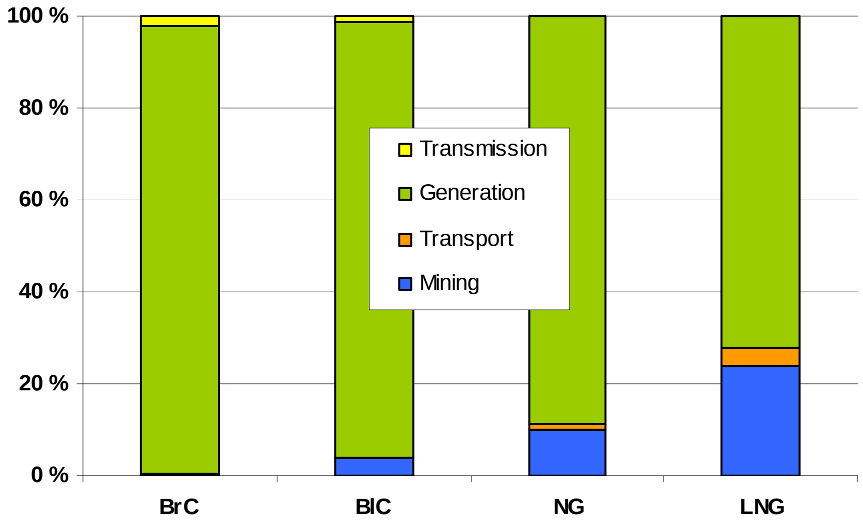


Figure 40 Average GWP distribution among different fuels.

Different impact categories are assessed in the study, where the most important ones are; climate change, acidification, photochemical smog, eutrophication, solid waste generation, particulates and abiotic depletion. The distribution seen in Figure 40 is not valid for the other impact categories than climate change, as other subsystems may dominate other impact categories. An example is the solid waste generated by mining of coal.

4.4 OVERVIEW OF RELEVANT CASE-STUDIES

A list of existing literature is presented in Table 9. Part of the literature is presented in a separate document, and those are marked with an "X" in the "Exemplified" column. The summary document emphasizes what might be utilized in an analysis of a local energy system with multiple energy carriers such as gas, district heating and electricity.

Table 9 List of LCA literature with case studies and data relevant to SEDS.

Author	Region	System	Energy Carriers	Comment	Format [6]	Exempl.	SEDS relevance (1-6) 6 is max
Eriksson O. et.al (in press)	Sweden	District heating & CHP	Waste, NG, Biofuel	Consequential LCA	J		4
Pehnt Martin (2006)	Germany 2010	Renewable el. and heat	Wide range of renewables	Only Renewables	J	X	4
Kato S. et.al. (2005)	Japan	Power plants	Wide range (coal, nuc., ren.)	Develops the weight-indicator NETS	J	X	3
Masruroh N.A. et.al (2006)		Solar thermal	Sun		J		1
Björk H. et.al (2002)	Sweden	Steam & District heating	Steam and heat	Process optimization	J		1
Kannan R. et.al.	Singapore	Power plants	Wide range (coal, nuc., ren.)		J		2
Magnussen et.al. (1999)	Norway	CCGT	NG		R	X	5
Vold et.al. (1996)	Norway	Hydro power	Hydro	Detailed case study	R	X	6
Gagnon L. et.al (2002)	World wide	Power Plants	Wide range (coal, nuc., ren.)		J	X	4
Dones et.al. (2004)	Switzerland and Europe	Heat and electricity	Wide range (coal, nuc., ren.)	From Ecoinvent (licensed)	J	X	5
Ardente et.al. *(in press)*	Italia	Wind power	Wind		J		4
Dethlefsen et.al.	Sweden	Power Plants	Wide range (coal, nuc., ren.)	Incl. power lines. Limited access (Vattenfall)	W	X	5
May J.R., Brennan D.J. (2003)	Australia	Power plants	Wide range of fossil carriers	Investigates different energy chains	J	X	4
Schleisner L. (2000)	Denmark	Wind power	On and off- shore wind	Tries to include related externalities	J		5
Diaz R., Warith M. (2006)	Canada	Solid waste	Coal, nuclear, hydro, gas and oil	Describes a solid waste model.	J		2
Skaar Christoffer (2004)	Norway	Wind power	Wind	Norwegian on-shore wind park	M		4

[6] J – Journal, R – Report, M – Masterthesis, B – Book, W – World wide web.

Author	Region	System	Energy Carriers	Comment	Format [6]	Exempl.	SEDS relevance (1-6) 6 is max
Chui (2006)	Canada	Hydrogen production	Wide range (coal, nuc., ren.)	Hydrogen production paths	J		4
Vattenfall (2006a)	Sweden	District heating and electricity	Peat and fossil	Environmental product declaration	R	X	6
Vattenfall (2006b)	Sweden	Electricity	Nordic Hydropower	Environmental product declaration	R		6
Vattenfall (2006c)	Sweden	District heating and steam	Waste	Environmental product declaration	R		6
Värmeforsk, Edholm (2000)	Sweden	District heating	Biomass	Processed vs. raw biomass	R	X	6
Fröling et.al. (2002)	Sweden	Production of district heating pipes		Much detail	R	X	5
Dones R. et.al. (2005)	Western Europe	Nuclear and natural gas energy system	Nuclear and gas	Upstream activities	J		4
Anonymous	Denmark	Electricity and heat	All relevant to Denmark		R		5
Cuperus M.A.T	Western Europe	CHP	Biomass	ECLIPSE	R		6
Frischknecht R. et.al.	Western Europe	LCI background data		ECLIPSE	R		6
Frankl P	Western Europe	Wind, CHP, PV, Fuel cells	NG, biomass, wind & sun	ECLIPSE	R		6
Briem S.	Western Europe	CHP	Natural gas	ECLIPSE	R		6
Jungbluth N. et.al. (2004)	Western Europe	Electricity production	Wind and solar energy	Case studies	J		4

Some literature is relevant for SEDS not through its case studies, but rather because of methodology or presentation and discussion of relevant LCA information in general. These are listed in Table 10, with an indication of the main theme and contribution towards SEDS.

Table 10 Relevant SEDS literature (methodology, framework etc.).

Author	Energy Carriers	Main contribution (Title)	Format[7]	SEDS relevance (1-6)
Curran et.al. (2005)	Electricity	Discussion on several key methodology concerns for electricity production	J	4
Solli Christian	Hydrogen	Presentation of hybrid LCA	M	5
Rebitzer et. al. (2004)	Non	LCA – Framework, goal and scope definition inventory analysis and applications. An introduction	J	5
Pennington et. al. (2004)	Non	LCA - Current impact assessment practice. An introduction	J	5
Miettinen et.al. (1997)	Non	How to benefit from decision analysis in environmental LCA	J	6
Kuemmel et.al. (1997)	Aggregated (whole society)	Book, containing LCA intro, and 3 aggregated case studies for Denmark	J	4
Baumann H, Tillman A, (2004)	Non	The hitch hiker's guide to LCA –An orientation in LCA methodology and application	B	6
Sollie Ole Kristian (2002)	High pressure vapour	Exergi analysis and LCA applied to Mongstad refinery	M	3
Bakkane Kristin (1994)	Oil and gas	Life cycle data for Norwegian oil and gas	B	4
Johansson et.al. (2003)	District heating	Livscykelanalyser av fjärrvärme – en förstudie	R	6
Setterwall C. et.al. (2004)	Non	ECLIPSE –Environmental and ecological life cycle inventories for present and future power systems in Europe	R	5
Anonymous (Svensk Fjärrvarme et.al. 2006)	A wide range	”Energianvändning och –försörjning för byggnader ur ett systemperspektiv”	R	3
Sundseth Kyrre	Electricity	Product category rules for environmental product decalration of electricity generation	M	6
Persson et.al. (2005)	A wide range	”Allt eller inget – Systemgränser för byggnaders uppvärmning”	R	6

Some EU projects are highly relevant, both for the methodology used and case studies/examples developed. These are all available at internet.

Table 11 Useful EU projects that somehow relates to LCA.

Project abbreviation	Energy Carriers	Main contribution	SEDS relevance (1-6)
ECLIPSE	Heat/electricity	Life Cycle Inventories (LCI) for new and decentralised power systems	6
ExternE	Heat/electricity	Monetary values on external effects caused by energy use and production for energy systems in western Europe, based upon a detailed LCI.	6
NEEDS	Heat/electricity	Evaluate the full costs and benefits (i.e. direct + external) of energy policies and of future energy systems	6
MAXIMA		Dissemination of external costs of electricity supply - Making electricity external costs known to policy-makers	4

[7] J – Journal, R – Report, M – Masterthesis, B – Book, W – World wide web.

4.5 FINAL REMARKS TO LITERATURE STUDY

From the many LCA results shown in this literature survey, it is possible to sketch some conclusions in an overview table, indicating the importance of different life cycle phases and impact categories for the different technologies. The unit is kWh electricity, but the generalisations also yield for heat production under most conditions. The renewables are split into specific technologies in order to display the variation in impact among renewables.

Table 12 Importance of different impacts for nuclear and fossil technology clusters.

Impact / kWh_{el}	Global and local emissions	Resource use	Fossil fuel use	Waste	Up and downstream processes	Building/ demolition	Operation
Fossil	!!!	!!	!!!	-	!!!	-	!!!
Nuclear	-	!!	!!!	!!!	!!!	-	!!!

Table 13 Importance of different impacts for different renewable energy technologies.

Impact / kWh_{el}	Global and local emissions	Resource use	Fossil fuel use	Waste	Up and downstream processes	Building/ demolition	Operation
Photovoltaic	-	!!!	-	-	-	!!!	-
Wind	-	-	-	-	-	!!	-
Biomass	!	!!	!	!!	!!!	!!	!
Hydro	-	-	-	-	-	!!	-

From this table and general impressions from the mentioned literature, there are some conclusions that can be drawn: There is significant difference between power plants consuming a fossil fuel and those running on a stream of wind, water, sun or other renewable sources, regarding global and local emissions, as well as relative importance of building/demolition and operation.
For renewable energies the construction/demolition phase is of importance as they have low environmental impacts during operation. The resources used during building are not comparable to the values from fossil power plants, but yields a relatively higher significance as impacts caused by operation are minor. Photovoltaic presents a special case, as energy requirements during building are considerable; however, PV is not very relevant for SEDS with Norwegian conditions.

Fossil fuel based power plants' environmental impact is dominated by the operation phase, as they continue to use fossil fuels over the whole lifetime.

Up and downstream processes are important for all three technology clusters. In this context fuel mining and fuel transport phases are essential. E.g. biomass transported over long distances or cultivated with help of large amounts of fertilizer might change the overall impact assessment of biomass use. N_2O is a very strong GHG (296 CO_2 equivalents), and is often emitted during biomass cultivation.

Fossil fuel use is also important for nuclear power plant as the remaining uranium resources are limited. New nuclear technologies might increase resource potential as thorium or plutonium might be utilised. In the context of SEDS is nuclear a modest important technology as SEDS focus on regional or local energy systems. However, the possibility of imported electricity from a nuclear plant could be a planning option.

In the framework of SEDS is it important to identify the scope, goal and use of LCA in energy planning. One has to assess the realistic available resources that a decision maker has to devote to LCA of the planned energy system alternatives. This literature overview gives some input regarding which are the main topics for an LCA of energy systems. Miettinen et.al. (1997) puts it this way:

> *The format and amount of the environmental information needed depends on the expected use of the LCA study results. Therefore, it is imperative to identify and define the decision making framework, the relevant objectives, related data needs and the desirable format for the environmental information. The LCA study contents should be designed based on these, so that the study resources can be targeted to those questions deserving the most effort.*

The observations made here enables some cut-offs that reduces workload considerably. For the practical utilisation of LCA in the context of SEDS there have to be made simplifications. Always when one execute simplifications it has to be done with care and caution. The trade-off between reducing work load and obtaining the needed accuracy in the results is an important challenge.

The next chapter tries to emphasize which life cycle stages of an energy system need more attention than others.

5 APPLYING AN LCA PERSPECTIVE TO AN ENERGY SYSTEM WITH MULTIPLE ENERGY CARRIERS

It has to be stressed that this section is far more indicative than absolute in the terms of the LCA results. A simplistic LCA-perspective is utilised as the goal is merely to present an overview than to execute full scale LCAs, which requires far more work and resources.

For a grid related energy planning problem one has an energy service demand which can be served by a portfolio of energy sources, converted to an energy carrier and transported through a grid, and/or by other means. A principal figure of energy system options is shown in Figure 41.

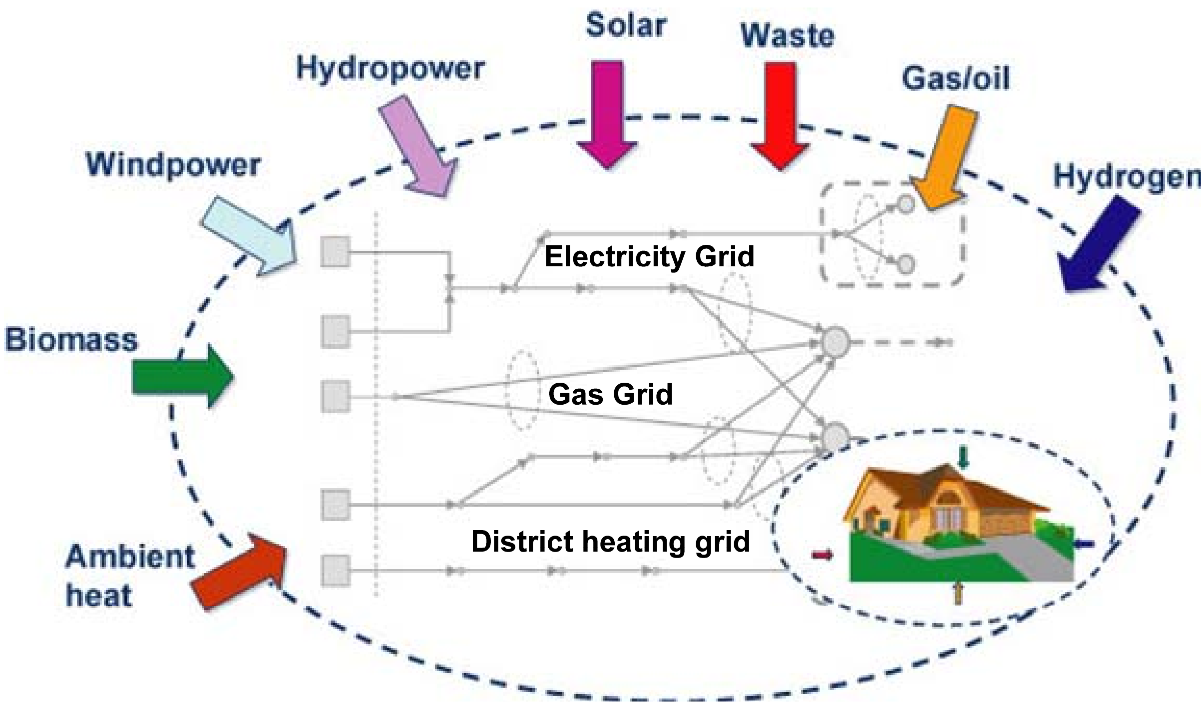


Figure 41 Planning options for an energy system.

This section tries to point out which life-cycle parts of the energy system that is of special interest, and where considerably new information is obtained through an LCA-perspective.

5.1 IDENTIFICATION OF IMPORTANT ELEMENTS

In a simplified overview of an energy system one may divide the energy-chain into “source”, “conversion”, distribution” and “end use” as shown in Figure 42.

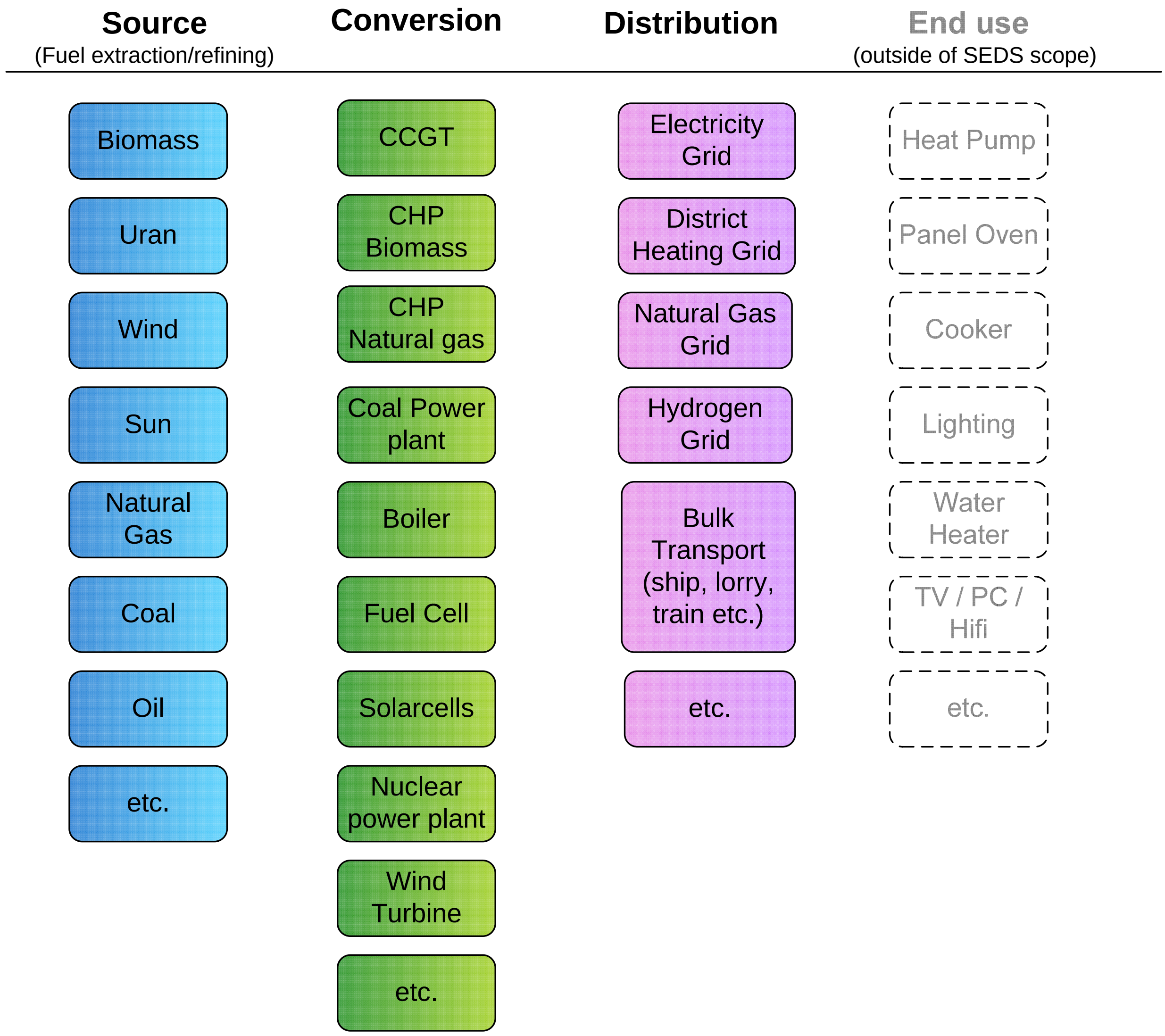


Figure 42 Simplified overview of some elements in a regional energy system.

An energy system consists of different parts displayed in Figure 42, where each element have to be build, operated and in the end disposed. Each of these life cycle parts have different environmental impact as explained in Figure 43.

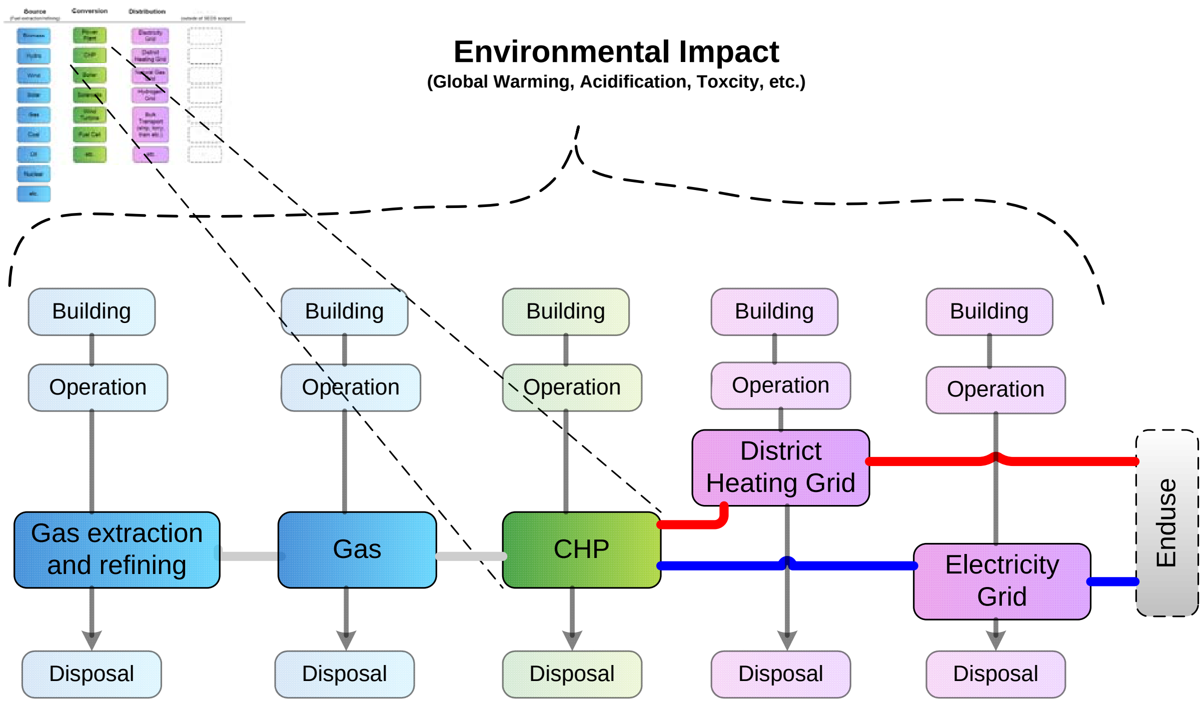


Figure 43 System boundaries for an energy system based upon a gas-fired CHP.

Out of the broad range of environmental impact indicators at hand with LCA, is only GWP (Global Warming Potential) chosen in this analysis, as indicated in Figure 44.

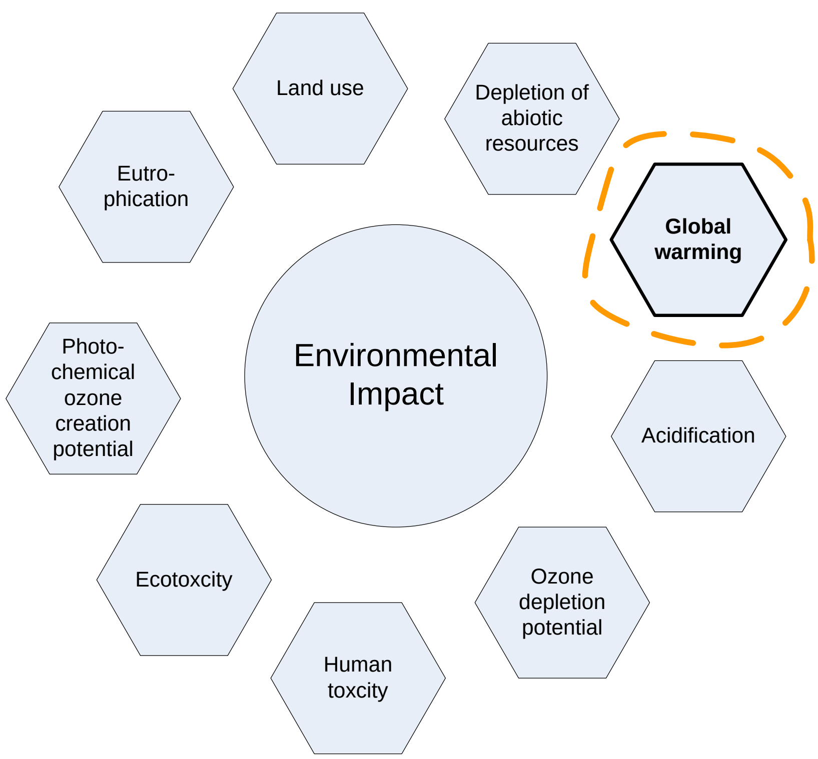


Figure 44 Common environmental impact categories, whereof only global warming is assessed in this study.

The main reason for this limitation is the lack of access to an LCA tool which would ease the analysis and ensure comparable system boundaries. The assessment undertaken here is based upon LCA literature, mainly Marheineke (2000), ECLIPSE (2006), Vattenfall (2006b). Others are qualitatively compared to ensure validity.

In order to give an impression of the importance of the different life-phases of an energy system, a standard scheme is utilised, where the four main phases of an energy service provision "Fuel chain, Conversion, Distribution and End use" have their own life cycles. The scheme facilitates comparison between technologies and provides a structure for aggregated LCA-data.

The transport of fuels is distinguished and analysed separately for some fuels (coal and biomass). Each life cycle phase is then grouped with the help of a colour bar to present the importance in an easy manner as shown in Figure 45. The dominant and important contributions are also quantified, presenting values mainly from Marheineke (2002), which is a comprehensive LCA study of different electricity generation options.

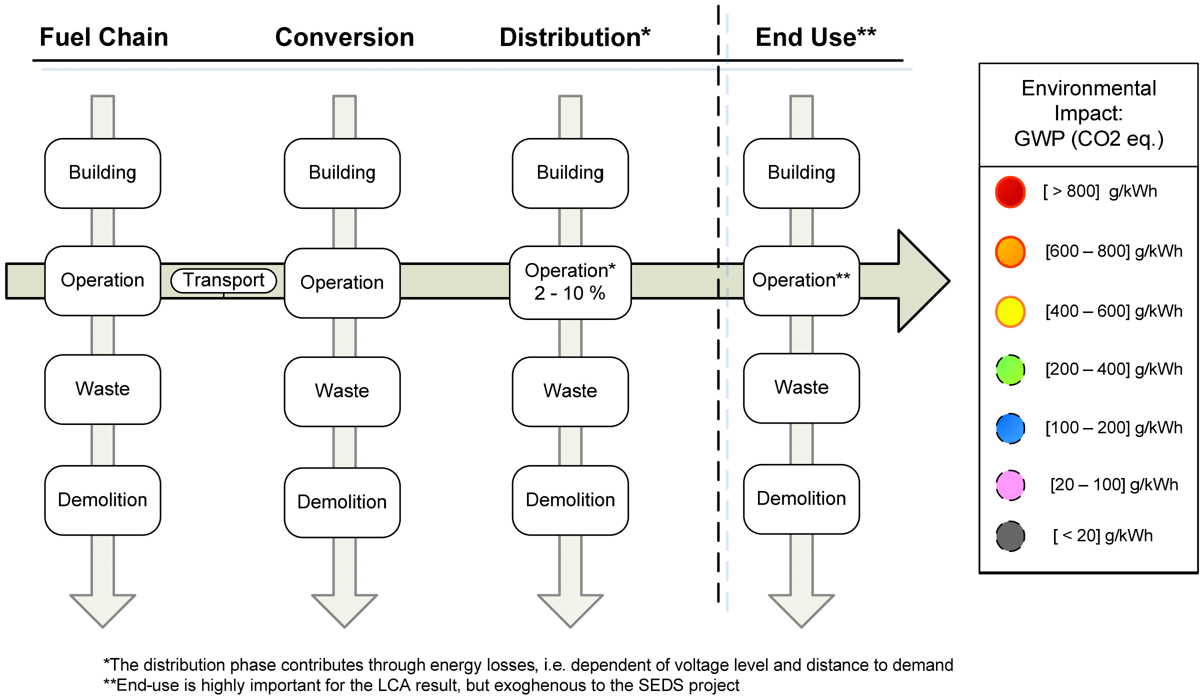


Figure 45 Grouping scheme utilised for describing where in the LCA the GHG emissions occur.

Many of the elements of the LCA are not significant compared with the aggregated results. To determine and classify the contribution it is practical to define some sort of classifications. The further analysis utilizes the following definitions:

Table 14 Classification for each specific LCA chain (relative).

Environmental impact (EI) [%]	Compared to specific LCA chain
50 < EI	Dominant
20 < EI < 50	Important
2 < EI < 20	Less important
EI < 2	Insignificant

Table 14 is used to classify *relative importance* of elements of a specific LCA chain (comparison within energy chain), while Table 14 is used to determine weather the environmental impact are important in *absolute terms* (comparison between all technologies).

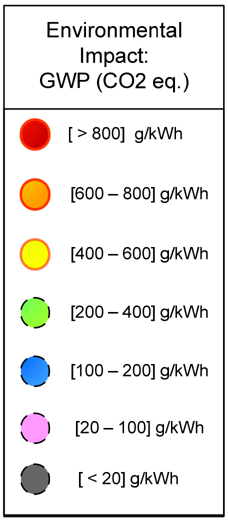


Figure 46 Classification of absolute environmental impact.

In order to know the absolute importance of an environmental impact, it is useful with a reference value, in order to distinguish between apparently important processes and absolute crucial elements. The building process of a wind farm seems to be important for its CO_2 eq. impact, contributing 90 % of the total, but nevertheless only 15 g/kWh compared to 379 g/kWh from a CCGT (Marheineke 2002). A reference table is therefore made to easily grasp the absolute magnitude, shown in Table 15 below. Natural gas as energy source is utilised since gas is seen as environmental friendly energy source in an European context, but seen as “highly polluting” (Norwegian Environmental organisations) in Norwegian context. It is therefore a suited middle value representing the long term marginal power in Norway (More CCGTs are built at the moment). The reference data is taken from Magnusson et.al. (1999). The heat production reference, based upon gas, assumes the same upstream processes as from Magnussen et.al (1999), but with an efficiency of 90 % instead of 58 %. This assumption holds because the upstream processes would be similar. The environmental impacts would be equal with a gas boiler with the efficiency as the only difference for the CO_2 emissions.

Table 15 Reference heat and electricity from natural gas.

Electricity Production Reference	Inventory	Colour
GWP	373 [g/kWh el]	[200 – 400] g/kWh
GWP	240 [g/kWh heat]	[200 – 400] g/kWh

Most of the figures and data presented in the following section are calculated with one kWh of electricity as functional unit. However, many of the energy chains are applicable with heat as product, by just compensating for the higher conversion efficiency. For the energy chains where heat is an alternative to electricity the corresponding value for heat is mentioned.

5.2 DISTRIBUTION

The distribution of energy is a major part of the SEDS project and thus receives some extra analysis here. The overall impression is that the only important part of the distribution “life cycle” is the operation, and then through the energy losses, which implies increased energy generation upstream of the distribution. This is further emphasised by an example in Chapter 5.2.5.

5.2.1 Electricity Grid

“Construction-operating-dismantling” power lines have environmental impact, predominantly in the construction stage. Production of metals, concrete, and insulation material generate emissions via the consumption of electricity and fuel. The power grid also has an impact on biodiversity. Lanes are regularly cleared creating a possible habitat for species normally inhabiting meadows and pastures. In addition lanes constitute border zones, which are generally considered more bio-diverse than homogenous areas. Wider lanes may constitute barriers that may cause fragmentation for some woodland species. The relative contribution from this life cycle phase is insignificant. Transmission and distribution losses depend on several factors, such as distance, load, feed voltage, and user connection voltage. The diagram shows average transmission losses in various situations, when an electricity generation plant feeds at national grid voltage.

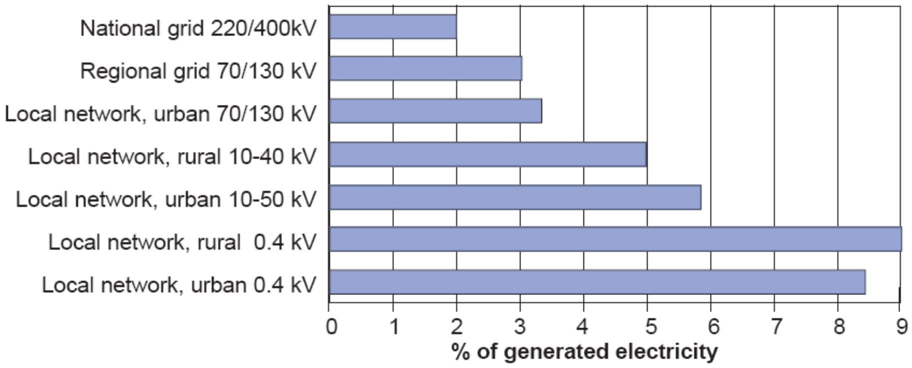


Figure 47 Average transmission losses at different voltages accumulated from the national grid – percentage of generated electricity (Vattenfall 2006b).

The environmental impact is thus dependent on the generation technology (conversion) and the fuel chain. The electricity distribution system is thus not elaborated more on specific impacts since these are site-specific. As seen from Figure 47 is 2 – 9 % energy lost through transmission. These losses contribute to corresponding increase in the upstream environmental impacts at the power plant because of increased electricity production.

5.2.2 Electricity cables

The same applies for electricity cables as for overhead lines; the major impact is caused by the energy losses. This is shown e.g. in a technical report from SINTEF Energy Research (Nyberg 1999).

5.2.3 Natural gas grid

No LCA study of a natural gas system is found, but it is likely to observe the same characteristics as for electricity grid and district heating grid, which implies that the energy losses are dominant. However, the energy losses from a natural gas grid might be much lower than for electricity or district heat. The losses are dependent on pipe material, inlet pressure, which types of compressors used, efficient structure of gas grid etc. The losses are therefore highly site-specific.

5.2.4 Hydrogen grid

For a hydrogen distribution grid one can assume the same characteristics as for a natural gas grid, see above. Additionally emphasis should be put into material choice, as more dense material than steel pipes are needed to hinder hydrogen leakage.

5.2.5 District heating grid

The major parameter in a district heating grid is the isolation i.e. the heat loss. The building and disposal process are minor. Construction/operation/reinvestment of the district heat distribution system contribute ca. 1% to the emissions of greenhouse gases, ozone-depleting and acidifying substances in the EDP from a CHP at Uppsala, Sweden(Vattenfall 2006a). Distribution losses, mainly heat losses to the surroundings, vary over the year and are largest during winter. The average yearly loss is ca.10% (Vattenfall 2006a). It is therefore the heat losses that should be emphasised. To further elaborate the contribution from construction of district heating grid is an example shown below.

Fröhling et.al. (2002) made an LCA of different district heating pipes produced at Hisings Kärra 1999 – 2000. Four different steel pipes were investigated. The main results are presented in Table 16.

Table 16 Main results from LCA of district heating pipes.

kg / pipe	**DN500 Single**	**DN100 Single**	**DN25 Single**	**DN25 Twin**
Length of pipe [m]	**16**	**12**	**12**	**12**
CO_2	4000	360	82	150
NO_x	12	1.1	0.31	0.49
SO_x	10	0.93	0.29	0.44
COD	1.5	0.16	0.04	0.07

To exemplify what this means in reality these data are applied to the district heating system in Trondheim. Some necessary data for this system is given below (TEV 2001):

Delivered energy in 2004:	360 million [kWh]
District heat grid size:	100 [km]
CO_2 emission with 100 % natural gas as input:	240 [g/kWh]

Resulting emissions (producing DH-pipes) from a grid composed by (length, km) 50 % DN500, 25 % DN100 and 25 % DN25, assuming 30 years lifetime and constant yearly energy delivery of 360 million kWh, is shown in Table 17.

Table 17 Inventory of the building phase of a district heating system (Trondheim).

[g / kWh]	**DN500 Single**	**DN100 Single**	**DN25 Single**	**Total [g/kWh]**
	25 km	50 km	25 km	
CO_2	0.58	0.14	0.02	0.74
Part of total grid	50 %	25 %	25 %	100 %
Length of pipe	25 km	50 km	25 km	100 km

The building phase of a district heating system is insignificant, as CO_2 per delivered unit of heat, corresponds to 0.52 % of reference heat, a result which is in line with the results from Vattenfall (2006a). The heat loss in the district heating system is thus of much more interest. A loss of 10 % in the district heating system is reported by Vattenfall (2006a). If one manages to decrease this loss to 9 %, one would decrease GWP with around 2.4 [g/kWh] CO_2 per delivered unit of heat, corresponding to 1 % of reference heat, i.e. twice the GWP from construction of the district heating system.

5.2.6 Conclusion to the distribution life cycle

The environmental impact (EI) from the building phase of DH systems is insignificant. However, the insulation properties are determined by the building process (choices regarding insulation quantity and quality), which has impact during the operation of energy system. This conclusion is backed by a EPD made by Vattenfall: "…Electricity and District Heat from the CHP at Vattenfall AB Nordic Heat Uppsala" where construction, reinvestment and dismantling are attributed with 0 % impact over all reported impact categories, where also the building/dismantling of the CHP is included (not only the DH grid) (Vattenfall AB 2006a).

5.3 BULK TRANSPORT

The transport of fuel is a much disputed area of an energy system, especially regarding biomass, where one can often hear that the energy used for transport and gathering is more than what one produces in the end, i.e. a clear market failure. This section tries to shed some light into this subject by using standard transportation data from Baumann et.al. (2004). The assumptions are elaborated and found in appendix 1.2, page 497 in Baumann The results are arranged as CO_2 emissions per delivered kWh of electricity at a power plant x km away from energy source.

5.3.1 Biomass transport

Data from Vattenfall for machinery transport, biomass chipping etc. are combined with the standard transport data. General assumptions are:

Biomass density	5000 kWh/ton
Biomass to el. conversion efficiency:	40 %

The larger transport options are assumed to need some initial short range transport by smaller vehicles in order to gather large amounts of biomass in a sustainable manner. That is why not all the graphs are starting at 0 km. The figure shows that transportation of biomass may be quite long ranged before the environmental impacts from kWh converted energy are comparable with reference electricity or heat. This is heavily dependent on transportation mode and site specific conditions such as; energy density in the biomass, moisture (water) content, biomass quality and conversion efficiency. The purpose of this section is not to produce exact data for transportation of energy commodities, but rather to show the result spread.

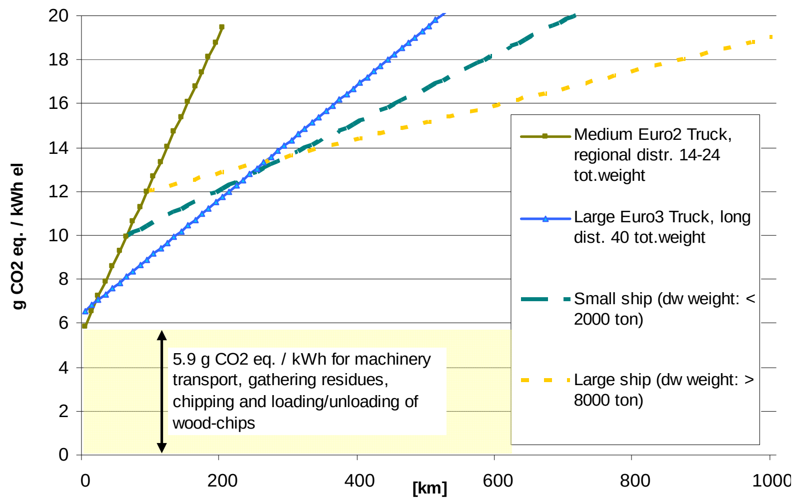


Figure 48 Biomass transport including collecting and chipping the wood.

5.3.2 Coal transport

Similar calculations are made for coal transport, based upon the same transport data from Baumann et.al. (2004). Some specific assumptions are:

Coal energy density	8300 kWh/ton
Coal conversion efficiency:	40 %

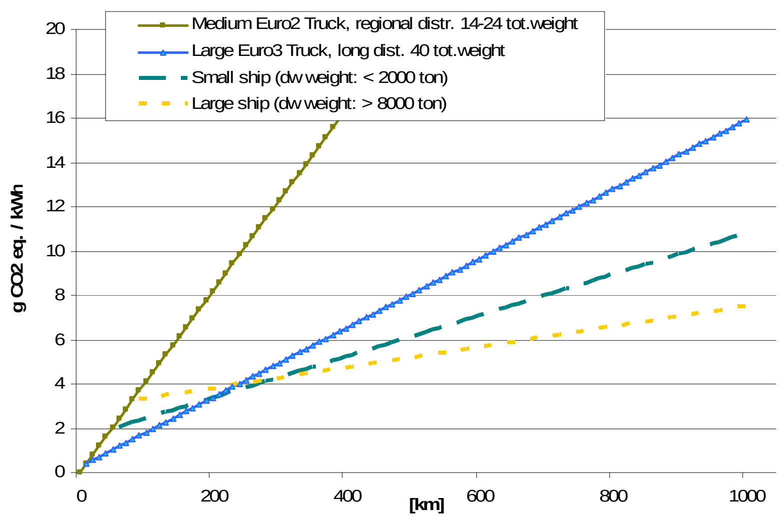


Figure 49 Coal transport with truck, small ship and large ship.

The Figure 49 only shows the CO_2 emissions related to transport of coal, no mining or other processes included. The transport of coal is thus not the major environmental impact of heat or electricity from coal, as long as a coal power plant emits around 700 – 800 [g/kWh] just during operation (stack-emissions).

5.4 CONVERSION OF ENERGY SOURCE INTO ELECTRICITY

This part analyses the contribution from other parts of the chain than the operation, by comparing a wide range of electricity generation technologies. First some fossil power plants, where the Norwegian CCGT reference is marked with a red line. The data is adopted from Marheineke (2002) except the reference CCGT. All power plants are located in Germany except the reference CCGT. The reference electricity from a Norwegian CCGT is shown as a dotted red line in the figure.

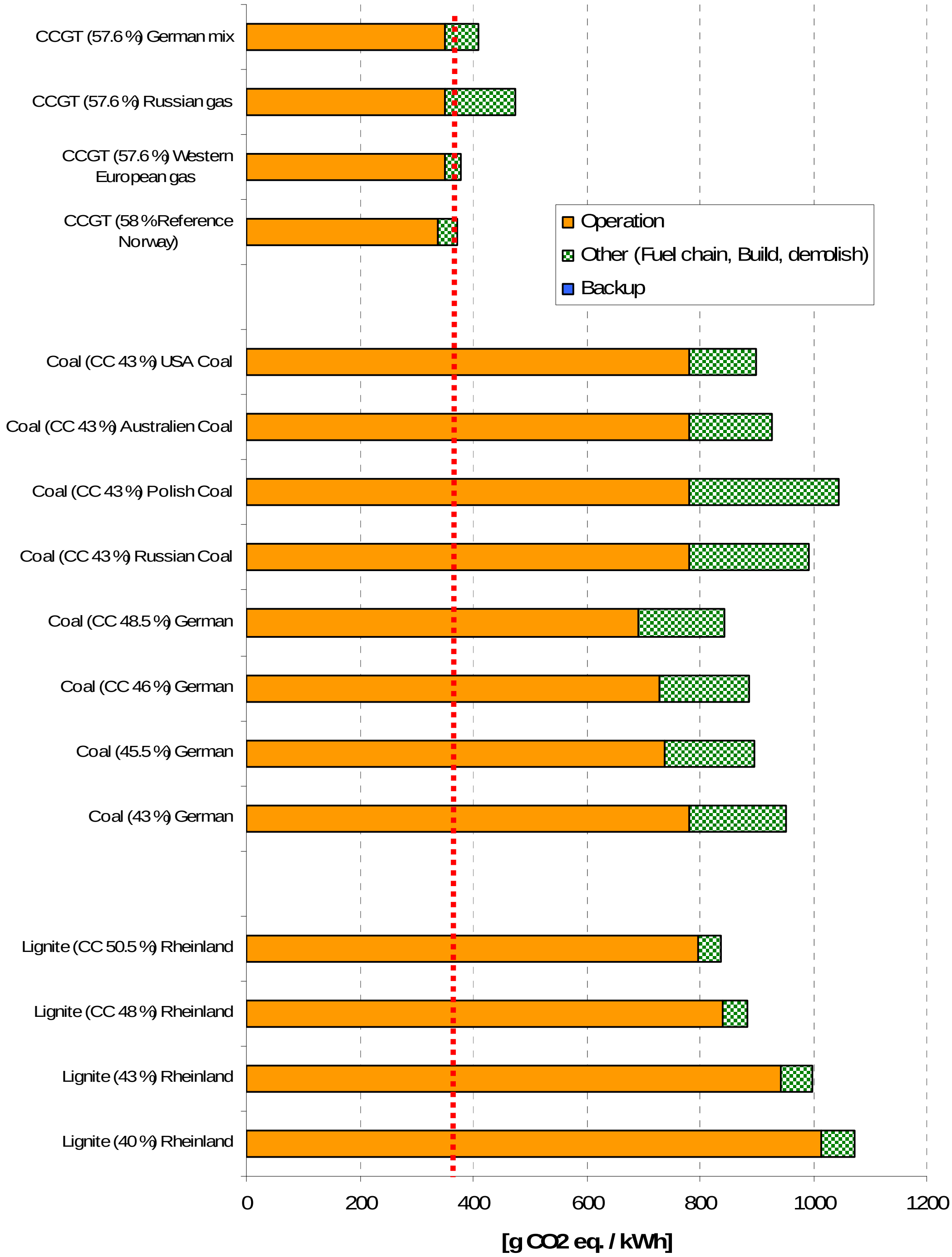


Figure 50 LCA results from a range of fossil fuel power plants.

It is clear from Figure 50 how the origin of the gas has much influence for the LCA results. Russian gas has much more emissions of GHG upstream than e.g. Norwegian gas. The share of “other” varies from 8 – 26 % of the total GHG emissions. The coal has similar characteristics, where also the coal quality is of major importance, e.g. is the kWh electricity produced from Australian coal cleaner than the kWh produced with polish coal, where the latter is situated in the neighbouring country. Lignite has such poor heating value that transport is seldom a realistic opportunity. Thus, the power plant is situated close to the lignite mine, and necessary energy transport is done with the power grid, ensuring small “other” share.

Some renewable electricity generation technologies are presented below, together with a nuclear option and a natural gas fed SOFC fuel cell. All data adopted from Marheineke (2002) when other not mentioned. All power plants from Marheineke are situated in Germany and the ECLIPSE data are typical Western Europe. The CCGT reference is marked with a red line.

The renewable energy sources without reservoir (PV, wind, run-off river) are modelled with additional back-up power plants, to make the comparison fair (Marheineke 2002).

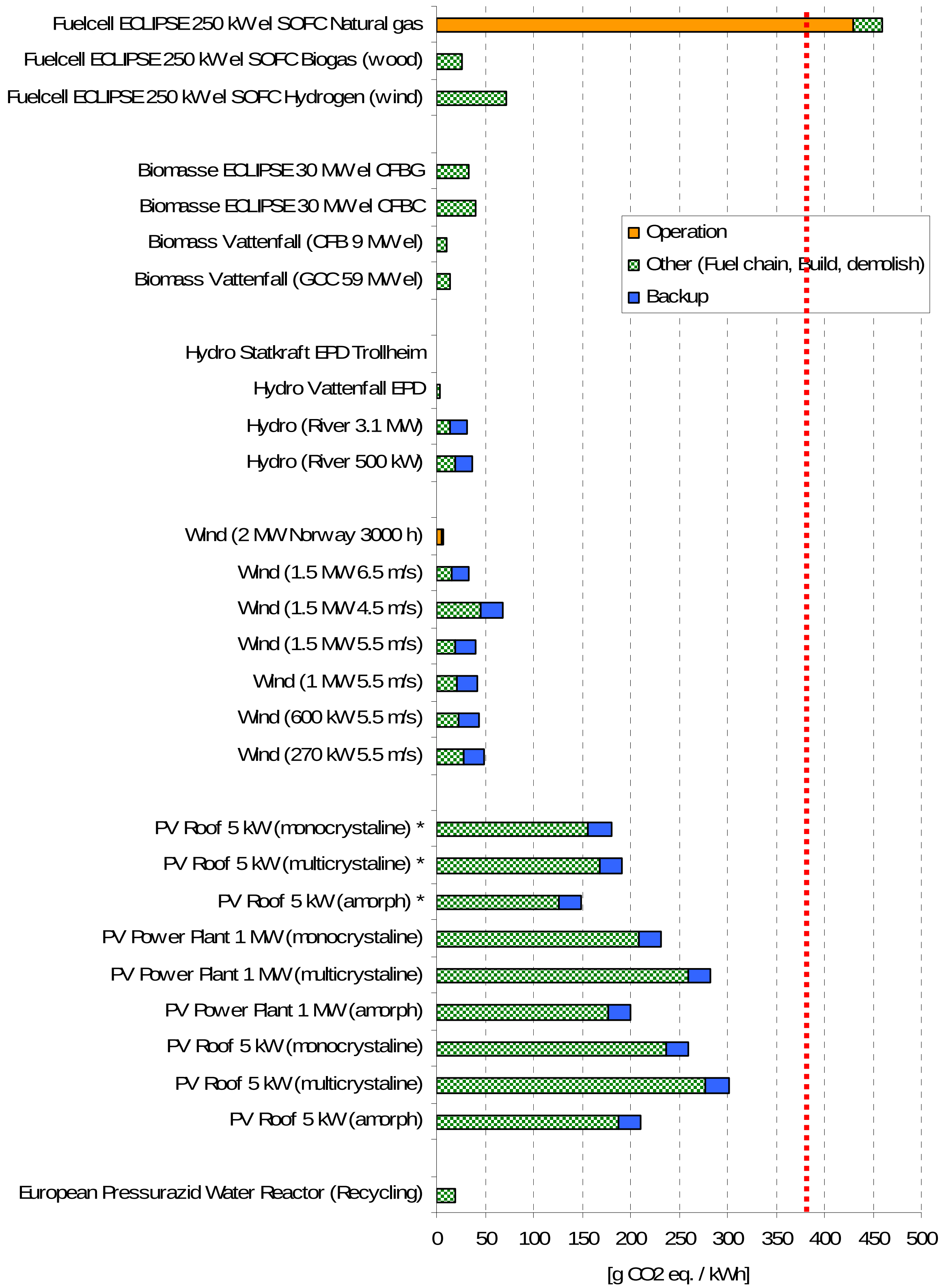


Figure 51 LCA results from renewable technologies, together with nuclear and fuel cells.

One characteristic for the renewables are the importance of the construction phase. Some of the PV technologies have almost the same overall GHG emissions as reference CCGT pr. kWh electricity. Important to bear in mind the solar radiation, as German conditions are not among the worlds best insulation areas. The technology learning should also be considered, as these technologies presented here are from 2002. Another German study by Pehnt (2006) presents lower emissions for 2010, coming down to 105 g CO_2 / kWh.

The fuel chain for the fuel cell is very important as one can easily see from Figure 51. Fuelled with natural gas it performs worse than the reference CCGT, with biogas or hydrogen made from wind power, the environmental impact is reduced several times.

The biomass examples are highly site-specific because of the local parameters influencing the overall performance. Among others these are; rate of return of the biomass (extent of CO_2 neutrality), biomass quality (heating value, moisture content, type of biomass), soil characteristics, use of fertilizer, transport distance, etc.

As for the importance of radiation to PV, the wind conditions are important for the overall result of wind power. The Norwegian example is from Skaar (2004), where average wind speed might be above 7 m/s.

The difference in results for hydro power plant is due to different sizes in installed capacity, as well as various assumptions regarding inundation. Vattenfall puts it this way (Vattenfall 2006b):

Damming causes inundated land to release organic matter, which is decomposed to CO_2 when subjected to oxygen in the water. Because the reservoirs are deep and the climate cool, no methane is formed. The new biomass generated in the water consumes CO_2. The net effect is calculated and reported for the lifetime of 100 years (for reservoirs), and distributed over electricity generation in the same amount of time.

A survey of several LCA studies performed in 1997 concluded that indirect emissions (not inundation) range from 1 – 10 g CO_2 eq. /kWh (Dones et.al. 2003). The direct emissions through inundation depends on several factors; climate (in tropical reservoirs, bio-degradation is faster); amount of flooded biomass; the nature of the flooded soil; the depth of the reservoir (a factor which controls methane oxidisation); and the ratio of energy produced to surface area. Soil, rich with peat in Finland has resulted in release of methane, with measured average emissions in the range of 65 – 72 g CO_2 eq. /kWh for such reservoirs (Dones et.al. 2003). It is thus a rather broad range of possible total environmental impacts from hydro reservoir. However; the most reservoirs in Norway are deep mountain-reservoirs with limited amounts of flooded biomass.

5.5 CONVERSION OF ENERGY SOURCE INTO HEAT

The figures above have focused on electricity generation. Much of the same upstream processes apply to production of heat (mining of coal, extraction of gas etc.). There is not as much LCA literature concerning production of heat as it is for production of electricity, and the level of detail is not as high, which makes it more difficult to distinguish between emissions from fuel chain vs. operation. The source of the data presented below is adopted from Dones et.al. 2003. The reference heat at 240 g/kWh is shown as red dotted line.

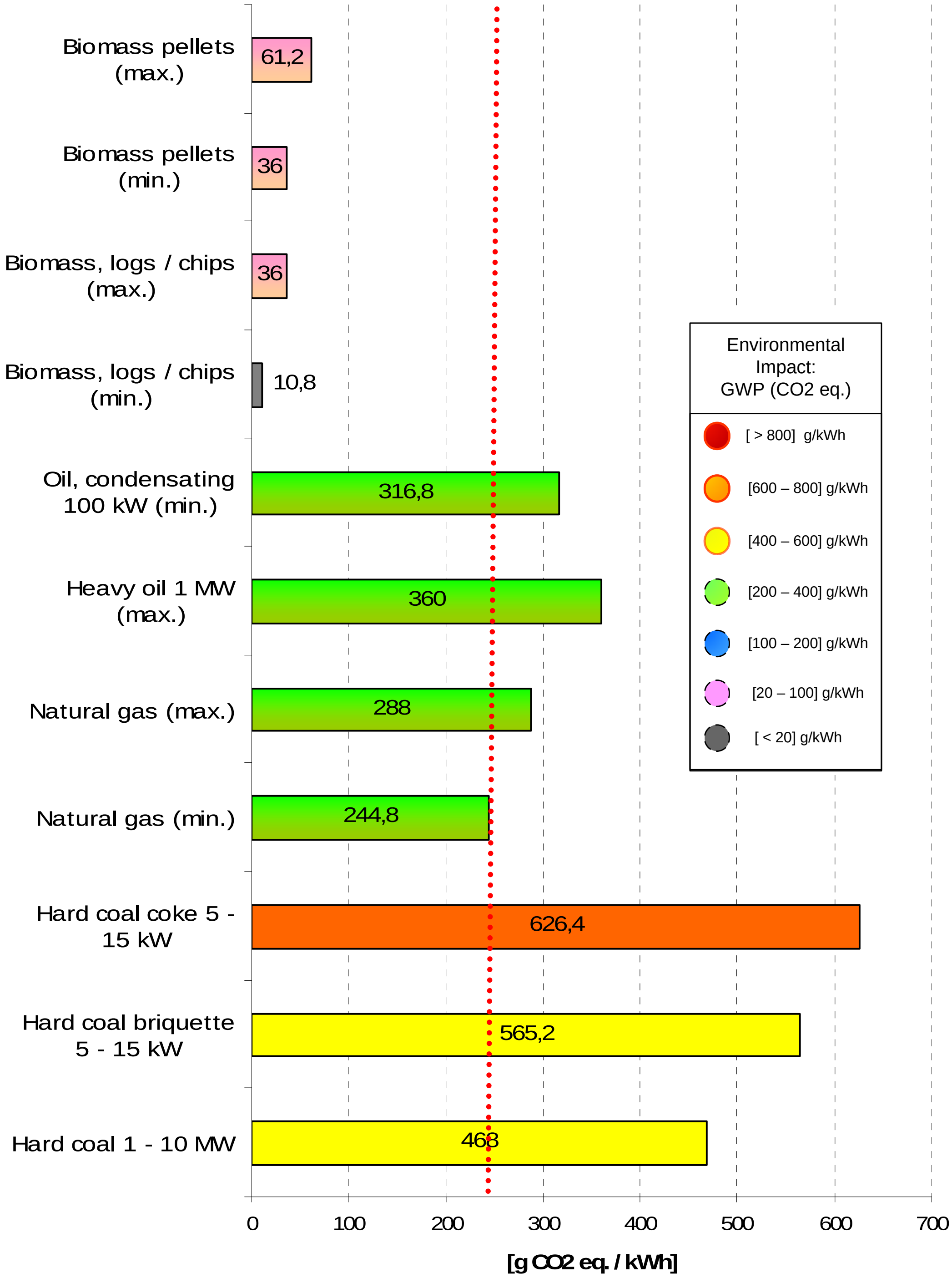


Figure 52 Total LCA chain results for some heating options (Dones et.al. 2003).

The same energy sources as for the electricity production emits less GHG because of the increased conversion efficiency. Most fuels are converted into useful heat with less than 10 % losses. The environmental impact is thus spread over a greater quantity of product. Lack of relevant literature for heat production has made it hard to split up the heat energy chain into different subsystems (fuel chain etc.), but more of the electricity energy chains presented below are highly relevant to heat production. This yields the use of natural gas, coal and biomass. Most up-stream processes would be similar for these fuels regardless whether one converts into heat, hydrogen or electricity.

This next part looks closer into each technology and examines which part of the life cycle is important for the overall LCA performance. All power plants are adopted from Marheineke (2002) when other not mentioned.

5.5.1 Coal power

Three different cases are presented: German coal power plant (η = 43 %) fed by coal from Poland, German coal power plant (η = 45.5 %) fed by domestic coal and a German lignite power plant (η = 40 %).

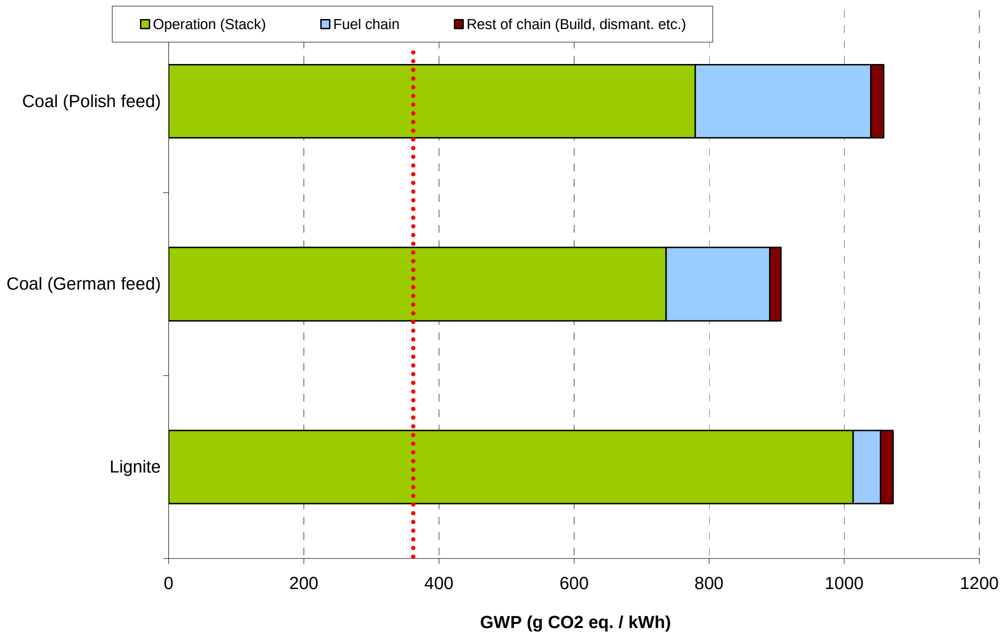


Figure 53 LCA results for coal power.

It is evident that besides the operation and the GHG emissions coming out of the stack is the fuel chain an important contributor to the overall results. The results are in line with other literature.

Table 18 Other LCA results from Coal technologies.

Technology	GWP (g CO_2 eq. / kWh)	Source
Lignite (min. – max.)	1060-1690	Dones et.al. 2003
Coal (min. – max.)	949 - 1280	Dones et.al. 2003
Coal	700	Vattenfall 2006d
Coal	960	Gagnon L et.al. 2002

By looking at the average of the three alternatives from Marheineke one obtains the following chart (an LCA of heat would give similar results):

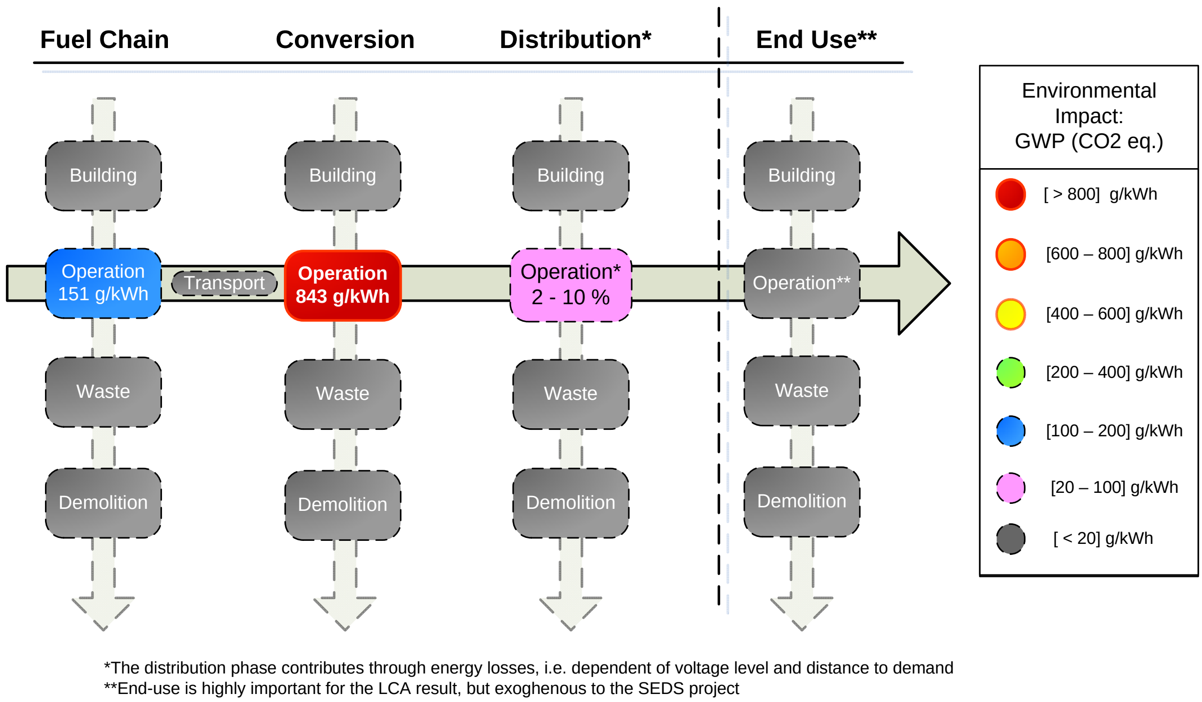


Figure 54 Main LCA contributions to GHG emissions from coal power.

It is thus not much environmental impact (GHG) from construction or demolition phases, rather the operation of the fuel chain and the power plant causes the most GHG emissions, which is also evident from Figure 53, where operation and fuel chain are dominating the environmental impact.

5.5.2 Combined Cycle Gas Turbine (CCGT)

The CCGT has similar characteristics as coal power, but at a lower scale, with total GHG emissions around half the emissions from coal power plants. The construction phase and other parts of the life cycle other than operation of power plant or fuel chain is not significant, as one can see in Figure 55.

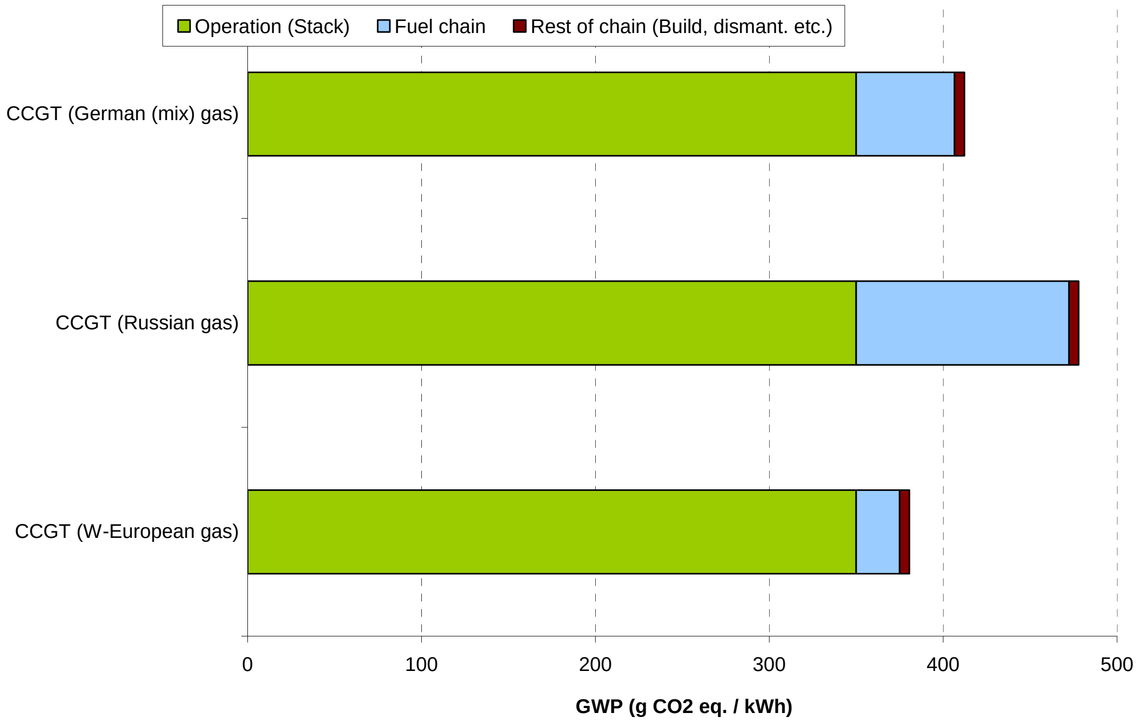


Figure 55 LCA results for CCGT.

The origin of the natural gas has high impact, as seen with the Russian gas. An average of the three alternatives above gives the following chart (an LCA of heat would give similar results):

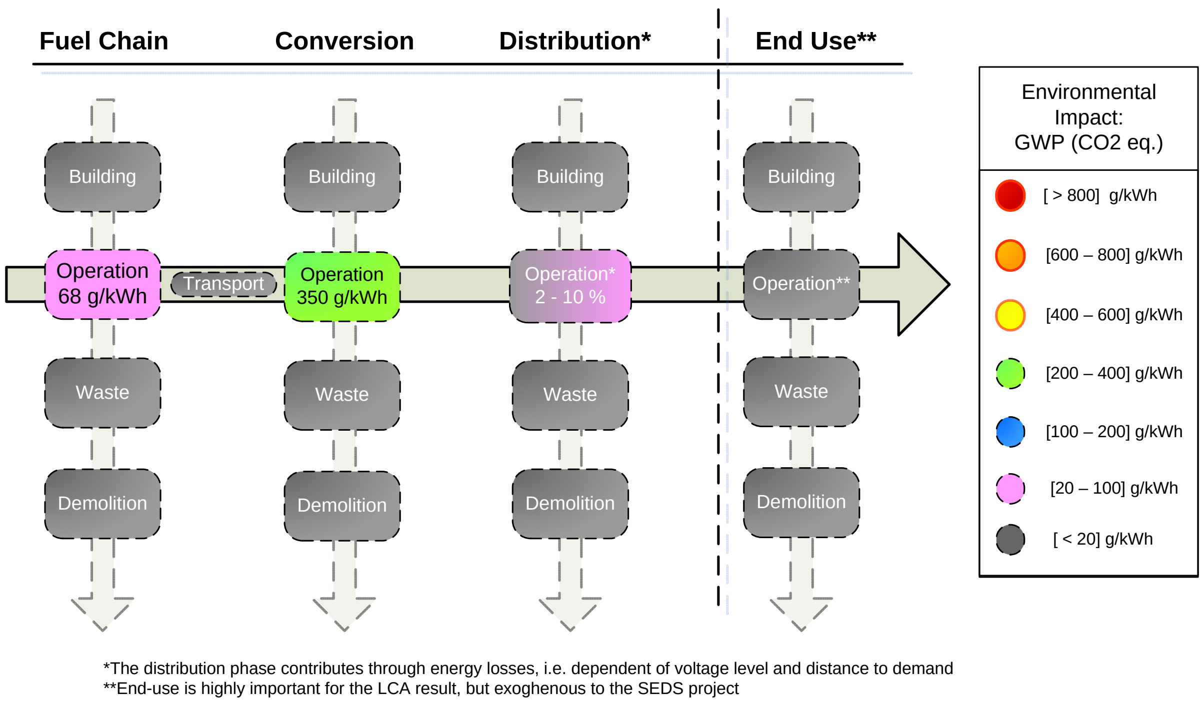


Figure 56 Main LCA contributions to GHG emissions from CCGT.

The operation of the fuel chain and the power plant is again the life cycle phases that are contributing the most to the overall GHG emissions.

The results here (Marheineke) are similar to values reported in other studies:

Technology	GWP (g CO_2 eq. / kWh)	Source
CCGT	410	Dones et.al. 2003
CCGT	373	Magnussen K. et.al. 1999
CCGT	405	Vattenfall 2006d
CCGT	443	Gagnon L et.al. 2002

5.5.3 Photovoltaic

Below are some PV technologies from Marheineke (2002) shown together with future predictions by Pehnt (2006). The latter is not divided between operation, construction etc. nor is “Back-up” included. But the insulation conditions should be similar as they are both German studies. The PV 2030 prediction is based upon dynamic LCA, which means that future electricity mix etc. is used as input in the processes. The principle is explained in Chapter 3.2.2. A solar thermal (parabolic trough) is also included, to demonstrate how other solar technologies might perform better than PV.

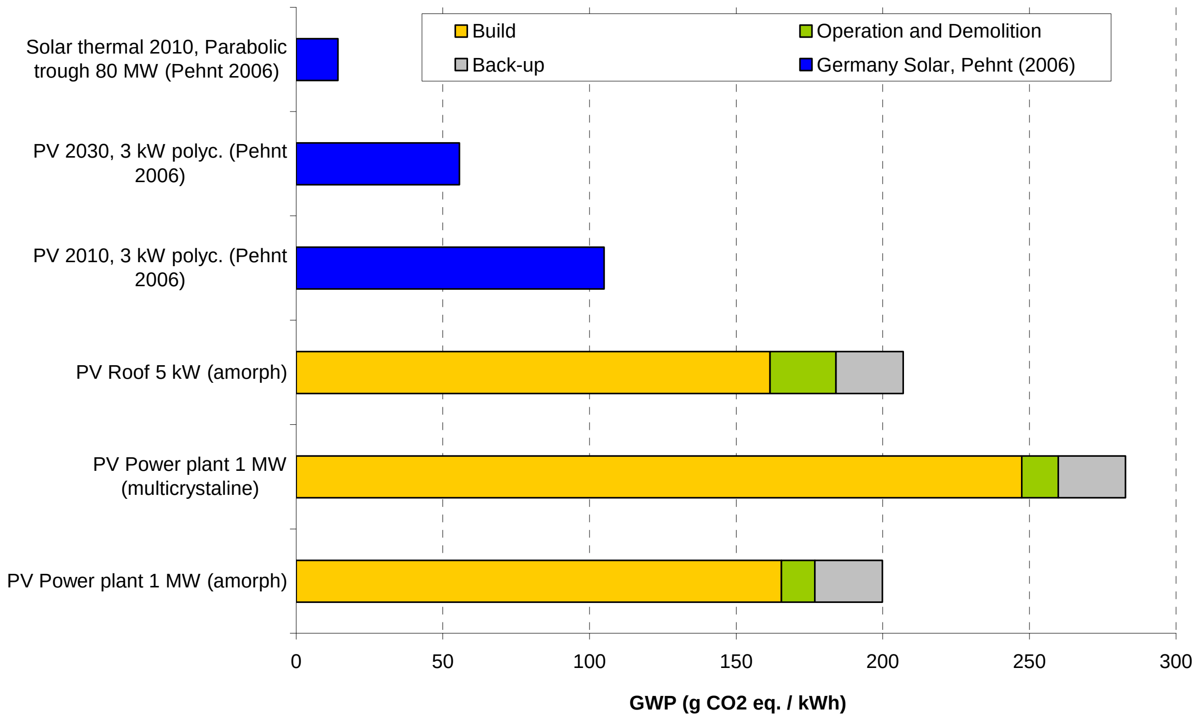


Figure 57 LCA results from PV in Germany.

One sees quite a spread in results, which stems from the efficiencies of the different technologies as well as the energy intensity in producing the material. Bear in mind that the reference CCGT has an environmental impact of 373 g CO_2 eq. / kWh, which is not so far off the worst performing PV plants, although the latter is seen as a renewable energy technology.

Because of less detail in the data from Pehnt and others, only data from Marheineke are used in the following figure. The use of solar for heat production would be totally different, as solar collectors are not made up from energy intensive wafers. An LCA of solar collectors is Masruroh et.al. (2006), which indicates total emissisons of 23-36 g/kWh produced heat from a "solarstore" system. This again is totally dependent upon solar conditions.

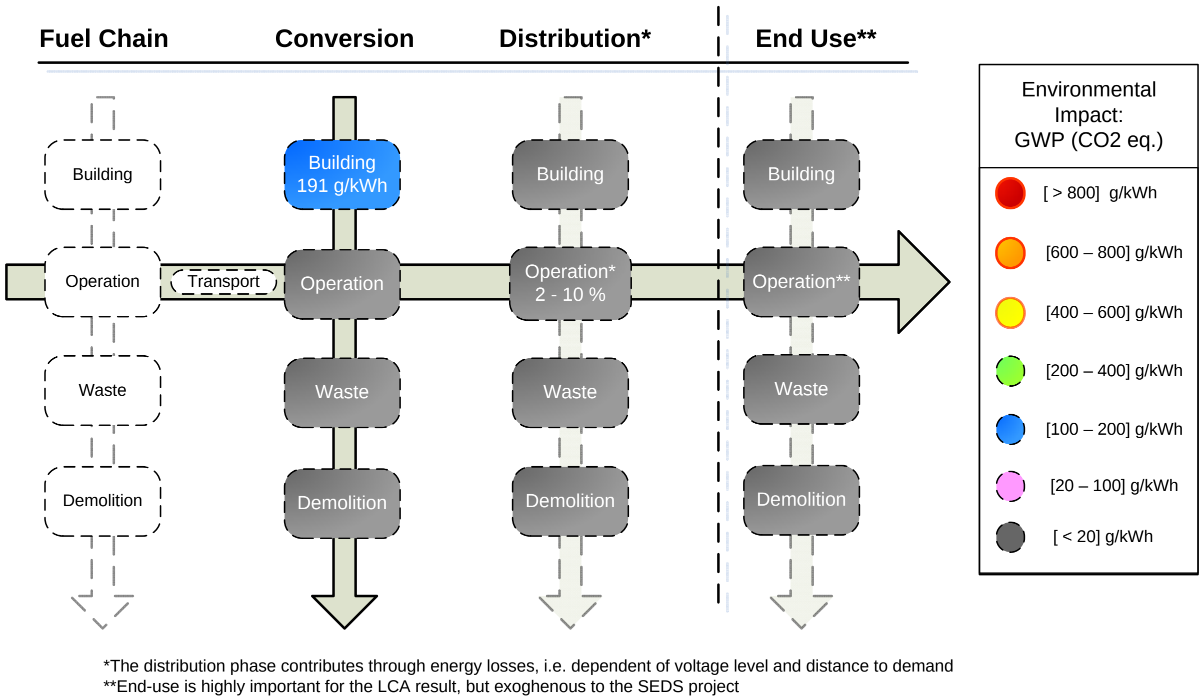


Figure 58 Main LCA contributions to GHG emissions from PV.

There is no impact from the fuel chain of a PV, most GHG emissions occur during production of the PV plant, where energy intensive wafer is an important component.

5.5.4 Wind power

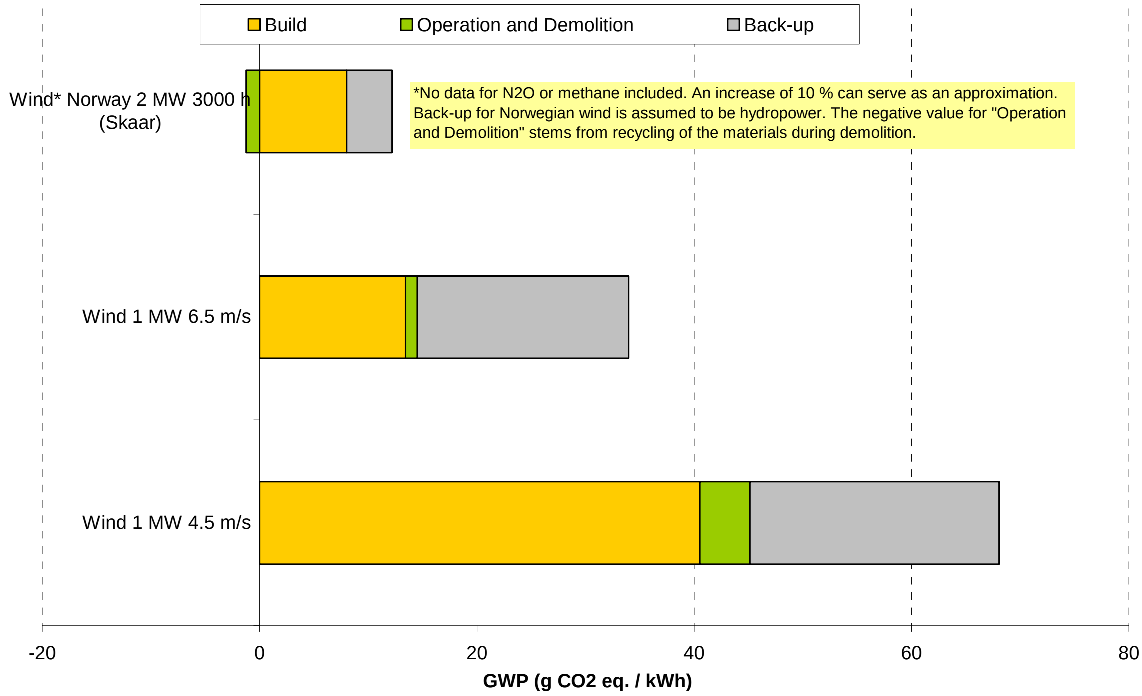


Figure 59 LCA results from different wind power alternatives.

The LCA footprint in terms of GHG of wind power is in general low, as seen from Figure 59. The average of the three constitutes the basis for the figure below:

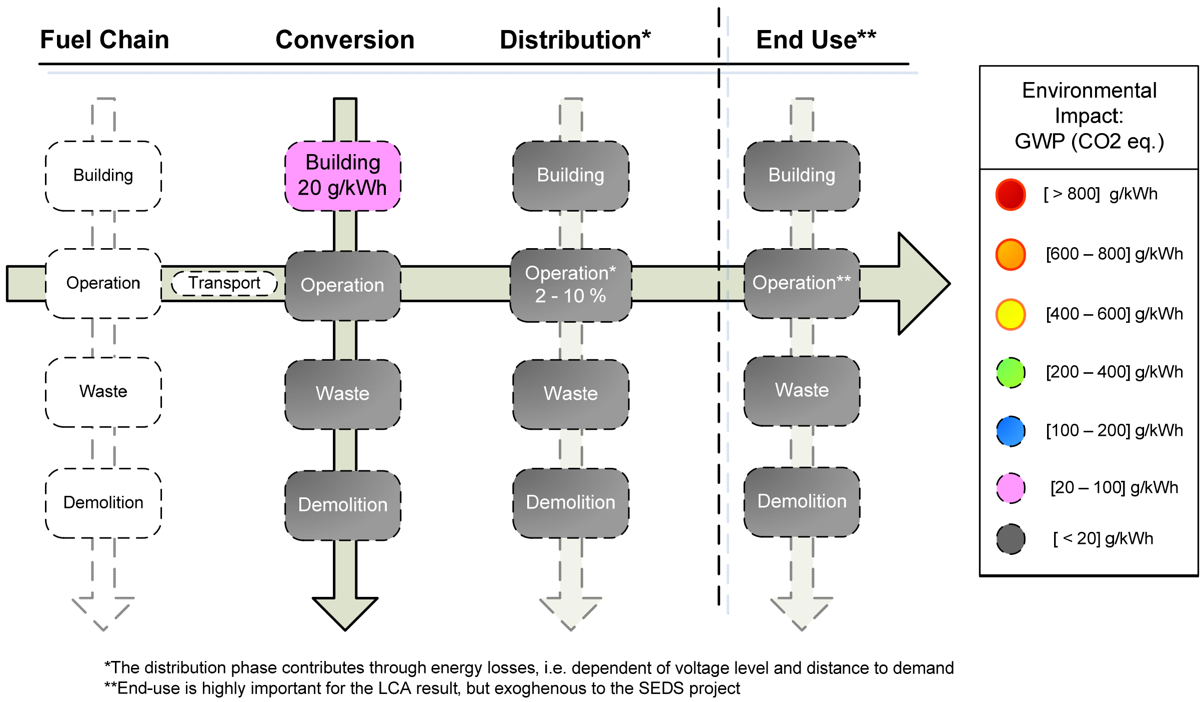


Figure 60 Main LCA contributions to GHG emissions from Wind power.

The values here are in line with other literature:

Technology	GWP (g CO2 eq. / kWh)	Source
Wind power (min. – max.)	14 - 21	Dones et.al. 2003
Wind power	15	Ardente F. et.al. In press
Wind power	10	Vattenfall 2006d

5.5.5 Electricity from Biomass

The comparison of different biomass alternatives is challenging as the assumptions are highly site-specific, and not as general as for most other energy technologies. An example from Vattenfall is presented here, where a gasification combined cycle (GCC) power plant is presented (Vattenfall 1996). An example of the spread in results is Pehnt (2006), which has results for biomass electricity ranging from 29 – 84 [g CO_2 eq. / kWh] (but has no allocation to the heat produced (no credit for heat), the number is thus somewhat higher).

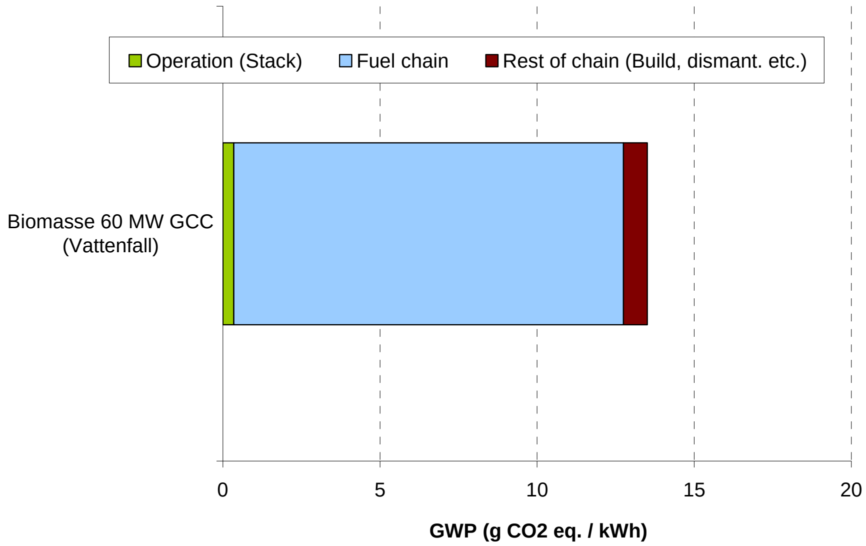


Figure 61 LCA results for electricity from biomass.

The critical part of the biomass life cycle is the fuel chain. If e.g. fertilizer is being used and the biomass is harvested in an unsustainable manner, the claim that biomass is a renewable energy might be questioned. The results for production of heat follow the same pattern as for electricity production shown below, with emphasize on the fuel chain.

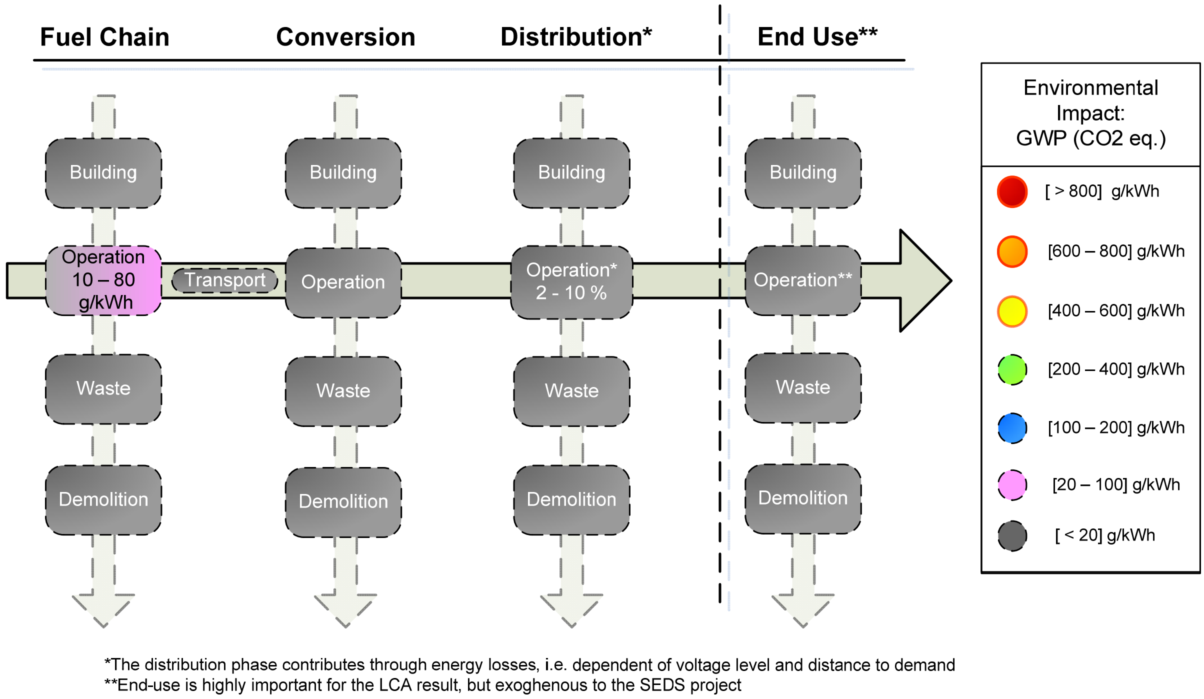


Figure 62 Main LCA contributions to GHG emissions from biomass.

Most of the impact arises from fuel chain, but under sound environmental management most energy converted from biomass has relatively low GHG emissions, compared to e.g. the CCGT reference at 373 [g/kWh]. The later Vattenfall study (Vattenfall 2006d) has nearly the same results for biomass electricity, with total GHG emissions of 16 g/kWh.

6 SMALL LCA CASE-STUDY OF HYLKJE

Without the proper LCA software, and available time, it is difficult to perform a real case study of Hylkje. This chapter however, tries to point out what kind of extra knowledge an LCA perspective would bring.

6.1 HYLKJE

Hylkje is a development area, where energy sources for heating and power have to be chosen. Two energy carriers are delivered to the system boundaries at Hylkje, namely electrical power and natural gas from the Norwegian continental shelf. This chapter tries to display the importance of upstream activities when environmental performance of an energy system is measured, and focuses therefore at the gas fired CHP-option. The LCA data is taken from existing LCA literature and are more indicative than absolute. Central in the case study is a 3.6 MW CHP engine. This engine is assumed to be fairly similar to one of the ECLIPSE cases (System 1: 2.1 MW, technology available 1990 – 2000).

6.2 EMISSIONS FROM STACK (OPERATION) VS. LCA

Traditional emission accounting would yields the following environmental impact during production of one kWh electricity together with 1.565 kWh heat (Briem S 2003):

Table 19 Emissions from operation of the CHP.

Flow	Amount	Unit
CO_2	564.4	g/kWh
NO_x	670.2	mg/kWh
CH_4	212.4	mg/kWh
NMVOC	23.6	mg/kWh
CO	380.7	mg/kWh
SO_2	5.5	mg/kWh
PM	0	mg/kWh

When one would analyse the whole chain, especially the fuel chain is important as Chapter 5 has emphasized. For the same categories as above one would obtain the following difference assessing operation vs. total LCA:

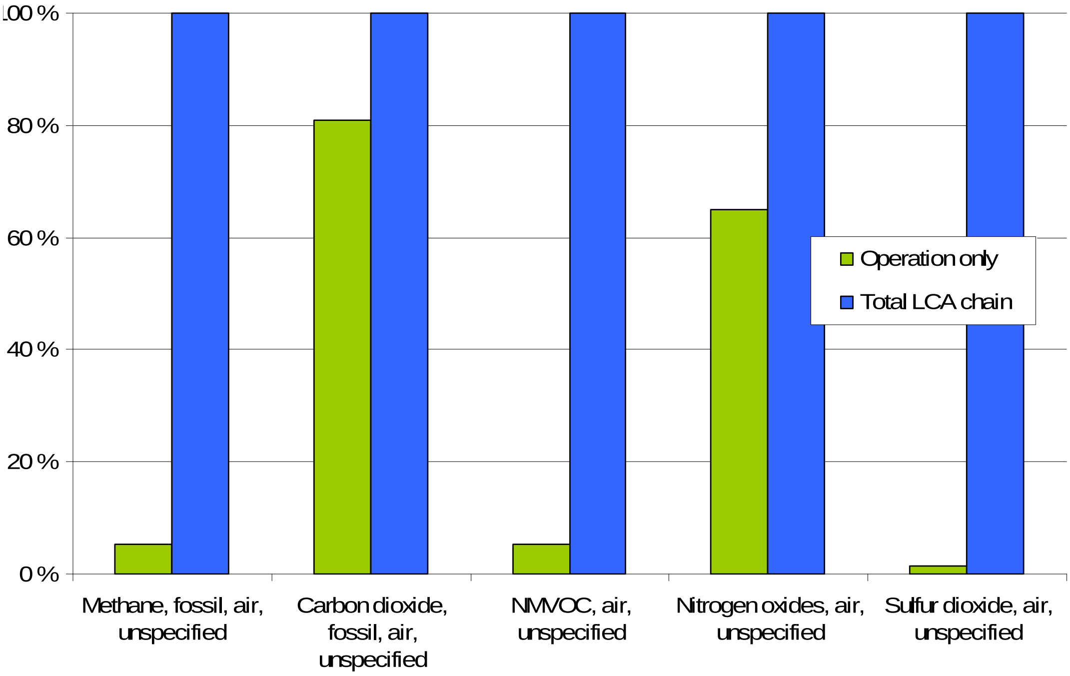


Figure 63 Difference in emissions to air between operation and full LCA.

As one can see from Figure 63, the difference is large, and even for CO_2 emissions the spread is 20 %. The methane emissions are worse, with a spread of 94.7 % between operation and full LCA. For global warming this would yield a difference of 27.3 % between stack emissions and LCA emissions.

The alternative to CHP in Hylkje is a strengthening of the electricity grid. There are different ways of looking at how the power mix generated upstream and imported at the system boundary (Hylkje) should be represented. Some will argue that this power is a marginal import from the neighbouring countries, building on the assumption that in an average hydrological year Norway is now importing power. The challenge is then to find a representative import power mix. One suggestion is as follows:

- Gas power from CCGT (Magnusson: 373 g CO_2 / kWh)
- Short-term marginal production delivered in the Nordpool market is mostly coal and gas power (Holttinen 2004) (400 – 1200 g CO_2 / kWh)

Thus, the assumption is that any increase in electricity consumption in the Nordel power market is covered by a thermal power mix, and the emissions should be accounted for accordingly. Further arguments and simulations are found in Holttinen 2004.

A different point of view is a model based approach with simulations considering seasonal and annual variations in hydro inflow in the Nordel area. This might give quite different results from the marginal approach since the hydro evidently covers a considerable share of the electricity consumption in the Hylkje area.

A full LCA would have given results for all impact categories for the different alternatives, and not only for the global warming:

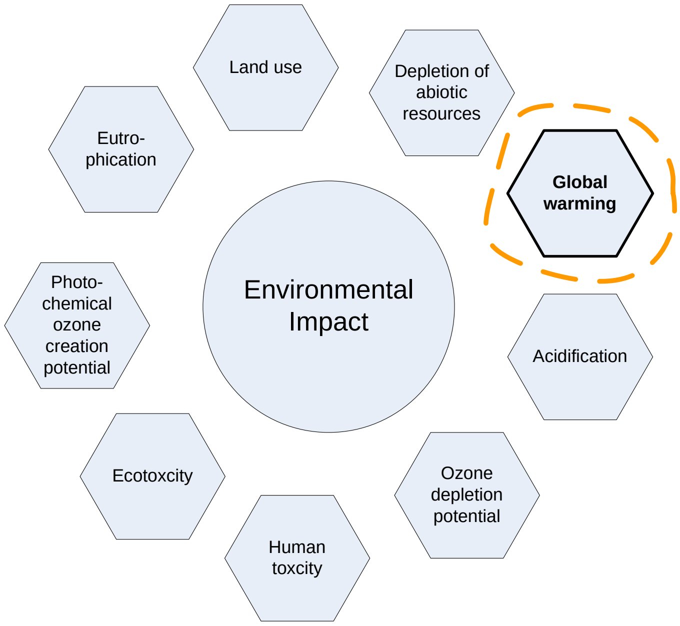


Figure 64 Common environmental impact categories.

The decision makers in the Hylkje region would thus have the information of what environmental impact the alternatives imply, not only in Hylkje, but at the Norwegian continental shelf, and other environments affected by the choice made for Hylkje. The different options could be valued using a weighting indicator, thus obtaining single scores for the overall LCA impact from the alternatives. This single score could serve as input to multiple decision analysis. The LCA perspective implies new information along three new dimensions: Firstly; the whole energy chain from "cradle to grave" is followed, secondly; many related sub-processes are analysed, and thirdly; all kinds of environmental impacts might be analysed and documented.

7 CONCLUSION

This study has provided an introduction to LCA in the context of energy planning, and tried to point out the major differences between emission accounting and a broader LCA perspective. It has been argued that for energy planning, it is important to bear an LCA perspective in mind in order to plan socio-economic optimal energy systems, since energy systems might have environmental impact outside of traditional system boundaries.

LCA is a holistic approach accounting for all environmental impacts occurring from the system's "cradle" to the "grave", together with all related activities throughout the lifetime of the system.

The LCA perspective provides new information along three new dimensions: Firstly; the whole energy chain from "cradle to grave" is followed, secondly; many related sub-processes are analysed, and thirdly; all kinds of environmental impacts might be analysed and documented.

The study has presented a broad range of different LCA studies concerned with energy systems, together with references to still other relevant LCA studies, thus providing a starting point for further studies of LCA of energy systems.

For most energy system utilising a fuel, the fuel chain is of great importance. This yields for both electricity and heat production, and from sources such as; coal, lignite, natural gas, biomass and oil. The building/demolishing etc. from these energy systems are seldom of great importance. The total GHG emissions are for coal around 1000 g CO_2 eq. / kWh, for CCGT 400 g CO_2 eq. / kWh.

For renewable technologies, the building phase is often more dominant, being the cause of the major environmental impact. This applies to solar energy, wind power, hydro power etc. However; the hydro power with reservoir, represents a special case, since e.g. the soil of the flooded area is of great importance for the methane emissions. All renewable energies are mostly below 100 g CO_2 eq. / kWh, with exception for PV, which has more emissions due to energy demanding wafers, which are important components. The PV examples from this study indicates GHG emissions in the range of 100 – 280 g CO_2 eq. / kWh, which is rather high from a energy source seen as renewable. This again is totally dependent of where the PV plant is situated, as solar radiation differs a lot.

Transport of biomass and other fuels are possible without having too much significance for the overall LCA results, as long as the distance is within limits, and done with proper transportation mode.

Construction of electricity grids or district heating grids etc. is shown to be of less importance in an LCA perspective, the most important part is the losses in the grids, which has to be compensated by increased production up-stream. This extra production yields the most environmental impact caused by the distribution grids.

The LCA perspective is useful and necessary for sound environmental planning of energy systems.

8 SUGGESTIONS FOR FURTHER WORK

This work is just a short introduction into an important field of study. A wide range of opportunities exist thus for continuing and extending the merging of LCA and energy planning. The energy technologies could be investigated for all LCA environmental impact groups, and not only global warming.

Life cycle cost of energy technologies could be found and compared against LCA, thus finding more rational for which energy technologies should be part of the energy system.
Generically data could be included in energy planning software in order to facilitate the merging of LCA perspective and energy system decision makers.

The data could be refined and extended for hydrogen systems and a broader technology portfolio.

9 REFERENCES

Anonymous Energianvändning och –försörjning för byggnader ur ett systemperspektiv Svensk Fjärrvarme et.al. (2006) (in Swedish)

Anonymous *Livscyklusvurdering af dansk el og kraftvarme 2001* Energi E2, Elfor, Elkraft system, Elsam, Eltra, VEKS 2001

Anonymous Livscyklusvurdering af dansk el og kraftvarme 2001 Opdateringsnotat 2004 Energi E2, Elkraft system, Elsam, København E, VEKS 2004

Ardente F. et.al. Energy performance and life cycle assessment of an Italian wind farm, Renewable & Sustainable energy reviews In press, accepted 24 May 2006

Bakkane K. K., *Life cycle data for Norwegian oil and gas,* Tapir publishers 1994 ISBN: 82-519-1175-3

Baumann H, Tillman A. The hitch hiker's guide to LCA –An introduction in life cycle assessment methodology and application, Studentlitteratur 2004 ISBN: 91-44-02364-2

Bengtsson M, Steen B, *Weightning in LCA – Approaches and applications,* Environmental Progress, vol 19, no 2, 2000 pp: 101-109

Briem S. *Gas fired CHP systems –Internal Combustion Engines Final Report* November 2003 IER University of Stuttgart ECLIPSE project, available at: www.eclipse-eu.org

Chui F. et.al. An intergrated decision support framework for the assessment and analysis of hydrogen production pathways Energy and Fuels 20, pp: 346-352, 2006

CML-IE *LCA resources at CML-IE* Institute of Environmental Sciences, The Netherlands http://www.leidenuniv.nl/interfac/cml/ssp/projects/lca2/index.html accessed 10.04.2006

Dethlefsen U. el.al. Vattenfall's electricity production system –A quantitative and qualitative study of emissions of greenhouse gases throughout the life-cycle World Energy Council, http://www.worldenergy.org/wec-geis/publications/default/tech_papers/17th_congress/3_4_14.asp Accessed 15.11.2006

Diaz R. et.al. Life cycle assessment of municipal solid wastes: Development of the WASTED model Waste management, 26, p: 886-901, 2006

Dones R. et.al. *Greenhouse gas emissions from energy systems: comparison and overview* PSI Annual Report 2003, Annex IV, Paul Scherrer Institut, Villigen, Swiss

Dones R. et.al. Life cycle inventories for the nuclear and natural gas energy systems, and examples of uncertainty analysis Int J LCA 10 (1) p: 10-23 2005

Duhn T et.al. *Environmental assessment of CHP supply from "cradle to grave"* News from DBDH 1/2002 Accessed 20.12.06; http://www.dbdh.dk/pdf/distribution-pdf/Craddle-to-grave.pdf

Dr. Ari, Rabl *Summary of the stakeholders concerns* Final seminar on External costs of energy and their internalisation in Europe Dialogue with industry, NGO and policy-makers Friday, 9 December 2005, Brussels http://maxima.ier.uni-stuttgart.de/ accessed 2007-01-31

ECLIPSE 2007 EU Project http://88.149.192.110/eclipse_eu/ accessed 2007-01-31

Energinet.dk 2006 *Baggrundsrapport til Miljøberetning 2006* Karen Hvid Ipsen 2006 http://www.energinet.dk/ accessed 14.12.2006

Environdec 2006, http://www.environdec.com/page.asp?id=105&menu=3,9,0&group=40, accessed 14.12.2006

EPD® 2007 Environmental Product Declaration: www.environdec.com Programme operator: The Swedish Environmental Management Council (SEMC) accessed 2007-01-31

EPD Norge, Environmental Product Declaration: www.epd-norge.no accessed 06.04.2007

Eriksson O. et.al. Life cycle assessment of fuels for district heating: A comparison of waste incineration, biomass- and natural gas combustion. Energy policy (in press; November 2006)

ExternE 2007 EU Project http://www.externe.info/ accessed 2007-01-31

Fröhling M., Holmgren C., *Miljöbelastning från produktion av fjärrvärmerör* Chalmers tekniska högskola, Kemisk Miljövetenskap FOU 2002:82 Svenska Fjärrvärmeföreningen 2002 (in Swedish)

Gagnon L. et.al. Life-cycle assessment of electricity generation options: The status if research in year 2001 Energy Policy, 30, p: 1267-1278, 2002

Guine´e JB, et.al. Handbook on life cycle assessment-operational guide to the ISO standard.

http://www.eclipse-eu.org/pdf/methodological_guidelines.pdf accessed: 23.11.2006

Grønli Morten, *Biobrensler*, SINTEF Energiforskning AS, Bionett Temablad, Only available in Norwegian.

Holttinen H, Tuhkanen S, *The effect of wind power on CO_2 abatement in the Nordic countries* Energy Policy 32, 2004 pp. 1639-1652

Johansson J. et.al. *Livscykelanalyser av fjärrvärme – en förstudie* FMS Forskningsgruppen för miljöstrategiska studier 2003 www.infra.kth.se/fms/pdf/LCA.fjarrvarme.pdf accessed: 23.11.2006

Jungbluth N. et.al. Life cycle assessment for emerging technologies: Case studies for photovoltaic and wind power Int J LCA p: 1-11 2004

Kannan R. et.al., Life cycle energy, emissions and cost inventory of power generation technologies in Singapore Renewable and Sustainlabel Energy Reviews, 11 p: 702-715 2007

Kato S. et.al., Environmental impact consolidated evaluation of energy systems by an LCA-NETS scheme Energy 30, p: 2057-2072, 2005

Leontief Wassily *Input-Output Economics* Second edition, Oxford university press 1986 ISBN 0-19-503525-9

NEEDS 2007 EU Project http://www.needs-project.org/index.asp accessed 2007-01-31

Nyberg R. Bjørn et.al. Teknisk-økonomisk analyse av miljøtiltak for kabler – Innledende studier

TR A4935, Juli 1999, SINTEF Energiforskning

Magnussen K. et.al. Life cycle assessment of a gas power station –Is life cycle assessment a good basis for economic valuation and environmental effects? Stiftelsen Østfoldforskning 1999 ISBN no: 82-7520-370-8

Masruroh N.A. et.al. Life cycle analysis of a solar thermal system with thermochemical storage process Renewable Energy 31, 2006, pp. 537-548

MAXIMA 2007 EU Project http://maxima.ier.uni-stuttgart.de/ accessed 2007-01-31

May J.R. Life cycle assessment of Australian fossil energy options Trans IChemE, Vol 81, Part B, p: 317-330, 2003

Pehnt M. Dynamic life cycle assessment (LCA) of renewable energy technologies Renewable Energy 31, p: 55-71, 2006

Pennington D.W. et.al. Life cycle assessment Part 2: *Current impact assessment practice* Environment Int. 30 2004 pp. 721-739

Persson A. et.al. Allt eller inget – Systemgränser för byggnaders uppvärmning ÅF-Energi og Miljö AB 2005 (in Swedish)

Rainer Friedrich *ExternE methodology and results* Final seminar on External costs of energy and their internalisation in Europe Dialogue with industry, NGO and policy-makers Friday, 9 December 2005, Brussels http://maxima.ier.uni-stuttgart.de/ accessed 2007-01-31

Rebitzer G. et.al. Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications Environment Int. 30 2004 pp. 701-720

Schleisner L. Life cycle assessment of a wind farm and related externalities, Reneable Energy 20, p: 279-288, 2000

Setterwall C. et.al., Methodological guidelines, Final Report ECLIPSE, Vattenfall AB 2004

Stene Jørn *Oppvarmingssystemer for lavenergiboliger* SINTEF Energiforskning AS Januar 2006, TR A6182

Sundseth Kyrre, Product category rules for environmental product decalration of electricity generation NTNU, The Industrial Ecology Programme, Prelimenary study 2007

Solli Christian, Fission or fossil? A comparative hybrid life cycle assessment of two different hydrogen production methods NTNU, The Industrial Ecology Programme, Master thesis 2004

Suh et.al Critical review; System boundary Selection in Life-Cycle Inventories Using Hybrid Approaches Env. Science and Tech. Vol 38 nr. 3 2004 pp. 657-664

Troels Duhn Personal email: td@veks.dk 15.12.2006
Vattenfall 2006a

Trondheim Energi 2001, *Fjernvarme i Trondheim – for et bedre miljø.* Available at: http://www.tev.no/pdf/fjernvarme_bedremiljo.pdf accessed 02.04.2007

Vattenfall AB 1996 *El & Miljö, Livscykelanalys för Vattenfalls elproduktion* Norberg, B.B. et.al. Vattenfall support/Ateljé&Grafiska feb. 1997

Vattenfall AB 2006, Vattenfall AB Nordic's certified Environmental Product Declaration EPD® for electricity and District heating from the CHP at Vattenfall AB Nordic Heat Uppsala S-P-00107 2006

Vattenfall AB 2006a, Vattenfall AB Nordic's certified Environmental Product Declaration EPD® for electricity and District heating from the CHP at Vattenfall AB Nordic Heat Uppsala S-P-00107 2006

Vattenfall AB 2006b, Vattenfall AB Nordic's certified Environmental Product Declaration EPD® of electricity from Vattnefall's Nordic hydropower S-P-00088 2006

Vattenfall AB 2006c, Certifiered miljövarudeklaration för –avfallshantering/förbränning – fjärrvärme –ånga från Vattenfall Värme AB Uppsala Block 5 S-P-00060 2006

Vattenfall AB 2006d Internet page: www.vattenfall.se/om_vattenfall/var_verksamhet/var_produktion/livscykelanalyser/ accessed 20.11.2006

Vold M. et.al. *LCA av norskprodusert elektrisitet basert på vannkraft* Stiftelsen Østfoldforskning 1996 ISBN nr: 82-7520-258-2

Värmeforsk, LCA-analysis; A comparison based on one refined and one unrefined biomass fuel Edholm A. ÅF Energikonsult AB 2000, (in Swedish)

Watkins Thayer, *Input-Output Analysis and Related Methods* San José State University Department of Economics, http://www.sjsu.edu/faculty/watkins/inputoutput.htm accessed 13.11.2006

APPENDIX 1: EPD OF TROLLHEIM HYDRO POWER STATION

Environmental Declaration ISO/DIS 14025 Type III

Statkraft

Hydroelectricity from Trollheim Power Station

EPD®

Norwegian Environmental Declaration

NEPD no.: 10E

Approved by the Verification Committee 30.06.2002
Valid untile: 31.12.2005

Figure 1. Inside Trollheim Power Station

The declaration has been prepared by:

Østfold Research Foundation

Stiftelsen Østfoldforskning

Statement from the certifying body

Det Norske Veritas (DNV) has certified Statkraft SF's Environmental Product Declaration (EPD) for hydroelectricity from Trollheim Pow-er Station. The contents of the EPD are correct and together with the back-ground studies, found to be in accor-dance with the relevant ISO-standards (ISO14025 TR, ISO14020 and ISO14040-43) and Nordic guidelines given in the NIMBUS project [2].

DNV

Information about the producer:

Trollheim Power Station, Statkraft SF, Norway.
Contact person: Tormod A. Schei/ Eivind Torblaa, Tel: + 47 24 06 70 00,
E-mail: tormod.schei@statkraft.no/ eivind.torblaa@statkraft.no
Organisation number: 962 986 277
Certified in accordance with ISO-14001: Reg.no. 2001 - OSL - SYMI – 8126

Table 1. Key data for Trollheim Power Station

Parameter	Units	Value
Catchment area	km^2	575
Reservoirs: Follsjø + Gråsjø	$mill.m^3$	384
Generator capacity	MW	130
Maximum flow rate	m^3/s	38,5
Number of turbines		1
Average annual operation time, full capacity	timer	6192
Average annual production	GWh	805 (369 summer, 436 winter)

Information about the product:

Parts of life cycle: Construction, operation and maintenance of the power station.
Year of study: 1999. Background data are from the period 1991-1999.
Functional unit: 1 kWh electricity produced at Trollheim Power Station. Environmental impacts from materials that are used for construction of the power station are divided by the production volume over 60 years (based on the production in 1997).
Estimated lifetime for the power station: 60 years.
Generation site: Trollheim Power Station.
Impacts assessed: Ozone depletion, global warming potential, acidification, resource use, nutrification, waste generation, photo-chemical ozone formation. Non-quantified environmental impacts are described in accordance with ExternE methodology.
Market area: Europe

RESOURCE USE

Resource use per kWh is calculated based upon the production of 805 GWh/year. Changes in production volume at Trollheim Power Station will not lead to changes in total resource use or environmental impacts.

Material resources

Table 2. Material resources consumed

	Unit	Construction	Operation and Maintenance	Total	Comments
Recycled, renewable resources	g/kWh	-	-	-	Recycled and renewable resources were not included in the inventory in the study that this declaration is based upon.
Virgin, renewable resources	g/kWh	-	-	-	
Recycled, non-renewable resources	g/kWh	~0,056	~0,019	~0,074	Approximately 50 % of the total amount of steel used in the large installations is recycled.
Virgin, non-renewable resources					
Coal feedstock	g/kWh	0,024	0,0026	0,027	These resources are used in the production of materials used for the manufacture of production equipment; i.e. steel for the transformer, turbine, reinforcement etc., as well as cement in dams and tunnels.
Oil feedstock	g/kWh	0,00011	0,000066	0,00018	
Iron ore	g/kWh	0,10	0,011	0,11	
Limestone	g/kWh	0,45	0,00092	0,45	
Stone	g/kWh	0,0060	0,00065	0,0066	

Land area

The effects of changes in land use are included in the ExternE evaluation in the 'Additional Information' section of this declaration.

Water resources

Water consumption is negligible for hydroelectricity production, as all the water used passes through the installation without being used up. The consequences of reduced water flow in the watercourses are included in the ExternE evaluation in the 'Additional Information' section of this declaration.

Energy resources

Some of the potential energy in the stored water in the reservoirs will be wasted during production of 1 kWh electricity, in the form of loss of head height, efficiency (less than 100%) and heat. This loss is included in the energy use under "Operation and Maintenance" in Figure 2 and Table 3.

The electricity consumption is not given specifically, but the energy used to produce this electricity is shown. This is done in order to document the use of resources and prevent double counting, which can easily occur when electricity consumption is also included in addition to primary energy use.

Table 3 Primary Energy Consumption

kWh/kWh		Construc-t ion	Operation and Maintenance	1 kWh to the net*	Total
Fossil energy					
	Crude oil	0,0016	0,00041	-	0,0020
	Natural gas	0,000050	0,000016	-	0,000066
	Coal	0,0000056	0,0000025	-	0,0000081
	Peat	0,00000019	0,000000074	-	0,00000027
Nuclear power		0,000025	0,000010	-	0,000036
Renewable energy					
	Hydropower*	0,00055	0,10	1,0	1,1
	Bioenergy	0,0000021	0,00000031	-	0,0000024
Energy from waste incineration					
	Energy	-	-	-	-
	Heat	-	-	-	-
Total		0,0023	0,10	1,0	1,1

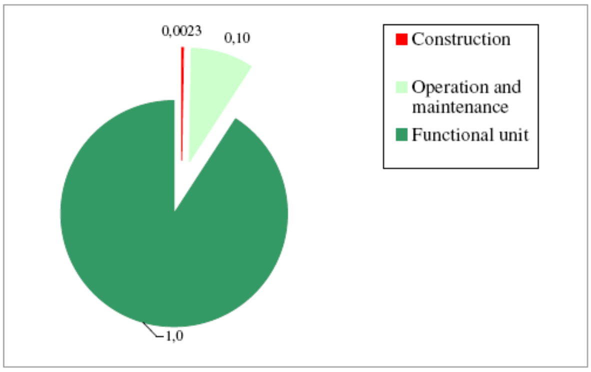


Figure 2. Energy loss during the production of 1 kWh electricity

*Hydroelectricity, 1 kWh which is the 'energy content of the product' is shown here. This energy is not used up and is therefore still available. The user of the information in this declaration must therefore take care not to 'double count' when using this data for other purposes.

MISSIONS AND ENVIRONMENTAL IMPACTS

Table 4. Emissions calculated in terms of environmental impacts

	Construction	Operation and Maintenance	Total
Waste, [g/kWh]	0,052	0,006	0,057
Nutrification, [g O_2-eq./kWh]	0,056	0,011	0,067
Ozone formation, [g POCP-eq./kWh]	0,00068	0,00016	0,00084
Ozone depletion, [g ODP /kWh]	0,0000000015	0,0000000009	0,0000000024
Acidification, [g SO_2-eq./kWh]	0,0078	0,0016	0,0093
Global warming,[g CO_2-eq./kWh]*	0,84	0,14	0,98

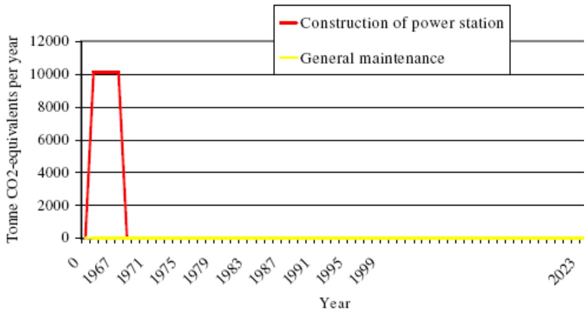


Figure 3. Emissions contributing to global warming during the construction, operation and maintenance of the power station during facility's lifetime.

Table 5. Emissions to air and water

	Construction	Operation and Maintenance	Total
Emissions to air			
CO_2 [g/kWh]*	0,57	0,14	0,71
CH_4 [g/kWh]*	0,00072	0,000082	0,00080
N_2O [g/kWh]	0,000015	0,0000081	0,000023
SO_2 [g/kWh]	0,0009	0,0002	0,0011
NO_x [g/kWh]	0,0056	0,0019	0,0074
NH_3 [g/kWh]	-	-	-
VOC [g/kWh]	0,000014	0,000040	0,000053
CO [g/kWh]	0,0021	0,00057	0,0027
Emissions to water			
Tot-N [g/kWh]	0,000017	0,00000042	0,000017
Tot-P [g/kWh]	0,000000017	0,0000000018	0,000000019
COD [g/kWh]	0,0000045	0,0000017	0,0000063

*The reservoirs contain little organic material in the sediments and the biological activity is low, such that the CO_2 and CH_4 emissions are very small (IEA 2000). Emissions from dammed areas are therefore not included in the study.

Most of the emissions from hydroelectricity production occur during construction of the facility. Although the emissions are divided up per kWh produced, in practice, these emissions occur during a short period. In Figure 3 above, we can see how the emissions actually occur over a period of 60 years.

Emissions of toxic substances and hazardous wastes are not registered during the construction and operational phases of the facility. Possible use of injection chemicals is not included in the inventory data this declaration is based on.

ADDITIONAL INFORMATION

ExternE

Local, environmental burdens from Trollheim power plant have impacts on ecosystems, cultural heritage and recreation, and include:

Reservoirs
- Follsjø: 6,4 km^2 dammed area; 45 m regulation height (100 % Trollheim)
- Gråsjø: 8,8 km^2 dammed area; 53 m regulation height (90 % Trollheim, 10 % Gråsjø Power Station).

Waterfalls with a large reduction in water flow (> 50 % reduction)- None.

Rivers with a large reduction in water flow (> 50 % reduction) - 39 km in total: Surna (22 km), Bulu (9 km) and Folla (8 km).

Impacted stretch of rivers with anadromous fish species - 32 km in total: Surna (30 km) and Folla (2 km).

New construction roads - 10 km in total, two roads of 6 and 4 km, respectively.

New power transmission lines - Less than 1 km in total (from the power station to the existing 132 kV line Aure – Rindal)

The environmental damage costs on ecosystems (including landscape aesthetic impacts), cultural heritage and recreation for the Trollheim power station can then be estimated at 0.06 – 0.08 eurocent/kWh. (ENCO 2001) (converted from NOK to euro using Purchasing Power Parities (PPPs) as of Spring 2002; see http://www.oecd.org/oecd/pages/home/displaygeneral/0,3380,EN-links_abstract-513-15-no-no-323-0,FF.html).

Environmental costs:
0,6-0,8 øre/kWh
= 0,06-0,08 eurocent/kWh

METHODOLOGICAL DECISIONS

LCA

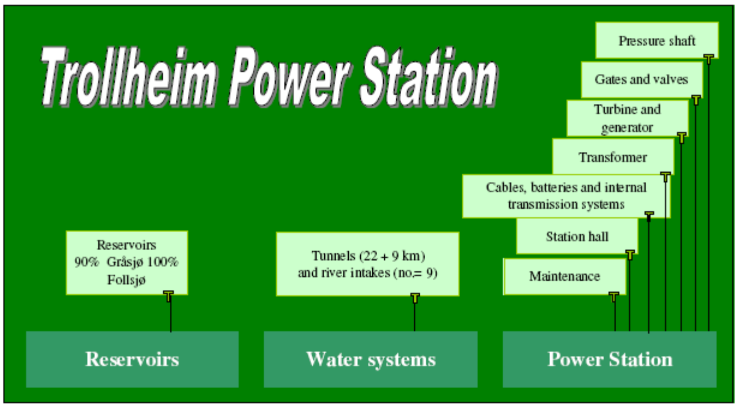


Figure 4. System boundaries for Trollheim Power Station.

Functional Unit: 1 kWh electricity, based on hydroelectricity produced at Trollheim Power Station.

System boundaries: The total contribution to environmental impacts for electricity delivered to the net. Construction, maintenance and operation of the power station, including manufacture and transport of production equipment.

The lifetime for Trollheim power station is assumed to be 60 years. It is unlikely that the power station will be demolished after 60 years. Normally, a power station is upgraded and will therefore begin a new lifetime of 60 years. Treatment of materials arising from demolition of the facility is therefore not included. The declaration is based on data from Trollheim Power Station [1], [7].

Over 99 % of the mass dealt with in the study comes from the removal of stone. Both the amount of stone and other materials included in the facility are based upon site specific data provided by Statkraft and the relevant suppliers. Where site specific data was unavailable estimates and assumptions have been used [2]. These are mainly associated with production of raw materials for equipment, generic data for energy consumption for transport/construction machines and data for maintenance.

The system boundaries were set at the power station's outer wall (except for the ExternE assessment), as it is difficult to assess the power station's share of the distribution net. Different customers will also be connected to different parts of the net. It is thus be more suitable for the customer to use one declaration for the electricity and another for the relevant distribution system.

Allocation rules: The raw materials and production processes are included for virgin materials. The recycling processes are included for recycled materials. The environmental impacts from Gråsjø reservoir are allocated between Gråsjø and Trollheim power station based upon the average production for these two power stations.

ExternE: In relation to the LCA study, the system boundaries here have been extended to include new power transmission lines from the power station to the main grid, since this is considered specific to this power plant. The total impact profile has been compared with similar profiles for the seven diversion projects in the Sauda development, where the environmental costs of the impacts have been estimated in the Norwegian implementation of the ExternE methodology. For a description of the damage function approach used in the EU-project ExternE (Externalities of Energy), see http://externe.jrc.es/. The results from the Norwegian implementation of the ExternE methodology for Sauda is reported at http://externe.jrc.es/Norway+Introduction.htm, and summarized in Navrud [4], [5]. Two different methods were used for transferring environmental damage cost estimates (benefit transfer techniques) from the Sauda project to Trollheim, i.e. unit value transfer from the basis project (Sauda) *with* and *without* adjustments for differences in burdens.

OTHER INFORMATION

Statkraft SF is, today, a purely hydropower based company, but they will also produce wind power starting in the autumn, 2002. Statkraft is working towards the development of new, renewable energy sources and energy carriers and is actively conducting research activities in areas such as energy from salt gradients and hydrogen based systems. Statkraft's vision is to be a leading company in Europe within the field of environmentally friendly energy.

REFERENCES

[1] ·Vold, M., Askham, C. and Borchsenius, C.-H.:*Life Cycle Inventory of Norwegian Hydroelectricity produced and distributed in Norway*, Østfold Research Foundation, OR 58.98 Norway, January 1999.

[2] ·Hanssen, O.J.; Stranddorf, H.K.; Vold, M.; Solèr, C.; Hoffman, L.; Tillman, A.M.; *"Nordic co-ordinating system for environmental product declaration (type III)"*, ISBN: 82-7520-425-9, Østfold Research Foundation, Norway, Juli 2001.

[3] ·ISO 14040-14043, 14025.

[4] ·ENCO 2001: *En sammenligning av norsk vannkraft med andre energibærere. Trinn 1 – Miljøkostnader av norsk vannkraft (A comparison of Norwegian hydropower with other energy sources. Step 1 – Environmental Costs of Norwegian hydropower)*. In Norwegian. M. Vågnes (ed.), S. Navrud, J. Riise og A. Tvede, ENCO Environmental Consultants a.s. EBL Kompetanse, Oslo, Publication no. 27 – 2001;

[5] ·Navrud, S. 2001: *Environmental Costs of Hydro Compared with Other Energy Options. International Journal of Hydropower and Dams*, Issue 2, 2001; 44-48., *IEA Technical Report 2000.*

[6] ·Navrud, S; *"Miljøvaredeklarasjon - Type III, Trollheim kraftverkt, Statkraft SF, Tilleggsinformasjon basert på ExternE metodikken."* (Environmental Product Declaration – Type III, Trollheim Power Station, Statkraft SF, Additional information based upon the ExternE method), Memo, 22. 05.2002

[7] ·Vold, M. og Nyland, C.A: *"Dokumentasjon av data, metodiske problemstillinger og svakheter, Miljøvaredeklarasjon type III, Trollheim" (Documentation of data, methodological problems and weaknesses, Environmental Product Declaration Type III, Trollheim),* Stiftelsen Østfoldforskning, Østfold Research Foundation, Norway, AR.01.02, juni 2002.

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