ENVIRONMENTAL EVALUATION OF CCS USING LIFE CYCLE ASSESSMENT (LCA)

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ENVIRONMENTAL EVALUATION OF CCS USING LIFE CYCLE ASSESSMENT (LCA)

Introduction

The most comprehensive way of evaluating the environmental consequences of CCS is to carry out a full Life Cycle Analysis. Such studies are detailed and time consuming as well as often being quite project and location specific. A number of LCA based studies have been carried out and hence to gain a better understanding of the findings the Jülich Research Institute was engaged to perform a survey of the relevant literature, draw some general conclusions and indicate what the focus of further studies in this area should be.

Summary of findings

The study identified 34 key references and of these 14 represented significant LCA studies of CCS. These were examined in detail in order to compare, scopes, methods and outcomes all of which are presented in written, tabular and graphical form in the detailed report. In terms of scope of coverage most studies concentrate on the capture element of the system, tending to treat transport and storage in less depth and in a more generic way. This probably reflects the uncertainty about locations of future storage site and hence also the routes from the capture plants to them. Also notable was that the majority of studies concentrated on coal fired plant, predominantly using post combustion capture so that comparisons with pre and particularly oxy combustion are very limited at present. Significant variations on the source and type of coal and how this might change during a projects lifetime is evident which makes comparison even of studies using similar processes difficult. The global warming potential and other impacts associated with fuel extraction are strongly influenced by the efficiency of the CCS plant and the study showed that there was a rather wide variation in assumptions about what efficiencies would be even amongst very similar processes.

A key component of any LCA study is the selection of the environmental impact categories which are considered. The table below gives an overview of which of the 14 commonly used indicators were considered in the studies examined. The last, 15th column, shows where authors have used an aggregated indicator which is synthesised by weighting some or all of the other impact categories. As can be seen all studies calculate the global warming potential (GWP)for the full life cycle and many also look at Acidification potential – basically related to sulphur dioxide emissions and Eutrophication potential – related to nitrogen oxide emissions. Other prominent indicators used are the photochemical oxidation potential and the total energy demand. There are a number of toxicity indicators covering humans, and different parts of the ecosystem some of which have been used in a few studies. However full assessments in these categories requires very detailed knowledge and documentation of release paths and toxicity effects through the full life cycle of a material and its breakdown products and this information is not all available and is very time consuming to assemble.

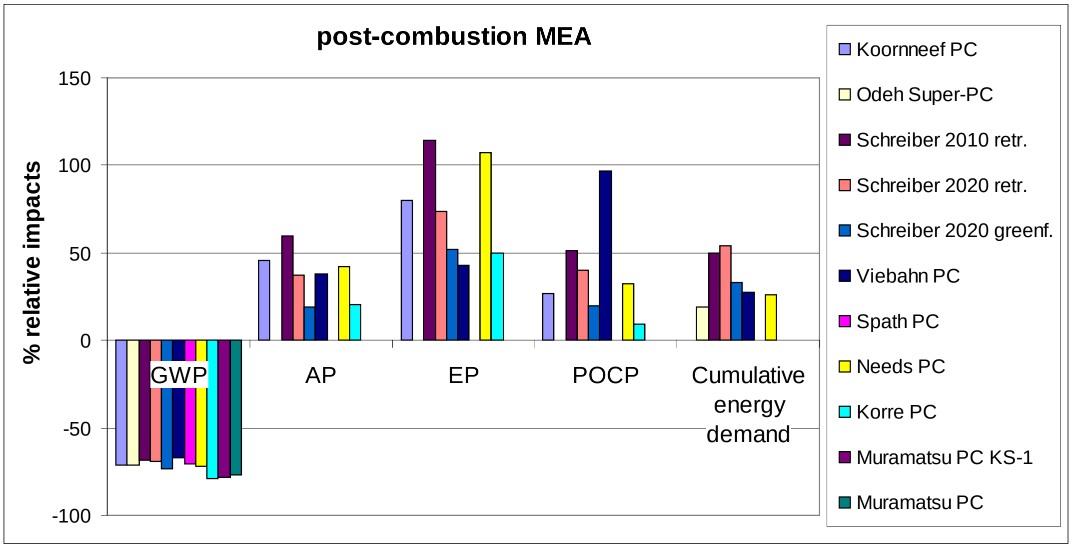
A key observation is that while GWP is by its nature a global impact, most other categories have only regional or local impact so that the outcome of studies can be very location dependent. Thus it is unlikely that LCA can be used to identify the best generic choice of capture technology, rather it will provide a good tool for making local and regional decisions and choices.

Study/Year	**GWP**	**AP**	**EP**	**POCP**	**ODP**	**HTP**	**FAETP**	**MAETP**	**TEP**	**CED / ADP**	**PM 10**	**LU**	**WU**	**W**	**AI**
Doctor/2001	x	x	x	x		x			x	x	x	x	x		
IEA/2006	x	x	x	x	x	x	x		x	x					
Khoo/2006	x	x	x			x	x	x	x	x				x	x
Koornneef/2008	x	x	x	x	x	x	x	x	x	x					
Korree/2009	x	x	x	x		x	x			x					
Lombardi/2003	x														
Modahl/2009	x	x	x	x						x					x
Muramatsu/2002	x														
NEEDS/2008	x	x	x	x						x		x	x		x
Odeh/2008	x									x					
Pehnt/2008	x	x	x	x		x				x					
Schreiber/2009	x	x	x	x	x	x				x					
Spath/2004	x									x					
Viebahn/2007	x	x	x	x						x	x				x

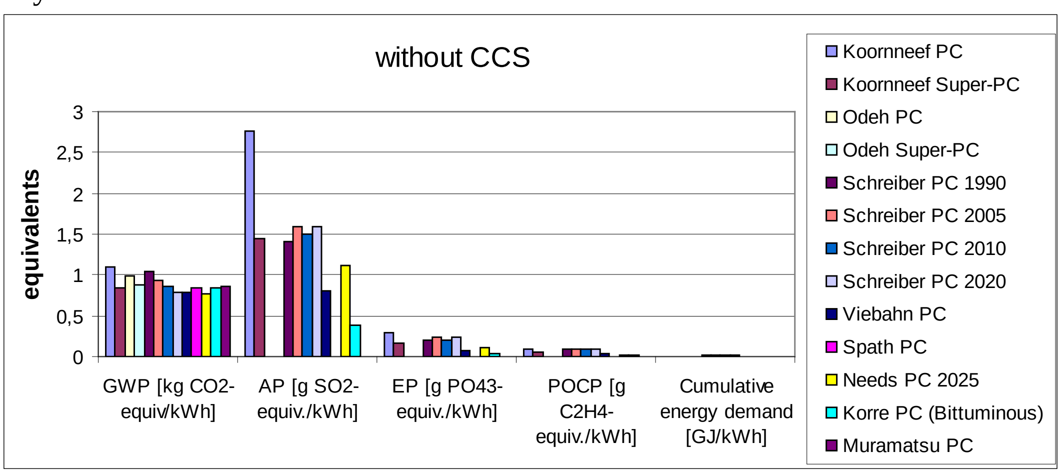
GWP Global Warming Potential, AP Acidification Potential, EP Eutrophication Potential, POCP Photochemical Oxidation Potential, ODP Ozone Depletion Potential, HTP Human Toxicity Potential, FAETP Fresh Water Aquatic Ecotoxicity Potential, MAETP Marine Aquatic Ecotoxicity Potential, TEP Terrestrial Ecotoxicity Potential, CED Cumulative Energy Demand, ADP Abiotic Depletion Potential, PM 10 Particulate Matter Equivalent, LU Land Use, WU Water Use, W Waste, AI Aggregated Indicator

The most notable outcome of the LCA studies is that in almost all cases in comparison with a baseline of no capture, all categories (except of course GWP) are increased by CCS. This is a somewhat surprising conclusion given that capture plant will significantly clean up flue gases. Examining the underlying reasons for this reveals that extraction and transport of coal and production of sorbant chemicals are responsible. The former effect is caused by the reduction in efficiency which demands more fuel which most researchers consider to be transported by ships burning very low quality bunker fuel. The marginal improvements in sulphur emissions at the capture plant are more than offset by increased sulphur emissions from the ships which apply no sulphur capture. An example of a graphical summary is shown below in which the impact effects in 5 main categories from 11 studies which considered coal fired capture using post combustion are compared. Depending on what weighting is given to the various categories the aggregate effect of CCS could be considered as either positive or negative.

This chart shows the relative impact for hard coal fired CCS plants using MEA based post combustion capture as compared to the baseline impacts shown in the chart below it.



Below are the base line impacts. Notice that there are agreed markers for these impact categories, AP is based on SO_2, EP in phosphate, POCP on ethylene. Toxic categories are usually related to 1-4 dichorobenzene.



A number of issues relating to LCA of CCS systems emerge as a result of this work. It is important to improve the benchmarking used in LCA,s. Even if the specific project under study has local variations it will be of great help in making comparisons if benchmark values for efficiencies and coal type were established for the industry. The report further proposes that many more LCA studies need to be done to get a clearer picture of the true impacts of CCS and also to extend it to a wider variety of processes and situations. It is inevitable that probing questions will be asked about the life cycle impacts of CCS and that these will be compared closely with other technologies, particularly renewable energy. It is thus important that the data needed to complete full LCA's considering all impacts is generated. In the field of toxicity this may be a considerable task.

A full LCA needs to consider the full set of "upstream" and "downstream" processes, for example if a chemical is consumed the impact of its production and that of the inputs which go in to its production, delivery and disposal. The report identifies that the extent to which these processes are analysed is variable and recommends that greater depth of analysis is needed in future studies.

Seepage of CO2 from storage is an issue which some have addressed by considering fixed percentage losses per year. This is not necessarily a very helpful way of approaching seepage since such a linear leakage rate is not realistic even though it does have some value as a simplistic way of exploring sensitivities. Acceptance of a more realistic leakage model based on such things as most sites having zero leakage, there always being a percentage of permanent trapping would be more representative.
An issue raised as a result of consideration of leakage is the time span for the LCA and the lifetime of CO2 in the atmosphere. It is not usual to have to consider time spans of thousands of years in LCA but if leakage is to be considered this becomes a requirement at least in the GWP category. CO2, unlike most other substances considered in LCA, does not have a defined lifetime in the environment, nor is it likely that one can be determined. Some consensus on how to tackle this issue is needed.

Another important issue which could serve to greatly simplify LCA for CCS is to determine whether all of the many impact categories, particularly the toxicity indicators, are really relevant. If studies can show that some have at most a minor impact it may be possible to discount these and concentrate on the important ones. However there are effects of CCS which do not appear to be well represented in the current suite of standard impacts. The effects of displacement of reservoir fluids are not covered and the effects of seepage on the marine sediment environment may be an area needing more attention.

Conclusion and Recommendations

This is a useful synthesis report which can serve as starting point for a more ordered approach to applying LCA to Carbon Dioxide Capture and Storage. Execution of a full LCA is a time-consuming and expensive undertaking and as such is beyond the budget of the programme. At the same time it is clear that the results of LCA could play a critical role in the decisions which are made on CCS and hence the programme should play a part in ensuring that the necessary unbiased information is made available in a timely manner. The report highlights the need for improved consistency between studies and suggests some specific areas such as generation efficiency and capture efficiency where wide variations in assumptions are affecting results. The programme could consider playing a role in setting up some reference points to allow benchmarking and hence proper comparison of LCA studies. Another area in which work could be done is in defining the environmental effects which are important to include in the scope of a CCS LCA and perhaps to suggest some standard way of making an aggregated comparison.

The report has highlighted that transport and mining emissions are much more prominent than hitherto realised and this is an area which the programme could address in more detail. However the control of emissions from international shipping is an area fraught with complications. At the very least the programme could attempt to set out the facts, indicate the technologies which might be applied and any emission accounting implications.

Another service which the programme could consider is to develop and maintain a database of CCS LCA studies and their results. This would best be done by contracting to a recognised leader in LCA. The existence of a central point for comparison could help to bring a more ordered approach as further studies are undertaken.

Synthesis report of environmental evaluation of CCS using Life Cycle Assessment (LCA)

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Executive Summary

In the last years several studies have investigated carbon capture and storage (CCS) from a life cycle perspective focussing on the environmental performance. Scope of this study is to compare systematically the different approaches of fifteen studies, to summarise the results, show the site specific differences, address methodological variations and formulate guidelines to assign the various conclusions gathered from the studies.

CCS is a wide field with various technological options. In almost all studies the main focus is set on the capture technology, while transportation and storage is less sophisticatedly investigated. All studies show the expected reduction in GWP but an increase in all other impact categories, regardless of capture technology and the fuel considered. Three parameter sets have been identified, which have a significant impact on the results. First there is the development of plant efficiencies and energy penalties connected with the capture process. Another group of parameters which is hardly considered so far is related to the capture efficiency and the purity of the CO_2. The third parameter set with a very high impact on the results is the fuel composition. As most studies consider different fuel compositions a comparison of technologies becomes unfeasible.

Although there are still big differences in the underlying assumptions of the studies and also some methodological shortcomings, LCA has proved to be a helpful tool to investigate the environmental consequences connected with the introduction of CCS. It also helps to identify research fields and development targets. Nevertheless, the number of existing studies is not sufficient to give a comprehensive picture and there is still a wide field of subjects and technologies which have not been covered yet.

Keywords

Carbon capture and storage, life cycle assessment, methodology approach, technology evaluation, study comparison

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Abbreviations:

ADP	Abiotic Depletion Potential
AI	Aggregated Indicator
AP	Acidification Potential
CED	Cumulative Energy Demand
CCS	Carbon Capture and Storage
CML	Institute of Environmental Sciences of the Faculty of Science of Leiden University
ECBM	Enhanced coal bed methane recovery
EDIP	Environmental Design of Industrial Products
EGR	Enhanced Gas Recovery
EI`99	Ecoindicator 99
EOR	Enhanced Oil recovery
EP	Eutrophication Potential
EPS	Environmental Priority Strategies in product design
FAETP	Fresh Water Aquatic Ecotoxicity Potential
GWP	Global Warming Potential
HTP	Human Toxicity Potential
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organisation
KS-1	Sterically hindered amine
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LU	Land Use
MAETP	Marine Aquatic Ecotoxicity Potential
MEA	Monoethanolamine
NGCC	Natural Gas Combined Cycle
ODP	Ozone Depletion Potential
PC	Pulverised Coal Combustion
PM 10	Particulate Matter Equivalent
POCP	Photochemical Oxidation Potential
SETAC	Society for Environmental Toxicology and Chemistry
TEP	Terrestrial Ecotoxicity Potential
W	Waste
WU	Water Use

1 Introduction

Carbon capture and storage (CCS) is gaining increasing importance and is being regarded as one option to mitigate CO_2 in order to protect our climate. While CO_2 capturing reduces direct CO_2 emissions from the power plant itself, upstream emissions resulting from additional fuel and material supply and downstream emissions resulting from waste disposal and waste water treatment are usually not captured. Therefore, a life cycle approach is required to provide an adequate method for a comprehensive evaluation of environmental effects of the new technology route. This includes also other environmental impacts, beside the reduction of CO_2.

In the mid 1990s IEA GHG undertook a life cycle analysis of selected power plants with CCS as part of its “Full Fuel Cycle study” [IEA 1994]. In this study full fuel cycle costs were assessed integrating external costs arising from the impact of the fuel cycle on the natural and human environment. Therefore, emissions had to be assigned to impacts and external costs, respectively. Since then, the CCS technology has developed further and new CCS technology routes have been developed. Moreover, since the mid 1990s, the methodology of Life Cycle Assessment (LCA) has been advanced to address the environmental aspects and potential impacts throughout the life cycle of a product or a technique from raw material acquisition through production, use, end-of-life treatment and disposal (ISO 14040/14044 2006). Thereby, LCA focuses on the environmental aspects considering greenhouse gas emissions, but also amongst others, effects such as acidification potential, eutrophication potential, ozone depletion potential, human toxicity potential, or resource use.

Since the IEA study, several other studies have addressed the environmental consequences associated with the introduction of CCS beyond CO_2 reduction in the power plant using LCA as a tool. The goal of this report is to evaluate those studies on CCS for power production with focus on LCA. Although several studies consider the same CCS technologies, the comparability of the studies and corresponding results appears questionable. Hence, the scope of this study is to compare systematically the different approaches, to summarise the results, show the site specific differences, address methodological variations and formulate guidelines to assign the various conclusions gathered from the studies.

2 Selected studies

The number of studies considering environmental impacts caused by the introduction of CCS is constantly rising. Following the IEA GHG study from 1994 this report considers only studies which have been undertaken after 2000. Furthermore, this study excludes CCS studies dealing with enhanced oil and gas recovery (EOR, EGR) to maintain comparability. While the primary purpose of EOR and EGR is to improve the recovery rate and has its own requirements for the CO_2 stream, the reason for CCS in other applications is to improve the environmental performance of fossil fuelled power production. The evaluated studies can roughly be arranged into four groups.

I. LCAs of CCS

The first group comprises studies using LCA to evaluate the environmental impacts of CCS in power generation processes. For this analysis, these studies are the most interesting ones.

I.-1. Carpentieri, M.; Corti, A.; Lombardi, L. 2005: Life cycle assessment of an integrated biomass gasification combined cycle (IBGCC) with CO_2 removal.

I.-2. Corti, A. and Lombardi, L. 2004: Biomass integrated gasification combines cycle with reduced CO_2 emissions: Performance analysis and life cycle assessment (LCA).

I.-3. D'Addario, E.; Clerici, G.; Musicanti, M.; Pulvirenti, G.; Serenellini, S. and Valdiserri, M.G. 2003: Environmental Analysis of different options of CO_2 capture in power generation from natural gas. cited as **[D'Addario/2003]**

I.-4. Doctor, R.D.; Molburg, J. C.; Brockmeier, N. F.; Lynn, M.; Victor, G.; Massood, R. and Gary, J. S. 2001: Life-Cycle Analysis of a Shell Gasification-Based Multi-Product System with CO_2 Recovery. cited as **[Doctor/2001]**

I.-5. IEA Greenhouse Gas R&D Programme (IEA GHG) 2006: Environmental Impact of Solvent Scrubbing of CO_2. cited as **[IEA/2006]**

I.-6. Khoo, H. H. 2006a: Life cycle evaluation of CO_2 recovery and mineral sequestration alternatives.

I.-7. Khoo, H. H. 2006b: Life cycle investigation of CO_2 recovery and sequestration. cited as **[Khoo/2006]**

I.-8. Koornneef, J.; van Keulen, T.; Faaij, A.; Turkenburg, W. 2008: Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO_2. cited as **[Koornneef/2008]**

I.-9. **Korre, A.; Nie, Z.; Durucan, S.**: Life cycle modelling of fossil fuel power generation with post combustion. cited as **[Korre/2009]**

I.-10. **Lombardi L. 2003**: Life cycle assessment comparison of technical solutions for CO_2 emission reduction in power generation. cited as **[Lombardi/2003]**

I.-11. Markewitz, P.; Schreiber, A.; Vögele, S.; Zapp, P. 2009: Environmental impacts of a German CCS strategy.

I.-12. **Modahl, I.S.; Nyland, C.A.; Raadal, H.L.; Karstad, O.; Torp, T.A.; Hagemann, R. 2009**: LCA as an ecodesign tool for production of electricity, including carbon capture and storage – a study of a gas power plant case with post-combustion CO_2 capture at Tjeldbergodden. cited as **[Mordahl/2009]**

I.-13. **Muramatsu, E. and Iijima, M. 2002**: Life cycle assessment for CO_2 capture technology from exhaust gas of coal power plant. cited as **[Muramatsu/2002]**

I.-14. **NEEDS 2009: Bauer, C.; Heck, T.; Dones, R.; Mayer-Spohn, O.; Blesl, M. NEEDS (New Energy Externalities Developments for Sustainability)**: Final report on technical data, costs, and life cycle inventories of advanced fossil power generation systems. cited as **[Needs/2008]**

I.-15. **Odeh, N. A. and Cockerill, T. T. 2008**: Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage. cited as **[Odeh/2008]**

I.-16. **Pehnt, M. and Henkel, J. 2008**: Life cycle assessment of carbon dioxide capture and storage from lignite power plants. cited as **[Pehnt/2008]**

I.-17. Schreiber, A.; Zapp, P.; Kuckshinrichs, W. 2009a: Environmental Assessment of German Electricity Production from Coal-fired Power Plants with Amine-based Carbon Capture.

I.-18. **Schreiber, A.; Markewitz, P., Zapp, P. and Vögele, S. 2009b**: Environmental Analysis of a German Strategy for Carbon Capture and Storage in Coal Power Plants. cited as **[Schreiber/2009]**

I.-19. **Spath, P. and Mann, M. 2004**: Biomass power and conventional fossil systems with and without CO_2 sequestration comparing the energy balance, greenhouse gas emissions and economics. cited as **[Spath/2004]**

I.-20. **Viebahn, P.; Nitsch, J.; Fischedick, M.; Esken, A.; Pastowski, A.; Schuwer, D.; Supersberger, N.; Bandi, A.; Zuberbuhler, U.; Edenhofer, O. 2007a**: RECCS Strukturell-ökonomisch-ökologischer Vergleich regenerativer Energietechnologien (RE) mit Carbon Capture and Storage (CCS). cited as **[Viebahn/2007]**

I.-21. Viebahn, P.; Nitsch, J.; Fischedick, M.; Esken, A.; Schuwer, D.; Supersberger, N.; Zuberbuhler, U.; Edenhofer, O. 2007b: Comparison of carbon capture and storage with renewable energy technologies regarding structural, economic, and ecological aspects in Germany.

I.-22. Wildbolz, C. 2007: Life cycle assessment of selected technologies for CO_2 transport and sequestration.

II. LCA of energy systems without CCS

The second group contains studies using LCA to evaluate the environmental impacts of other energy technologies without CCS. These studies provide a basis and serve as comparing systems.

II.-1. IEA Clean Coal Centre 2005 (Mills, S.): Coal full life cycle analysis

II.-2. Dones R., Faist M., Frischknecht R., Heck T. and Jungbluth N. 2007: Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries.

III. CCS without LCA

The third group includes studies describing technical, economical and/or environmental parameters of power plants with CCS. These studies serve as comprehensive data basis for many LCA studies.

III.-1. Göttlicher, G. 1999: Energetik der Kohlendioxidrückhaltung in Kraftwerken.

III.-2. IEA Greenhouse Gas R&D Programme 1994: Full fuel Cycle Study on Power Generation Schemes Incorporating the Capture and Disposal of Carbon Dioxide. ETSU

III.-3. IEA Greenhouse Gas R&D Programme 2007 (Adams, D. & Davison, J.): Capturing CO_2.

III.-4. IPCC (Intergovernmental Panel on Climate Change) 2005: IPCC Special Report on Carbon Dioxide Capture and Storage.

III.-5. Khoo, H. H. & Tan, R. B. H. 2006: Environmental Impact Evaluation of Conventional Fossil Fuel Production and Enhanced Resource Recovery with Potential CO_2 Sequestration.

III.-6. OECD/IEA 2008: CO_2 Capture and Storage: A Key Carbon Abatement Option.

III.-7. Rao, A. B. and Rubin, E. S. 2002: A technical, economic, and environmental assessment of amine-based CO_2 capture technology for power plant greenhouse gas control.

III.-8. Rubin, E. S., Chen, C.; Rao, A. B. 2007: Cost and performance of fossil fuel power plants with CO_2 capture and storage.

III.-9. Thitakamol, B.; Veawab, A.; Aroonwilas, A. 2007: Environmental impacts of absorption-based CO_2 capture unit from post-combustion treatment of flue gas from coal-fired power plant.

III.-10. Tzimas, E.; Mercier, A.; Cormos, C.; Peteves, S. D. 2007: Trade-off in emissions of acid gas pollutants and of carbon dioxide in fossil fuel power plants with carbon capture.

IV. Overview Reports on LCA and CCS

This report compares existing studies concerning Life Cycle analysis of power plants with CCS techniques.

IV.-1. Holloway S.; Rowley, W.J. 2008: Environmental Sustainability of Electricity Generation Systems with carbon dioxide capture and storage.

IV.-2. IEA Greenhouse Gas R&D Programme 2007 (Vendrig, M.; Purcell, M.; Melia, K.; Archer, R.; Harris, P.; Flach, T.): Environmental Assessment for CO_2 capture and storage.

3 Comparison systematic of the selected studies

When attempting to compare competing energy technologies using LCA, a thorough understanding of each system and its boundaries is required. A comparison can only be made if the same assumptions regarding system boundaries and generic data are used.

Additionally, LCA as the pre-eminent tool for estimating environmental effects, despite its popularity and codification by organizations such as the International Organization for Standards (ISO) and the Society of Environmental Toxicology and Chemistry (SETAC), is still in need of improvement. The relatively wide range of approved performance possibilities and methodological shortcomings make a close investigation of the studies and their comparability necessary.

Several studies have already focused on this matter, some of which with a wider more general scope [Reap 2008a, b; Guinée 2002], others with focus on energy systems [IEA 2005, (Mills)] and some already in the context of CCS [Holloway 2008]. Many aspects of the general or energy system specific argumentation hold also for the CCS subject.

In the next section a systematic classification is made. A rough division into technology driven and LCA methodology driven analysis is established.

3.1 Technology driven differentiation

The different studies vary in the CCS technologies which are analysed. Some studies compare different CCS technologies against each other, while other studies concentrate on one specific CCS technology and/or compare CCS routes against alternative new technologies such as energy or hydrogen production by renewable energy sources, respectively.

3.1.1 Capture technology

The three technology routes for the capture process, post-combustion, oxyfuel and pre-combustion constitute the first differentiation criteria of the studies. While post-combustion is chosen most often as the investigated system, the other two technology routes are analyzed less often, oxyfuel technology is studied least. Additionally, post-combustion technology is not one specific technology, but encompasses a variety of techniques where CO_2 is captured after the combustion process. MEA scrubbing is the most mature post-combustion technology, some data are already available and thus the majority of studies focus on this technology.

Secondly, the energy source, natural gas or coal (hard coal, bituminous coal, lignite), differs in the studies. In combination with the different capture routes and different capture technologies this results in a differentiation into more than 50 possible concepts. Only very few have been covered by LCA studies so far.

As CCS is a future technology, the technological representation varies considerably. The estimated process performance figures sometimes represent bench-scale, sometimes full-scale commercial plants for other applications. No common understanding of future efficiency development for commercial power production exists, let alone of energy penalties due to capture. Table 3-1 summaries net efficiencies for different capture technologies from the 2007 IEA GHG CO_2 capture report [IEA 2007].

Fuel	**Power Generation Technology**	**CO_2 Capture Technology**	**Net Efficiency % (LHV)**
Coal	Pulverised fuel	None	44.0
		Post-combustion	35.3
		Oxy-combustion	35.4
	IGCC, dry feed	None	43.1
		Pre-combustion	34.5
	IGCC, slurry feed	None	38.0
		Pre-combustion	31.5
Gas	Gas turbine combined cycle	None	55.6
		Post-combustion	49.6
		Oxy-combustion	44.7

Table 3-1: Power plant thermal efficiencies [IEA 2007]

Some Life Cycle Inventory (LCI) data, such as efficiency of power conversion are based on detailed process performance information from commercial scale operations, while others such as capture process performance can only be based on limited information or assumptions. If available at all data can only be extrapolated by up scaling from the performance of pilot or demonstration plants.

3.1.2 Transport and storage

After capture the CO_2 must be stored. Capture and storage sites will not generally be in the same location thus transport has also to be included in the investigation. However, many studies place most emphasis on the capture technology. Although, only limited information on CO_2 transport, injection and storage is available, many studies additionally include CO_2 transport (almost all via pipeline). Also, several studies consider data for CO_2 injection and storage (mostly on-shore). The variety of transport systems (e.g. pipeline, ship) and storage options (e.g. depleted oil or gas fields, saline aquifer, and ocean) in combination with the different capture routes and capture technologies further diversifies the systems.

One study [Wildbolz 2007] investigates transport and storage exclusively, taking data for the capture process from other studies and analysing different transport and storage options in more detail.

Especially for transport and storage, site specific information is necessary, which confirms the uniqueness of each study on this element of CCS. Only generic studies have been performed so far with indicative descriptions of the technology employed.

3.2 LCA methodology driven differentiation

Life Cycle Assessment is framed to address the environmental aspects throughout the entire life cycle of a technology or a product. The LCA procedure was harmonized and revised in an international standard ISO 14040/14044 in 2006, being a four step approach compromising (1) goal and scope definition, (2) inventory assessment, (3) impact assessment and (4) interpretation [ISO 2006].

The goal and scope definition identifies the intention of the study and therefore describes the spatial and technical system boundaries of the system under investigation. Typical parameters addressed are the functional unit, the time horizon, the region, the inclusion and origin of upstream and downstream processes, and the impact categories considered.

A core element of every LCA is the inventory. Within the inventory analysis (LCI) the data related to the system being investigated are gathered. It describes the system by its inputs from and outputs to the environment quantified and calculated in a model. The main outcome is an inventory table of the inputs and outputs, which is then either used to carry out the impact assessment or interpreted in itself according to the goal and scope.

Life cycle impact assessment (LCIA) converts inventory data into environmental impact estimates. The mandatory elements for a LCIA involve the selection of impact categories, category indicators and models, the assignment of LCI results to the impact category (classification), and the calculation of category indicator results (characterisation).

In the interpretation analysis the results (of either LCI or full LCA) and all choices and assumptions made during the analysis are evaluated in terms of soundness and robustness. Finally, overall conclusions are drawn and recommendations are given considering the goal and scope of the study.

Although the standard defines the procedure of an LCA, the margin of flexibility in how to perform an LCA is still wide. Some choices will have a high impact on the overall results.

Most studies have different goals and scopes and consequently yield different results. It is important to interpret the results in combination with the defined goal and scope. In the following typical methodological aspects are described. They might be CCS specific or general LCA shortcomings.

Decisions during goal and scope definition such as functional unit, system boundaries or time and spatial coverage are pivotal. Their partial dependence on study goals limits the capacity to generate solutions purely via scientific and technical consensus building. However, their strong influence on a study's outcome makes the inaccuracies introduced by an inappropriate decision high. It might, therefore, be more appropriate to think of this issue as one of "problematic decisions".

3.2.1 Functional unit

The functional unit quantifies the performance of a product system for use as a reference unit in a life cycle assessment study. Its purpose is to provide a reference to which the inputs and outputs are related and to ensure comparability of LCA results [ISO 2006]. For an electricity production process the functional unit typically is 1 kWh of net electricity produced.

Looking at CCS a second product created in power plants is CO_2. Although CO_2 is regarded as a waste product which has to be stored, the gas is produced in different qualities, purities and pressures by the different capture systems. These different characteristics of CO_2 have an impact on energy penalty and therewith on emissions produced. This should be kept in mind by comparing apparently equal systems.

In some regions CO_2 is even regarded officially as a product with an economic value according to CO_2 emission allowances or CO_2 tax systems. As yet no study (but one, see section 4.2.1) allocates CO_2.as the functional unit.

Additionally, for CCS systems the co-production of other products beside electricity is possible. For example in a pre-combustion system hydrogen might be a product. Elemental sulphur is another possible product. In a different operation mode of the air separation unit in the oxyfuel process nitrogen could be produced at pressure or as a liquid as a saleable product. In a multi-product system the environmental burdens have to be allocated appropriately.

This allocation problem has the distinction of being called one of the most controversial issues of LCA. The ISO standard provides a three step approach: (1) avoiding allocation by system expansion or dividing the unit process, (2) allocation based on physical relationships or (3) allocation on basis of other relationships (e.g. prices). Whatever procedure is chosen, it will have a huge impact on the results.

3.2.2 Data quality and availability

One of the most common shortcomings in LCA is the quality of input data. The existence and easy availability of comprehensive databases are clearly important, although all modules or unit processes are unlikely to be available for the particular system being addressed. This is especially true for complex or future systems. In order for LCA to be accepted widely, specific and well-researched data are required to establish the fundamental environmental impacts of even the basic raw materials.

Standardised databases of LCA data are sought to reduce the burdens of data collection. Some data, such as those covering current energy, transport and key raw materials, are now more easily available across many systems, as well as treatment and waste disposal models. Nevertheless, future data are often rare and based on assumptions that are unlikely to be unique for all data sources. Inevitably, some data will be characterised by a greater degree of uncertainty and this must be taken into account when interpreting the results.

With regard to specific requirements encountered when examining power generation cycles, some types of data may be more easily accessible than others. For instance, the data required to address many greenhouse gas emissions and acid rain precursors have now been relatively firmly established and are generally accepted in inventory data collection work. In contrast, for example, where photochemical smog is concerned, it may prove necessary that a particular range of VOCs is specified; the alternative may be the necessity of accepting considerable uncertainty [IEA 2005, (Mills)].

Where available, external data can be of unknown quality. When data is not measured by the LCA practitioner, the accuracy, reliability, collection method, and frequency of measurement may not be known and the limitations of the data cannot necessarily be deduced. Specific attention must be paid when the results are dominated by data from upstream and downstream processes, which are most often not so well known and which quality are poor due to higher generalisation of system boundaries.

3.2.3 Time horizon

Another point of interest will be the time horizon and the associated state of the technology. This has an impact on the future technical parameters which are selected for CCS but also those selected for competing technologies. In the IEA GHG CO_2 capture and storage report from 2008 [IEA 2008] several process parameters for capture processes are listed dependent on the time window being considered (see Table 3-2).

year	1995	2005	2015 and later
Chemical Absorption			
Thermal energy	4.2 GJ/t CO_2	3.2 GJ/t CO_2	2.0 GJ/t CO_2
Power equivalent	0.292 kWh/kg CO_2	0.178 kWh/kg CO_2	0.083 kWh/kg CO_2
Electrical equivalence factor	0.25	0.20	0.15
Power for capture	0.040 kWh/kg CO_2	0.020 kWh/kg CO_2	0.010 kWh/kg CO_2
Power for CO_2 compression	0.114 kWh/kg CO_2	0.108 kWh/kg CO_2	0.103 kWh/kg CO_2
Total power used	0.446 kWh/kg CO_2	0.306 kWh/kg CO_2	0.196 kWh/kg CO_2
Oxyfuel processing			
Cryogenic air sep.		0.210 kWh/kg O_2	0.196 kWh/kg O_2
Membranes systems			0.147 kWh/kg O_2

Table 3-2: Process parameters for chemical absorption and oxygen production depending on time [IEA 2008]

In many studies which consider future systems (not only CCS related) the first-order processes (representing the final production processes) are extrapolated or projected into the described future. Second and third order processes (or background systems) are seldom adjusted in the same way. However, for some background systems (e.g. energy mix, waste treatment) change is likely and can have a considerable impact on the results.

Another methodological choice related to time occurs in the impact assessment. Global warming potentials (GWP) depend on the time horizon to which integration is performed. The International Panel on Climate Change (IPCC) has compiled a list of ‘provisional best estimates’ for GWPs with time horizons of 20, 100, and 500 years. This yields in different characterisation factors for different emissions. Although CO_2 is the major emission time horizon has a minor effect, because the CO_2 characterisation factor is always 1 kg equivalent for all time horizons. Nevertheless, studies for capture processes using different time horizons cannot be compared directly.

The choice of time horizon plays an important role evaluating the storage process and especially possible leakage. Even with a GWP based on 500 years, the long-term emissions are implicitly cut off. Comparison between short and long-term emissions is an open question in LCA methodology and especially relevant for CCS.

Beyond this it is not clear, how far the long-term CO_2 emissions will have a negative environmental effect in the remote future due to the highly insecure forecast e.g. about climate conditions as well as CO_2 buffer action of ocean and biosphere. However, the calculation of CO_2 lifetime as the balance between the rate of quite large removal and re-emission processes is not in the focus of the selected studies.

The selection of storage sites will also favour sites with no leakage, so only a certain percentage will leak at all and be probably abandoned quite early.

In discussion about weighting of short and long-term emissions against each other fundamental differences are observable in attitude and perspective of the people involved. Some people weight long time effects higher than short term, while others believe that long term environmental problems will be solved by technological developments. Some people mean that every possible effect should be taken into account seriously, while others are only engaged in scientifically proven issues. Hofstetter [Hofstetter 1998] picked up the different “types” of people and developed a very simplified characterisation of “archetypes” (Hierarchist, Individualist, Egalitarian) using different criteria in time perspective, manageability and required level of evidence, which are used in some LCA validation methods (e.g. Eco-indicator, see also 3.2.7).

3.2.4 Spatial representation

In the CCS chain especially the storage sites and their description are highly site specific. So it is questionable, if an average storage modulation, with average leakage is applicable at all. The site specific question of storage capacity is not explicitly addressed in LCA, but has to be kept in mind by setting up the scenario boundaries.

For transportation the processes can be described by average processes, with only distance parameters being site specific (as usual). In case of capture, the processes are described in a usual procedure. Nevertheless, it has to be kept in mind, that site specific regulation and legislation (e.g. environmental standards) might be considered in the technology description.

For second order processes many products are very site specific, such as the fuel supply/origin or electricity mix. This is not an explicit CCS issue, but has a high impact on study outcomes.

The environmental impacts contribute on different scales. Climate change and stratospheric ozone depletion are on a global scale, other impacts such as acidification or eutrophication have more regional or even local effects. The mechanism for global impact categories is the same world wide. Related to the geographical location the impacts for regionally or locally scaled emissions can vary widely, depending on the ecosystem sensitivity. The methodological framework for these emissions and their impacts is still under discussion. Based on previous studies which have produced country-dependent characterisation factors for acidification and terrestrial eutrophication, further efforts have been made recently to improve these characterisation factors [Seppälä 2006, Posch 2008]. Seppälä explored new site-dependent characterisation factors for European acidifying and eutrophying emissions based on accumulated exceedance (AE method) as an impact category indicator, which integrates both the exceeded area and the amount of exceedance. The risk of ecosystem damage for a country is quantified by the accumulated exceedance and is defined as the area-weighted sum of all critical load exceedance within the region (country). The study from Posch 2008 picks up the AE method and compares them with more simple methods (acidifying and eutrophying potentials alone, deposits from an atmospheric dispersion model). The key outcome is that there is no shortcut to achieve advanced characterisation factors of acidification and terrestrial eutrophication without atmospheric dispersion models and information on ecosystem sensitivity (critical loads). However, the current situation does not allow using the AE method outside of Europe due to the lack of suitable atmospheric dispersion models and measures of ecosystem sensitivity. For this reason, there is a need to improve information on ecological sensitivity in areas outside Europe (including sea areas) especially due to the increasing world trade (e.g. coal ships).

As yet the analysed studies in this report do not pick up this progress in the impact assessment. The noticeable enhanced effort and the lack of data might be the reason for that. However, when comparing different capture technologies different ecosystem aspects should be excluded to focus only on technological aspects. Otherwise the technological based differences could be obliterated.

If the best location for a technology is to be found site specific information is necessary, but then LCA is not always the best method to use. For example, Environmental Impact Assessment (EIA) or Risk Assessment (RA) are often more appropriate.

EIA is a procedural tool for evaluation local environmental impacts, which generally takes into account time-related aspects, the specific local geographic situation, and the existing background pressure on the environment. Besides quantifiable aspects, EIA also provides qualitative assessment of issues like landscape as well as archaeological and cultural aspects. Moreover, the participation of potentially affected people, the public and other stakeholders in the process are required.

RA is commonly used in assessing the environmental, health and safety related risks posed by chemicals, harmful substances, industrial plants, etc. The risks examined in the assessment can be physically (radiation), biologically (genetically modified organism), or chemically (toxic substances). In RA site-specific impact modelling is possible because RA is concerned with processes located at one or a limited number of sites. RA results are defined in time and therefore provide information concerning the timing of impacts, which is not possible with LCA [Jeswani 2010]. However, both methods can be used as complementary tools to get the whole picture. For example, data generated from Risk Assessment are useful in assessing toxicity, an impact category used in LCA.

LCA provides technically and environmentally based quantitative or qualitative information for a better informed decision-maker. In contrast to that the focus in the forecasting procedural frameworks like Environmental Impact Assessment (EIA), Strategic Environmental Assessment (SEA), Sustainability Assessment (SA) or Multi-Criteria Decision Analysis (MCDA) is to support the decision-making process. LCA is part of the assessment process. Therefore, combinations of LCA with some of the procedural frameworks can be used to provide a more comprehensive picture. For instance EIA can complement LCA by providing information on local, site-specific aspects and on the other hand LCA provides information on global impacts.

Although in principle LCA can inform decision-makers on environmental grounds, often they need additional information on other sustainability dimensions as well. In order to provide such information, it has been argued that there is a need to expand the ISO LCA framework by sustainability assessment. On the one hand it has been suggested a ‘‘deepening’’ of ISO 14044 guidance related to definition of system boundaries, allocation methods, dynamic aspects, scenario specifications, etc. On the other hand a second proposal is the ‘‘broadening’’ of ISO 14044 that means the integration of social and economic dimensions of sustainable development into LCA. Although the need and opportunities for broadening and deepening are numerous, it should also be kept in mind that the LCA method would be strongly stressed due to significantly more time and financial resources required. Since LCA is already a complex tool, more complexity could increase uncertainties and decrease acceptability [Jeswani 2010].

3.2.5 Upstream and downstream processes

System boundaries are selected in the Goal and Scope section of the study and define the relevant processes to be included or excluded from the LCA. This includes not only temporal and spatial coverage but also upstream and downstream processes. There is no clear cut answer as to where to set system boundaries and it is not always obvious what to include or exclude. It is always a balance between what makes completion of the assessment possible and the resources devoted to it.

The boundaries of the systems commonly encompass all processes between the fuel extraction (mining of the coal or production of the natural gas) and storage of the captured CO_2. However, some of the LCAs only consider subsets of this system such as power plants, i.e. they exclude upstream and downstream processes.

The share of the environmental impacts of upstream and downstream processes differs with respect to the impact category. Therefore, life cycle approaches are necessary to get a holistic evaluation of the whole system.

3.2.6 Impact categories

Another part of the LCA process of great influence is the assignment of the relevant inputs and outputs gathered in the inventory during the impact assessment. While the chemical/physical correlations of emissions and impacts are defined in the LCA standard, the selection of impact categories which have to be considered is left to one's own choice.

Serious data and model quality limitations arise, as there tend to be large discrepancies between a characterisation model and the corresponding environmental mechanism. For some impact categories there are several characterisation models and category indicators suggested. So it might be possible that studies, although addressing the same impact categories, cannot be compared directly, because they us different category indicators. To transform the results into the same indicator a detailed knowledge of all emissions is indispensible and mostly not available to an individual LCA practitioner.

After the classification and characterisation step the impact assessment should be completed by applying a normalisation step in order to gain a better understanding of the relative importance of an effect on the environment as a whole. Each effect calculated for the life cycle is benchmarked against the known **total** effect for this class, such as the total impacts of a specific region (e.g. world, Western Europe, specific country) and therefore translates abstract impact scores for every impact category into relative contributions to a reference system.

3.2.7 Operational Valuation/weighting methods

It is generally recognised that the valuation requires political, ideological and ethical values and these are influenced by perceptions and worldviews. Not only the weighting factors, but also the choice of valuation methodology, and the choice of using a valuation method at all, are influenced by fundamental ethical and ideological valuations [Hofstetter 1998]. Since there is no consensus on these fundamental values, there is no consensus either on weighting factors, or on valuation methods, not even on the choice of using a valuation method at all. If no valuation method is used at all, comparisons are made category by category, and not on an aggregated level. Several methods for valuation in connection with LCA have been developed during the 1990s and are further under development. In [Finnveden 1999] there is a detailed review about valuation methods. He classifies the methods in several groups: Proxy, Monetisation, Distance-to-target and Panel methods.

Proxy approaches are qualitative valuation methods and are therefore not further discussed here.

Monetisation

There are a large number of different approaches for monetising environmental impacts (e.g. EPS system, Tellus method, Impact Pathway Analysis). Often the “willingness-to-pay method” is used. Thus, somebody is willing to pay a certain amount of money in order to avoid something. Other monetisation methods are often based on an estimation of costs to do something, without considering who will pay for it. One example is the ‘impact pathway’ methodology which has been developed in the series of ExternE projects [Krewitt 1998]. The impact pathway analysis aims at modelling the causal chain of interactions from the emission of a pollutant through transport and chemical conversion in the atmosphere to the impacts on various receptors, such as human beings, crops, building materials or ecosystems. Welfare losses resulting from these impacts are transferred into monetary values based on the concepts of welfare economics

Distant-to-target

The Distance–to–target methods are relating the valuation weighting factors to some sort of target. In the EDIP political targets for the year 2000 for pollutants are used. The EDIP method translates the cumulated inventory data of an examined system into potential contribution to various impacts within the main groups environment, resources and working environment. The EDIP 2003 method includes spatially differentiated characterisation modelling. The IMPACT 2000+ method proposes an implementation of a combined midpoint/damage approach. All types of LCI results are linked via midpoint categories (e.g. human toxicity, ecotoxicity, global warming, ozone layer depletion, etc.) to four damage categories (Human health, Ecosystem quality, Climate change, Resources). In order to that the IMPACT 2000+ method takes advantages both from midpoint based indicators and from damage based methodologies. In contrast to that the Eco-indicator 99 is a fully developed damage approach. The developers of Eco-indicator 99 defined three types of damage: Human health (measured as **D**isability **A**djusted **L**ife **Y**ear**s**; DALYs), Ecosystem quality (measured as the loss of species over a certain area during a certain time in **p**otentially **d**isappeared **f**raction PDF*m^{2}yr) and Resources (expressed as the surplus energy needed for future extractions of minerals and fossil fuels in MJ). These damages were weighted against each other in a panel approach. The panel found damage to Human health and damage to Ecosystem quality equally important while damage to Resources was considered to be half as important. In order that the Eco-indicator 99 has an exceptional position due to the use of damage approach and panel method. An inherent problem of the damage approaches is the question how to handle future impacts. The choices concerning discounting and/or a cut-off can have a decisive influence on the results. As a consequence the Eco-indicator 99 use three different “archetypes” with different attitudes and perspectives about time horizon (the “Hierarchist” is chosen as default [Hofstetter 1998]; see also 3.2.3).

Panel

In Panel approaches people (experts, stakeholders, persons concerned) are asked via questionnaires, interviews or group discussions to give weighting factors. Panel approaches are often used in specific case studies.

One conclusion can be drawn: the comparison of different impact assessment methods along parallel evaluations of case studies helps to detect similarities and dependencies between them and also supports the accuracy of the assessment. [Mizsey 2009]. However, one of the major problems with the present methods is that there are significant data gaps. Since many methods have data gaps in the same areas, e.g. concerning emissions of toxicological relevance, the results should be cautiously interpreted even if all applied valuation methods point in the same direction.

In many studies the different impact categories are simply listed equally side by side, though some use an aggregation to give a valuation as one environmental figure.

3.3 Boundary conditions and the methodological choices of the investigated studies

The 15 studies investigated cover different system boundaries and therefore provide different results. Before the effect of system choices on the study outcomes is described in more detail, Table 3-3 gives an overview of the different scopes of the studies. The studies are expressed systematically.

Study/Year	Region	Time horizon	Fuel			Capture			Coverage	Outcomes			
			Hard coal	Lignite	Gas	Post-comb.	Pre-comb.	Oxy-fuel	Capt./Trans. Storage	Emissions	GWP	Other Impacts	Normal. step
D'Addario/2003	Middle Italy	present			X	X	X			X	X	X	
Doctor/2001	US	present	X				X		(C+T)		X	X	
IEA/2006	global	present-2050	X		X	X	X			X	X	X	
Khoo/2006	US	present	X			X			X	X	X	X	X
Koornneef/2008	Netherlands	2000/ 2020	X			X			X	X	X	X	X
Korre/2009	global	n.a.	X			X				X	X	X	
Lombardi/2003	Hypothetic (Italian costs)	n.a.	X		X	X	X			X	X		
Modahl/2009	Norway	n.a.			X	X			X		X	X	X
Muramatsu/2002	Japan	present	X			X			X	X	X		
NEEDS/2008	Europe	2020-2050	X	X	X	X	X	X	X	X	X	X	
Odeh/2008	UK	2005	X		X	X	X		X	X	X		
Pehnt/2008	Germany	2020		X		X	X	X	X	X	X	X	
Schreiber/2009	Germany	2020	X	X		X			X	X	X	X	X
Spath/2004	US	present	X		X	X			X	X	X		
Viebahn/2007	Germany	2020	X	X	X	X	X	X	X	X	X	X	

n.a. not available

Table 3-3: Scope of LCA studies

4 Analysis of system choice impacts

In the following, the impacts of various system choices on the study outcomes are compared and evaluated. In accordance with the structure of section 3 the effects of technology or LCA driven choices are distinguished.

4.1 Technology driven differentiation

The published studies vary in their coverage of technology representation. While several focus only on one capture technology (e.g. Koornneef, Korre, Schreiber, Spath), others reveal a wider picture of a future CCS system (e.g. D'Addario, Pehnt, Viebahn, NEEDS). Depending on the method of publication (e.g. paper or full study report) the description of assumptions and underlying system boundaries is more or less detailed. Therefore, it is not always possible to draw a full picture of study outcomes and assumptions relationship for all studies.

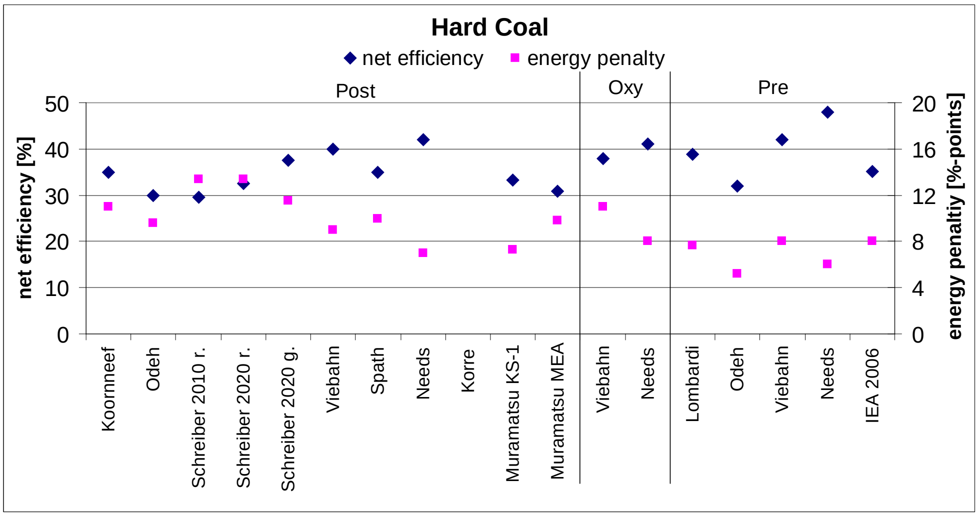
4.1.1 Power plant concepts/Capture technology

All studies, but one (Doctor), expect post-combustion capture technology as one possible future CCS system. The technology of choice is always MEA scrubbing, probably due to its most mature status. Only Khoo and D'Addario investigate/compare other post-combustion technologies and Muramatsu other solvents as well. Khoo compares chemical absorption (MEA), membrane separation, cryogenics and pressure swing adsorption technologies, which differ in their demand of energy but in the product CO_2 also (see also Table 4-2). D'Addario also considers membrane technology (**M**embrane **G**as/liquid **C**ontractors, MGC). Muramatsu compares two amine based solvents, a sterically hindered amine named KS-1 and the conventional MEA solvent.

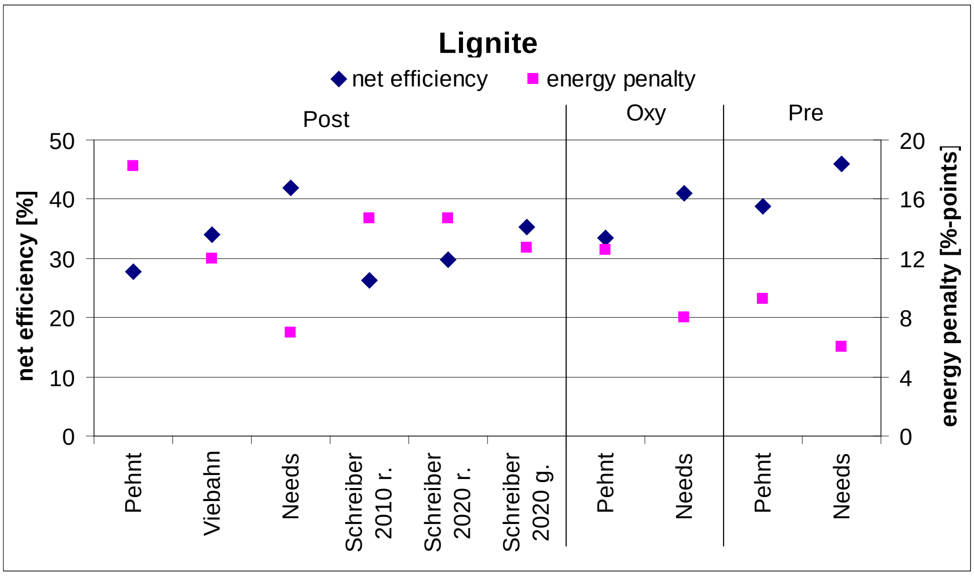
The oxyfuel process route is described only in three studies, being the least investigated technology group. A high share of energy is needed for the oxygen production. The specific demand is still very unclear, figures ranging from 160 kWh/tO_2 in [Babcock 2009] up to 320 kWh/tO_2 in Pehnt. Latter considers this as the highest source of uncertainty. The IGCC/NGCC technology with integrated pre-combustion technology is the objective of 8 studies.

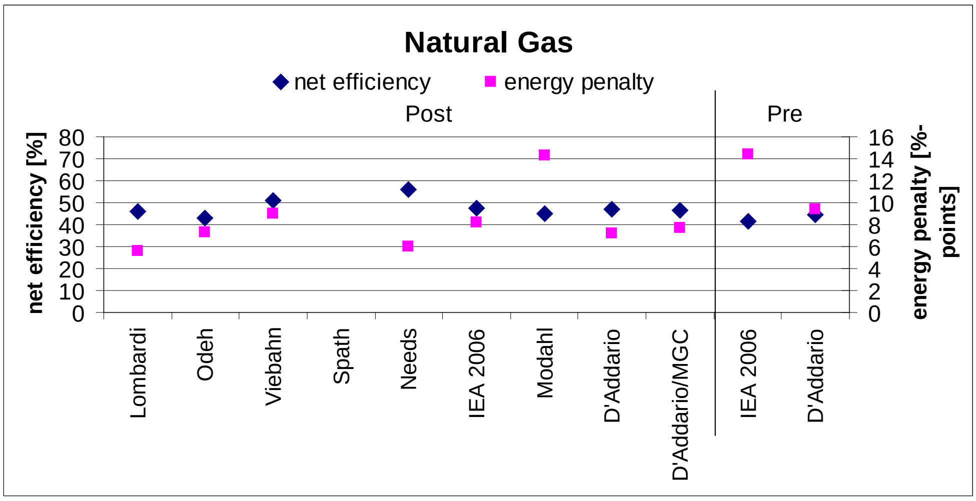
As fuel hard coal is considered in most studies (11). This emphasises the fact, that CO_2 capture is most valuable for hard coal fuel cycles. In those studies, which look at the German electricity production (4), the local fuel lignite becomes an interesting option as well. All projected demonstration plants in Germany are lignite based. Looking at a wider European or even world level, natural gas has to be integrated as well (8 studies).

In Figure 4-1 the net efficiencies and the assumed energy penalties of the different studies are presented with respect to the fuels used.



Values for Korre are not available





Values for Spath are not available

Figure 4-1: Net efficiency and energy penalty

All technology routes are covered, except the oxyfuel process for natural gas fuelled plants. The prospected net efficiencies vary between the studies. For hard coal post-combustion values between 29.6 % (Schreiber, 2010 retrofit) and 42 % (NEEDS, 2050) can be found. For the pre-combustion route the difference between the lowest (32 %, Odeh, 2005) and the highest (48 %, NEEDS, 2050) is even higher.

Part of the significant difference originates from the underlying time perspective of the studies. As expected NEEDS, the study with the furthest time horizon 2050 assesses the highest net efficiencies for all process routes and fuel used. In most cases it also stands for the lowest energy penalty connected to the capture process. Nevertheless, this correlation cannot be found in all studies. IEA has always lower values although having the same time horizon. Background for this is the technological representation. Especially for the pre-combustion process no common understanding of the future technology exists. While for lignite powered plants the prospects for the development are nearly the same, assumptions for gas fuelled plants diverge only slightly, but for hard coal they vary noticeable. The consensus on the performance of conventional future lignite fuelled power plants does not apply for the forecast of efficiency losses due to capture. The expected energy penalty differs between 7 %-points and 18.2 %-points. In general, energy penalties for pre-combustion processes are the lowest and for post-combustion the highest. The difference can also occur when different states of technology are considered. The capture technology can be retrofitted to an existing power plant leading in higher energy penalties or being integrated into an optimised greenfield power plant, as explicitly analysed in Schreiber and Modahl. In many studies it is not clear which detailed technical assumptions e. g. about technological representation or emission reduction efficiencies are used for the analysis.

As mentioned above the purity of the CO_2 stream is not always stated. Nonetheless, the purity has a major influence on the compression energy. Especially the amount and composition of impurities is a key factor for energy demand, as shown in Figure 4-2. It shows the simple compression work for a two component mixture varying in the kind of impurities. In the studies, it is often not clear which amount of energy is connected to the compression work. It cannot be reconstructed to which extent the compression process might vary.

Figure 4-2: ***Relative difference of compression work for a two component gas [Castillo 2009]***

Also the compression system used has an influence on the results. Figure 4-3 shows the necessary compression energy, storage capacity and gas purity for pure CO_2 compared to different compression/purification systems for a typical IGCC off gas. The results show, that there is a multidimensional optimisation process, as higher purity yields in higher storage capacity but to the disadvantage of more energy needed.

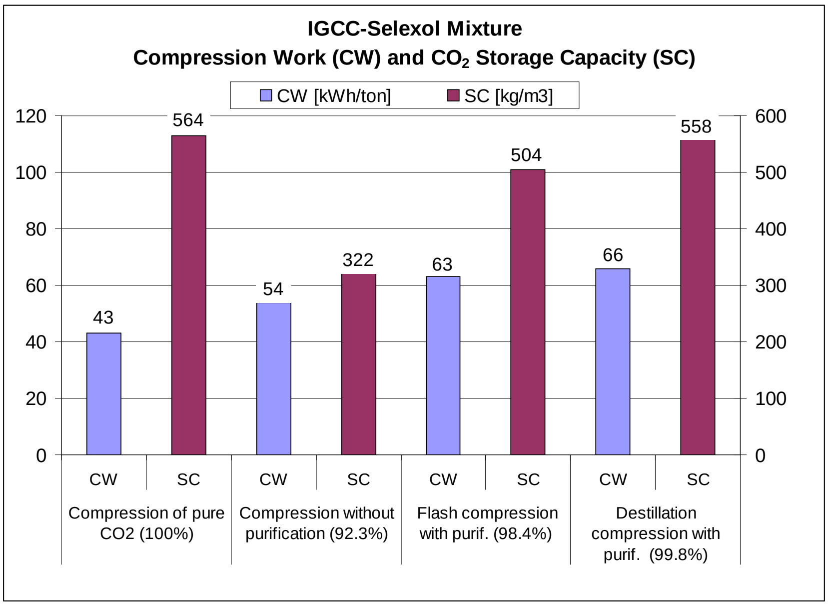


Figure 4-3: ***Compression work and storage capacity for different systems [Castillo 2009]***

Important for the comparison are the assumptions about the reference system. All studies compare the CCS systems to more or less developed technology using fossil fuels. Within a mitigation discussion CCS also has to compete against other measures. Beside efficiency improvement of fossil fuelled technologies, also renewable energy systems are an option. Only two studies (Viebahn and Spath) choose renewable energy as reference system also. While Spath investigates biomass power production Viebahn considers wind offshore and solar thermal power systems for energy and hydrogen production. Both studies state, that renewable technologies have a higher GWP reduction potential. Viebahn investigates other impacts (AP, EP, POCP) also. The renewable technologies have clearly lower values there as well. Anyhow, they have other impacts such as change of biocoenosis for wind and impairment of habitat for solar power. For the choice of system the different impact developments have to be weighed against each other. Beside the environmental figures both studies show that cost estimations as well as the development of the investigated energy system play an important role in decision making. Most often the combination of both measures, increase of renewable energy and introduction of CCS, will be necessary to reach the ambitious environmental reduction targets.

A second way to consider renewable energy in the analysis is used by Modahl and Spath. Here, the additional energy necessary due to the penalty for the CCS system is provided by a bio-fuelled power plant. While in Spath the biofuel co-fired system has less GWP compared to the coal CCS system, Modahl shows, that an optimal integration of CCS into the gas driven plant reaches better GWP, AP, EP and POCP values than a system delivering the amine regeneration energy using a bio-fuelled steam boiler. This contrary outcome of results shows, that more studies are necessary to validate the data.

The three studies show also, that the integration of renewable systems into the comparison increases the complexity of the study enormously.

4.1.2 Transport and storage

About 80 % of the studies include transport and storage in their investigation. Table 4-1 summarises the assumptions concerning transport technology and distance as well as storage system and possible leakage rates. For transportation options pipeline is considered in all studies. Khoo also looks at ship transport. Depending on the regional focus the transport distances vary between 20 km for a system in Japan and up to 1800 km for an US system.

Khoo, Modahl, Muramatsu and Odeh consider off-shore storage sites. The others model different options for onshore storage, mostly depleted gas fields. Only Viebahn and Khoo include leakage rates in a sensitivity analysis.

Study/Year	Transport	Storage
D'Addario	-	-
Doctor/2001	Pipeline (only construction) Distance:100 km	–
IEA/2006	–	–
Khoo/2006	Ship, Distance: 300 km Pipeline, Distance: 250–500 km	Offshore/Onshore 9 different sequestration options Leakage rate: system dependent variation
Koornneef/2008	Pipeline Distance: 50km	Onshore natural gas storage Leakage rate: not considered
Korre/2009	–	–
Lombardi/2003	–	–
Modahl/2009	Pipeline Distance:150 km	Offshore Heidrun Gas field Leakage rate: not considered
Muramatsu/2002	Pipeline Distance: 20 km	Offshore gas field (1250 m – 2000 m)
NEEDS/2008	Pipeline Distance : 400 km (200 km)	Onshore depleted gas field (2500 m), (800 m aquifer) Leakage rate: not considered
Odeh/2008	Pipeline Distance:300 km	Offshore depleted gas field Leakage rate: not considered
Pehnt/2008	Pipeline Distance:325 km	Onshore depleted gas field Leakage rate: not considered
Schreiber/2009	Pipeline 400 km	Onshore saline aquifer Leakage rate: not considered
Spath/2004	Pipeline Distance:300-1800km	Unspecified on-shore underground storage Leakage rate: not considered
Viebahn/2007	Pipeline Distance:300 km	Onshore depleted gas field Leakage rate: 0.1 to 0.0001%/a in sensitivity analysis
Wildbolz/2007	Pipeline Distance: 200 km and 400 km	Onshore saline aquifer (800 m) gas field (2500 m) Leakage rate: not considered

Table 4-1: Transport and storage options

Khoo presents the most detailed LCA study on two CO_2 transport and nine storage processes. For ocean and geological sequestration, six and three case studies are presented, respectively. The ocean storage cases are known as (1a) vertical injection, (1b) inclined pipeline, (1c) pipe towed by ship, (1d) dry ice, (1e) gaslift advanced dissolution (GLAD) system, and (1f) CO_2 hydrate. For geological storage, (2a) enhanced oil recovery (EOR), (2b) enhanced coal bed methane (ECBM) recovery, and (2c) CO_2 storage in a saline aquifer is explored. Khoo also considers the different injection and disposal depth of the various sequestration options, because the amount of CO_2 sequestered permanently depends largely on these parameters. For an overall comparison, a final score for each combination of four CO_2 recovery processes and nine sequestration options is attained. For each normalisation and weighting steps are provided. The least environmental burdens come from the three geological sequestration methods, especially saline aquifer followed by ECBM and EOR. For ocean storage, the best case is presented by vertical injection combined with chemical absorption technology followed by inclined pipeline, dry ice, CO_2 hydrate, and GLAD. The worst case is displayed by pipe towed by ship combined with any CO_2 removal processes.

In addition to Khoo a Diploma Thesis [Wildbolz 2007] investigates selected technologies for CO_2 transport and sequestration in detail by using LCA. The focus of this study lies first on the energy and material requirements associated with the construction, dismantling, disposal, and operation of the pipelines transporting supercritical CO_2 over 200 and 400 km without and with one recompression stage, respectively. Secondly, LCI data for the construction of the double well for geological storage in deep saline aquifers (800m) and in depleted gas fields (2500m) are provided. In contrast to the other studies the chosen functional unit in this study is “1 kg stored CO_2”. Wildbolz compares the various options by using GWP and Eco-Indicator 99 (EI`99). As expected, both indicators increase in the order of increasing transport distance and injection depth. The storage in a deep saline aquifer with 200 km pipeline transport represent the best option in terms of overall environmental burdens measured by EI’99 and GWP, while storage in a depleted gas field with 400 km pipeline transport presents the worst case. Nevertheless, along the whole CCS chain (including power plant and CO_2 capture process) CO_2 transport and storage processes have only a marginal influence on the additional emissions caused by CCS and amount to 0.5 % - 1.9 % in Wildbolz. The share of the CO_2 transport is mostly smaller than the share of the storage. Wildbolz determines that the key factor of the storage process is the required energy for injection, which markedly increases with injection depth. The injection energy again depends on the injection pressure and the volume flow of CO_2. In a sensitivity analysis the variation of the pressure for injection has been verified and it changed in a wide range between -60 % up to 44 %.

Although transportation and storage is included in the studies, the associated data are not always expressed separately. The estimated share sometimes varies one order of magnitude. While Modahl, Muramatsu and Pehnt calculate a share of transport and storage on the total GWP of less than 1 %, Schreiber, Viebahn and NEEDS determine between 3 % and up to 10 %, depending on the investigated system and fuel. As before, not enough studies present figures and no clear picture becomes visible.

4.2 LCA driven differentiation

4.2.1 Functional unit

The functional unit for the compared studies is always 1 kWh electricity produced. Only D'Addario keeps the amount of captured CO_2 constant also. The fixation of the CO_2 amount can be regarded as an extension of the functional unit to a second parameter. The results of this study are not directly comparable to the others. By adjusting the amount of captured CO_2 to one specific value he changes the capture rate of the systems compared in contrast to the other studies where it is kept constant. Although CO_2 in some countries already has an economic value, in none of the studies investigated is an allocation procedure performed. This is probably due to the fact, that in most of the countries the CO_2 emission trading system is still in an early stage with volatile prices on the market for CO_2 emission allowances.

Additionally, there is no information about the quality of CO_2 produced. As an example shown in Table 4-2, four different capture processes with different energy requirements, capture rates and end products are compared. Condensed CO_2[1] gas, CO_2 gas, and liquid CO_2 will have most likely different purities and are also not the same product. In his study Khoo combines these processes with 9 storage options, which need further CO_2 treatment and most likely have different requirements for the CO_2 quality.

CO_2 removal technology	Energy requirement in kWh/ton	Percentage capture	End product
Chemical absorption	330 340	95% 98%	Condensed CO_2
Membrane separation	70 75	82% 88%	CO_2 gas
Cryogenics	600 660	90% 95%	Liquid CO_2
Pressure swing adsorption	160 180	85% 90%	CO_2 gas

Table 4-2: Post-combustion capture technologies, their products and the lower and upper limits for energy demand and capture rate [Khoo 2006b]

[1] It is not clear to the authors whether condensed CO_2 in liquid form or dense phase CO_2 is meant

By comparing the studies it is not clear to what extent a different CO_2 quality might influence the results, as also the operating expenses for compression and transport (see 4.1.1 and 4.1.2) are dependent on the CO_2 purity.

In only one study (Doctor) an allocation procedure has been carried out for a multi-product system (IGCC with energy and hydrogen production) as a case study. All emissions before separation of H_2 and CO_2 (including CO_2) are allocated according to the energy content of hydrogen and fuel gas, which is further used for electricity production as two product fuel streams. No other study assumes a second product beside electricity.

4.2.2 Data quality and availability

Data for the studies investigated are gathered in many different ways. There are measured data for some process components, modelled data for specific systems, expert's assumptions on technology development, literature data for conventional technologies, estimations for data gaps and data from databases especially for upstream and downstream processes.

For the life cycle modelling nearly all studies use commercially available LCA software (SimaPro, TEAM, GaBI, Umberto), only a few develop their own software/model. The underlying power plant information is either done by own modelling (often using Aspen) or by literature study. Typical literature which is quoted regularly is [Göttlicher 1997], [Rubin 2007], [Tzimas 2007], [Thitakamol 2007], or [Rao 2002]. They describe capture processes in detail, though without environmental focus. Also expert's knowledge from energy producing companies or possible provider of CCS technology is used, especially when modelling future technology which does not so far exist. As several of the studies focus on Europe the Ecoinvent database [Ecoinvent 2009] is often used for background data and upstream and downstream process chains, respectively. Ecoinvent includes data values for Western Europe in general but also for specific countries for a wide variety of products.

4.2.3 Time horizon

Almost all studies consider present and future power plant and CCS systems up to the year 2020 when the CCS technology is expected to be commercial. Only in NEEDS and IEA are the power plants which are considered extrapolated up to 2030 and even to 2050. Thereby, the processes of the main process chain (first-order processes) are updated with more favourable data. Only Viebahn updates the data for the background systems also. This can have a considerable impact on the results. So, Viebahn uses more suitable data for energy mix as well as for steel and aluminium production based on higher metal recycling rates in the year 2010. Koornneef uses updated data for flue gas cleaning units and enhanced capture units based on improved emission factors and electrical equivalence factor, respectively.

Also other studies (Odeh, Schreiber, Viebahn) describe improvements assumed for some emission factors. Altogether one can assume that all studies have estimated technical progress in one or the other way, without mentioning it explicitly.

Another point of interest is the modification of coal imports in time due to shifts in supply and demand. For Germany this is especially relevant due to the phase out of subsidies for local hard coal mining in 2018 [Deutscher Bundestag 2007]. Therefore, Schreiber uses three different German import coal structures in the analysis (Figure 4-4).

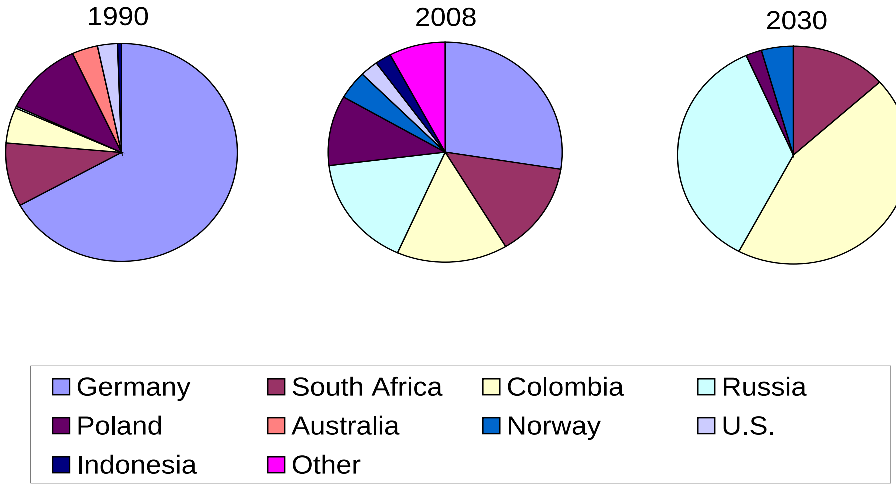


Figure 4-4: ***Example for a modification of the German hard coal import structure during 1990 – 2030 [Ecoinvent 1.3, OECD/IEA 2007, Schreiber 2009b]***

Due to the different coal deposits, exploration requirements and associated routes of coal transport the environmental impacts of the coal supply chain is different too, (Table 4-3).

Impact [kg equiv./kg coal]	**1990**	**2010**	**2030**
GWP	0.3468	0.3119	0.2617
AP	0.0012	0.0020	0.0028
EP	0.0001	0.0002	0.0004
HTP	0.0242	0.0321	0.0391
ADP	0.0194	0.0182	0.0171

Table 4-3: ***Environmental profile of time-dependent German coal import structure per kg hard coal [Ecoinvent, Schreiber 2009b]***

As shown in Table 4-3 two impact categories (GWP, ADP) decrease from 1990 to 2030, meanwhile the other scores of impacts increase. The GWP decreases due to lower methane emissions during coal exploration in other countries. The AP increases considerably due to increasing SO_2 emissions from longer ocean ship transports driven by heavy oil.

The results shown in Table 4-3 can be regained, if the time-dependent coal supply chains are completed by the full power plant process chain. The decrease in GWP (-3.3 %) is also reflected in Figure 4-5, if the coal import mix 1990 is updated to the import structure in 2030 and added to the same power plant. The same effect is even more intensified by adding a CCS power plant with its additional required coal caused by energy penalty (-15.3 %; third column in Figure 4-5).

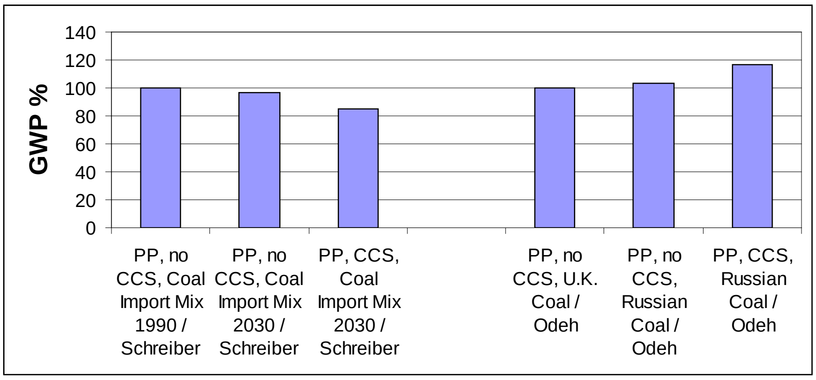


Figure 4-5: Sensitivity analysis of coal supply relating to GWP in Schreiber und Odeh

An opposed effect can be observed in the study from Odeh. If the locally mined UK coal acting as reference is completely exchanged by import coal from Russia (though assuming the same composition), the GWP increases (+3.5 %). For the CCS power plant the increase is again more clear (+16.9 %). In the other studies no time-dependent coal import structures were analysed. Only Viebahn updates the German natural gas import mix of the 90ies to 2010 in his study.

The time relation of GWP is only mentioned in a few studies. Nevertheless, it can be assumed, that all studies use the 100 year time basis, as this is the most commonly used. One would expect that the choice of a different time basis would have been mentioned.

The time-dependence also plays an important role in the analysis of possible leakage of CO_2 during the long-term storage. Thereby, the following still open questions should be answered:

- What leakage rate will be assumed?
- Does the leakage start at the beginning of the CO_2 storage or later?
- Which time horizon will be assumed (1.000, 10.000, 100.000 years or more)?

As shown in Table 4-1 only Viebahn and Khoo consider leakage in a sensitivity analysis, to get an idea of the impact and not to underestimate the storage phase by ignoring it at all. Viebahn examines different annual leakage rates (1, 0.1, 0.01, and 0.001 %/year) for 40.000 years. Of course, 0% leakage rate presents the best case. In the case of 0.1 %/year leakage after 6000 years the total CO_2 stored will be emitted again. If the leakage rate assumed to only 0.01 %/year, than after 40.000 years the total CO_2 stored has been emitted. Already after nearly 7000 years half of the CO_2 stored will be released (half-value-period). Because a constant leakage is unlikely Viebahn made two assumptions: (a) during the fill time of the storage (40 years) CO_2 will be hardly emitted; (b) the continuously emission of CO_2 will start after the forty first year and runs inversely exponential. The actual leakage rates, the used storage volume as well as the emitted mass of CO_2 at any point of time are calculated by iterative equations.

Until now in LCAs no differentiation between short-, middle-, and long-term emissions are carried out. If short-, middle-, and long-term emissions are calculated in the same matter and no complete tightness of the storage site will be assumed, than CCS systems per se results in increasing score of GWP, even if minimal leakage rates are assumed. Consequentially, a method suitable for LCA should be developed for discounting long-term greenhouse gas emissions to compare these with short-term emissions in a fair way. Until now only [Hellweg 2003] presents a method for comparing and weighting of short-term emissions from waste incineration against long-term emissions caused by landfill. At this point it must be stressed again, that the atmospheric lifetime of CO_2 is highly uncertain. Furthermore, there is no consensus regarding the consideration of what the long-term time scale should be.

Of course the GWP only increases, if the leaked CO_2 actual enters the atmosphere. Many storage sites will have multiple sealing layers, so CO_2 leakage from the main reservoir will not necessarily reach the atmosphere. Another issue to consider with respect to leakage is whether CO_2 leakage has any impacts on sediments or the marine environment and also on groundwater (e.g. acidification, displacing). In the selected LCAs these issues have not been addressed. Due to the lack of knowledge about these processes in the underground, it will be difficult for further LCAs to achieve satisfying and robust impact results.

4.2.4 Spatial representation

Some elements in the CCS process chain are highly site specific, such as coal origin and extraction as well as storage site. Therefore, it has to be kept in mind, that in this report only studies are analysed regarding the specific circumstances in Europe (e.g. Germany, Norway, Italy), three with an US focus and one for Japan, but no studies from Australia and other Asian countries (especially China) are included here. For coal Doctor and Spath use an American coal “Illinois No. 6”, Viebahn and Koornneef calculate with a specific coal import mix of Germany and Netherlands for one year, respectively. Muramatsu considers an unspecified coal composition of an Australian coal. NEEDS and Schreiber employ in each case two coal types with different heating values.

As already noted in the last sector, the coal origin, the site-specific extraction requirements and the enclosed routes of coal transport to the power plants have a major influence on the outcome of the studies. So, power plants using low rank coals, e.g. sub-bituminous, lignite and brown coal with relatively high moisture and low heating values need more coal per kWh_{el} than power plants firing with hard coal. Furthermore, the coal sulphur content and the ash content can also have a major impact on the emissions.

Table 4-4 demonstrates the composition of lignite and hard coal types used in different studies (Doctor, NEEDS, Odeh, Schreiber, Spath). The differences in compositions are clearly visible. As described in Schreiber the different heating values of the coal types result in higher coal demand per kWh_{el} produced for Lusatia lignite and South African coal. Although the coal from South Africa has a lower heating value than the North American coal, the SO_2 emissions from the firing with South African coal are lower due to the much lower sulphur content. In the appendix all the resulting different emissions and impacts are listed for the combustion of the four coal types in Schreiber.

Content, dry, [mass %]	**Lusatia Lignite**	**Rhenish Lignite**	**German lignite**	**Coal from North America**	**Coal from South Africa**	**Illinois#6**	**UK Bituminous**	**Hard coal mix**
Study	Schreiber	Schreiber	NEEDS	Schreiber	Schreiber	Doctor, Spath	Odeh	NEEDS
Carbon	0.69	0.6580	0.64	0.7656	0.7065	0.679	0.6	
Hydrogen	0.0511	0.0480		0.0526	0.0378	0.048	0.039	
Sulphur	0.0073	0.0074	0.48	0.0300	0.0065	0.027	0.016	0.009
Oxygen	0.1911	0.2400		0.0588	0.0798	0.073	0.06	
Nitrogen	0.0053	0.0035	0.71	0.0144	0.0162	0.013	0.015	
Chloride	0.0002	0.0001		0.0006	0.0000	0.003		
Ash	0.055	0.0430	5.95	0.0780	0.1532	0.103	0.15	0.1
Water	0.5640	0.5400	0.58	0.0550	0.0730	0.053	0.12	0.09
Heating value, dry [kJ/kg]	23700	24857	20956	31438	26959		24500	26000

Table 4-4: Example for compositions of lignite and hard coal types [Schreiber, Odeh, Spath, NEEDS]

In the case of lignite, Viebahn uses a locally mined German lignite mix consisting of Rhenisch Lignite, and Lignite from the west and east side of the river Elbe. However, this lignite mix is not time-dependently updated in the study. NEEDS calculates with an average lignite, Pehnt uses Lusatia Lignite, and Schreiber utilizes Lusatia Lignite as well as Rhenish Lignite. Because of the great influence of the coal fuel type on the overall results the use of the different fuel types in the studies should be kept in mind when interpreting the results.

In those studies where storage is included, no site specific information is used to describe the process. The reason for this is, that in general no site specific LCA is performed and a more general discussion takes place. Additionally, only very limited LCA specific information from the few existing storage sites is available. The only site related assumptions concerning storage which are made are the transportation distances between power plant and storage site.

As mentioned in section 3.2.4 it is questionable if average data for such a site specific theme is suitable and if LCA is the right method to analyse it, at all. Nevertheless, section 4.2.5 will show, that impacts related to transport and storage are small compared to the power plant itself.

Some upstream and downstream products/processes, such as NaOH, electricity or waste treatment, are highly related to the region of the investigation. Those studies, with a European background often use the Ecoinvent database for upstream and downstream processes. In Ecoinvent typical second order processes can often be found for different regions. Whether the different process chains are used in the studies is often not clear.

Although there are some approaches for including regionally different environmental impacts (see 3.2.4, Posch 2008, Seppälä 2006) no study uses site or region dependent impact factors for locally or regionally acting impacts. The desirable inclusion of regionally different impacts would also result in an even less comparable situation due to the invisibility of differences in technology.

A first agreement to consider regional references is the normalisation step. Normalisation makes it possible to translate impact scores for the impact categories into relative contribution of the product/system to a reference situation. Those studies which include the normalisation step in their analysis (Koornneef, Modahl, Schreiber) use the same approach of CML 2001 [Guinèe 2002] but country specific data to set the relation. Therefore, the normalisation step is a necessary part of LCA studies to gain a better understanding of the relative importance of an effect on the environment as a whole but also for a specific region.

4.2.5 Upstream and downstream processes

The studies are differing in their profoundness of investigation of upstream and downstream processes and their associated emissions. Table 4-5 shows the processes which are considered in the different studies and indicate those studies, where upstream and downstream processes are considered.

Study/Year	Construction	Mining and transport	Operation	Dismantling	Up stream	Down stream
D'Addario		X	X		X	
Doctor/2001	X	X	X	X	X	X
IEA/2006		X	X		X	X
Khoo/2006		X	X		X	
Koornneef/2008	X	X	X	X	X	X
Korre/ 2009		X	X		X	X
Lombardi/2003	X	X	X	X	X	
Modahl/2009	X	X	X	X	X	X
Muramatsu/2002	X	X	X		X	
NEEDS /2008	X	X	X	X	X	
Odeh/2008	X	X	X	X	X	X
Pehnt/2008	X	X	X	X	X	
Schreiber/2009		X	X		X	X
Spath/2004	X	X	X		X	
Viebahn/2007	X	X	X	X	X	

Table 4-5: Consideration of life cycle phases and upstreams and downstreams

Most of the studies include the construction and dismantling of systems. For conventional power systems it has often been proved, that those life cycle phases can be neglected. Some of the studies include the assessment in their analysis (see also Table 4-5). Koornneef and Pehnt consider a share of less than 0.2 % on the total GWP is connected to the construction and dismantling of the power plant. The share of infrastructural requirements for CO_2 capture, transport and storage to the total GHG emissions cumulates to 0.3 % in Koornneef. The inclusion of CCS technology increases the values. The studies differ in their estimation of the proportions between 0.34 % in Lombardi for a hard coal based IGCC and 4.9 % in NEEDS for a lignite fuelled oxyfuel system. Koornneef also calculates the contribution of third-order processes to GWP of approx. 5 %. This contribution is dominated by infrastructural requirements for the coal supply chain. There is even no consensus in the ranking of the three process routes or the fuel used. In general the construction and dismantling is of minimal importance.

One study [Weber 2009] looks exclusively at the constructional expenditures for the MEA absorption unit in more detail (see Figure 4-6). The results show that construction and deconstruction have only minor influence on the total losses of less than 2 %.

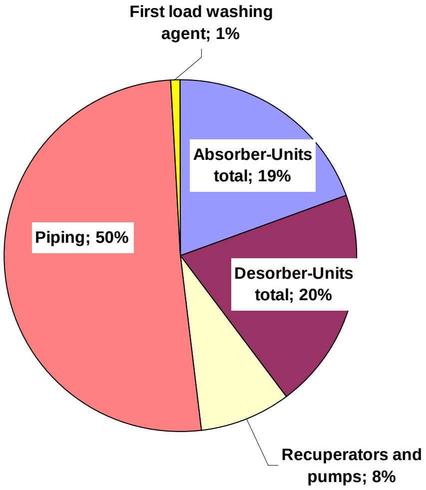


Figure 4-6: Cumulated energy demand (CED = 908457 GJ) of single component assemblies for the construction phase [Weber 2009]

The analysis of the different studies clearly shows the significant influence of the upstream and downstream processes on the overall emissions and their impacts. For power plants with CCS it is in general higher than for power plants without CCS. For the different impact categories the share can vary considerably. Figure 4-7 shows the share of upstream and downstream processes regarding GWP.

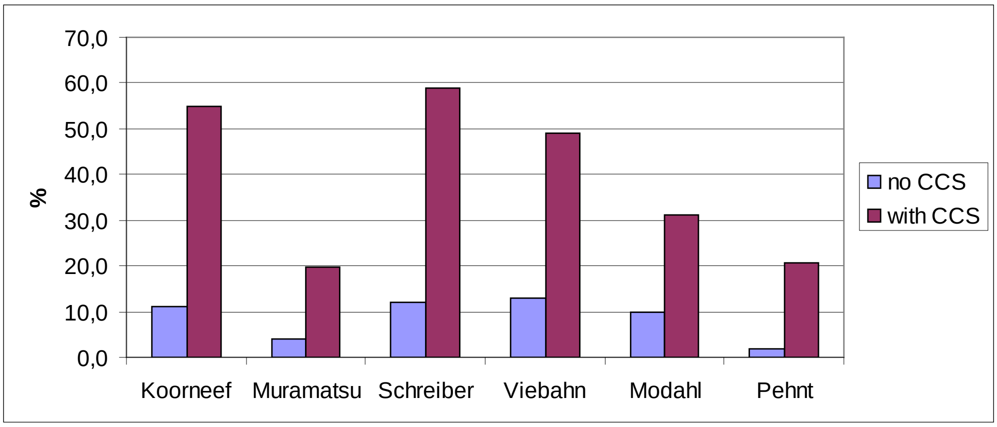


Figure 4-7: Share of upstream and downstream processes regarding GWP in power plants without and with CCS for several studies

The results for hard coal power plants (Koornneef, Schreiber, Viebahn) are very similar. Only Muramatsu shows lower values. The share of the upstream and downstream processes increases from about 10 % up to 50-60 % for the power plants without and with CCS, respectively. In the cases of a NGCC (Modahl) and a power plant fired by lignite (Pehnt) the share of the upstream and downstream processes are markedly smaller and amount to only 30 % and 20 % for the CCS plants, respectively. The reason for that is the higher influence of hard coal supply chain on the score of GWP in comparison to the natural gas and lignite supply chain. Nevertheless, Odeh states that methane emissions from natural gas extraction have a high impact on the overall GWP results.

The contribution of upstream and downstream processes to the overall results has been investigated especially for the case of MEA plants and is discussed at some length here. The results for the GWP show a significant reduction in CO_2 equivalents for the CCS power plants. Schreiber compares coal fired plants and post-combustion power plants with MEA wash capture technology. The reduction of direct CO_2 emissions amounts to 86 % and 87 % for hard coal and lignite, respectively. This figure is lower if upstream and downstream processes are included. In this case the reduction for GWP only amounts to 72 % and 83 % for hard coal and lignite, respectively. Koornneef achieves almost the same results, 86 % and 71 % reduction of GWP without and with upstream and downstream processes, respectively. This result is due to the fact that other chemicals, some with high GWP are emitted along the full process chain, e.g. methane (CH_4), carbon monoxide (CO) and nitrous oxide (N_2O). These gases with impact on the GWP are mainly emitted in the coal supply chain, such as CO_2 emissions from ocean transport of coal and methane emissions from coal mining.

Although the direct SO_2 and NO_x emissions are reduced by adding CCS due to the higher removal of SO_2 and NO_x during the post-combustion capture process via MEA, the resulting AP and EP are higher than for the power plants without CCS. The reason for that is on the one hand, that the CO_2 capture process is not enough to offset increased NO_x emissions caused by the efficiency penalty. On the other hand, another important contributor to both AP and EP is the emission of NH_3 from MEA degradation as well as NH_3 slip. Furthermore, more SO_2 and NO_x are emitted during the ship transport of additional coal caused by the efficiency penalty. In Koornneef the contribution of the coal supply operation (2nd order processes) and coal supply infrastructure (3th order processes) regarding AP and EP amounts to approx. 85% in case of power plant without CCS. With CCS the share amounts to approx. 80% and 60% for AP and EP, respectively. In Schreiber the share of coal supply amounts to approx. 30% for each case regarding to NO_x, SO_2, AP or EP. Koornneef states for the future decreasing SO_2 and NO_x emissions for coal transport can be expected due to stricter regulations to reduce sulphur content in marine fuel and to limit NO_x emissions during ship transport. In contrast to that, in [Schreiber 2009] the SO_2 and NO_x emissions strongly increase by 48% and 58%, respectively, from 1990 up to

2030 due to the modification in German hard coal import mix structure and therefore also a change in coal transport distances (Figure 4-4).

Furthermore, increasing SO_2 and methane emissions caused by additional coal transport and mining, respectively, due to the energy penalty induce an increase in POCP.

With respect to the Human Toxicity Potential (HTP) the direct MEA emissions from the capture process contributes only to a very small extent (0.005 %) to the HTP score [Koornneef 2008]. However, the MEA production chain accounts for an extreme increase in the HTP score due to the emission of ethylene oxide to air and water during MEA production. In contrast to that the MEA production chain and the disposal of reclaimer bottoms contributes to the score of ozone depletion potential (ODP) only slightly (13 %, Koornneef).

In summary it is found that the coal quality and coal origin associated with the specific coal supply chain contributes strongly to some impact categories, such as POCP, AP, EP and abiotic resource depletion. Another significant upstream process chain with respect to increasing impacts (HTP) is the MEA production chain. The disposal of hazardous waste from the capture processes has a noticeable contribution too.

Nevertheless, upstream and downstream process chains are often not represented with the same quality as the main processes. For example, the score for HTP is highly uncertain due to possible inaccurate data on the production chain of MEA [Koornneef 2008, Schreiber 2009b]. This data should be verified in the future studies because they have a major influence on the outcome.

The handling especially of downstream processes is often not very clear. The results of downstream activities must be handled with great caution, as some studies might have included downstream chains in their investigation without mentioning it.

4.2.6 Impact categories

The inventory phase is the core element of every LCA. In the LCI all inputs and outputs connected with the production of 1 kWh electricity are gathered. It is not possible to present the enormous amount of data for all technologies considered in the study. Normally, they are managed in a data base of an LCA software. Nevertheless, the estimated emissions build the basis for the subsequent impact assessment and the anticipated comparison. For better understanding and transparency, some studies present selected input and output data. As input data these are typically the amount of coal or scrubbing solution. Frequently discussed emissions are SO_2 or NO_x. Generally CO_2 emissions are accounted. Some studies (Doctor, Koornneef, Pehnt, Schreiber) also include other, less frequently measured emissions, such as HF, HCL, MEA, NH_3, which affect other environmental impacts. Koornneef and Thitakamol suggest that pilot plants are used to install environmental measurement systems to get information about those emissions which are normally not reported yet highly uncertain. In appendix A some selected emissions are presented. Normally in LCAs the impacts are discussed.

The evaluated impact categories vary from solely GWP assessment in Lombardi and Muramatsu to a wider spectrum with 10 environmental themes in Koornneef. Table 4-6 gives an overview of the considered impact categories used.

Study/Year	**GWP**	**AP**	**EP**	**POCP**	**ODP**	**HTP**	**FA ETP**	**MA ETP**	**TEP**	**CED/ ADP**	**PM 10**	**LU**	**WU**	**W**	**AI**
D'Addario	x	x	x	x							x		x		
Doctor/2001	x	x	x	x		x			x	x	x	x	x		
IEA/2006	x	x	x	x	x	x	x		x	x					
Khoo/2006	x	x	x			x	x	x	x	x				x	x
Koornneef/2008	x	x	x	x	x	x	x	x	x	x					
Korre/2009	x	x	x	x		x	x			x					
Lombardi/2003	x														
Modahl/2009	x	x	x	x						x					x
Muramatsu/2002	x														
NEEDS/2008	x	x	x	x						x		x	x		x
Odeh/2008	x									x					
Pehnt/2008	x	x	x	x		x				x					
Schreiber/2009	x	x	x	x	x	x				x					
Spath/2004	x									x					
Viebahn/2007	x	x	x	x						x	x				x

GWP Global Warming Potential, AP Acidification Potential, EP Eutrophication Potential, POCP Photochemical Oxidation Potential, ODP Ozone Depletion Potential, HTP Human Toxicity Potential, FAETP Fresh Water Aquatic Ecotoxicity Potential, MAETP Marine Aquatic Ecotoxicity Potential, TEP Terrestrial Ecotoxicity Potential, CED Cumulative Energy Demand, ADP Abiotic Depletion Potential, PM 10 Particulate Matter Equivalent, LU Land Use, WU Water Use, W Waste, AI Aggregated Indicator

Table 4-6: Impact categories considered in the studies

For comparison only those categories were chosen for which a sufficient number of studies use the same impact indicator. The considered categories are: GWP, AP, EP, POCP, and CED (representing to a good deal the use of fuel resources). It has to be stated, that Koornneef and Korre cover this information in the category "Abiotic Depletion Potential" (ADP). As they are the only two, the CED was chosen and without detailed knowledge of the emissions the values cannot be transformed.

One impact category which is significantly affected by CCS technology is the Human Toxicity Potential (HTP). Those studies which include this category often show an increase from nearly 200 % for systems with CCS. Unfortunately, HTP is one of the impact categories with still high research demand for consolidation of exposure pathways of emissions and on selecting the most appropriate impact model with its impact indicator. Although HTP is considered in most studies several impact indicators used make a wider comparison impossible. Normalisation also shows that HTP for conventional power production systems is quite low and even a dramatic increase keeps the fraction low.

Beside HTP, in some studies other toxicity potentials, such as FAETP, MAETP or TEP are considered. For instance, Koornneef expects a reduction in MAETP score (27 %) by adding CCS due to the increase in the removal efficiency of HF in the CO_2 capture process by reaction with MEA. Unfortunately, MAETP is one of the impact categories which have been a subject of discussion too. Thereby, the characterisation factor used for HF emissions in the CML method is still unclear and possibly too high. This can result in an overestimation of the positive effect of HF removal and in a dominance of HF in the contribution to the total MAETP score (Koornneef 2008). In the end, it should be stressed that the scores for the toxicity potentials are often highly uncertain due to inaccurate data on production processes or open questions in the characterisation step.

4.2.7 Operational Valuation/weighting methods

Weighting and grouping are optional steps of LCA. Only four studies use models to weight and aggregate the results to a single score (Table 4-6). Khoo and Modahl have chosen two and three different aggregation methods, respectively, to see the robustness of the results. Khoo used EDIP [Prẻ Consultants 2002] (a problem-oriented mid-point approach) and the Eco-indicator `99 [Goedkoop 2001] (a damage-oriented end-point approach), while Modahl has selected a combined midpoint/damage approach IMPACT 2002+, EDIP and a monetizing method EPS 2000 [Prẻ Consultants 2002] too. In EDIP Khoo used the indicators GWP, Acidification, Human toxicity, Eutrophication, Ecotoxicity, Waste and Resources. In the Eco-indicator 99 the indicators are: PDF modelling the ecosystem quality, DALY modelling the effect on Human health and resource damage quantifying the depletion of primary resources in MJ. For ocean sequestration methods the highest environmental benefits are found in combination with chemical absorption with 98% CO_2 recovery rate. The least environmental benefits are observed using the pipe towed by ship. For geological sequestration the highest environmental benefits are for all methods combined with chemical absorption with 98% CO_2 recovery rate, too. The worst environmental performances are for the combinations with cryogenics and membrane separation. While the trends in the results of EDIP and Eco-indicator 99 in Khoo are similar, the discrepancy in magnitude demonstrates the distinction between the mid-point and end-point approaches. In Modahl all results display nearly similar trends. She states that in the EDIP method toxic effects are strongly in focus, while in the EPS 2000 and IMPACT 2002+ methods the use of non-renewable energy is dominant. Beside a very detailed description of emissions NEEDS presents the final results using the Eco-indicator and external costs (Figure 4-8).

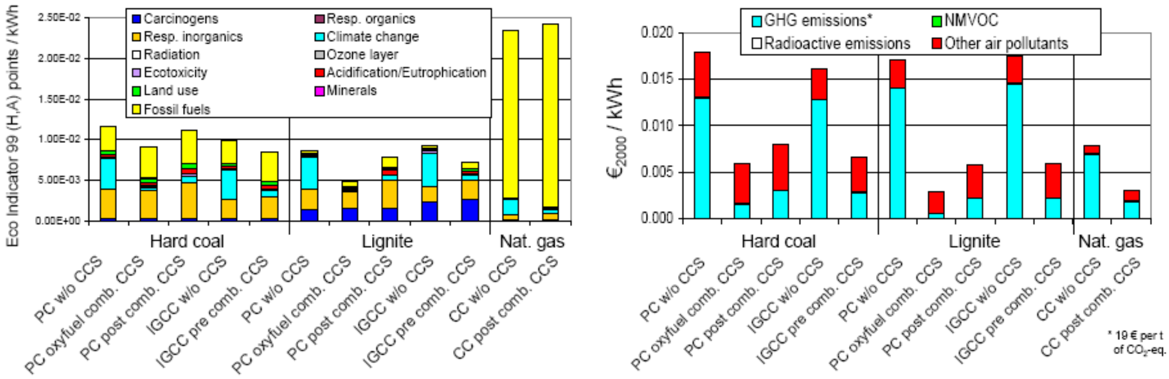


Figure 4-8: ***Life cycle assessment results of fossil electricity technologies in 2050 presented using Eco-indicator (left) and external costs (right) [Bauer 2008]***

Other than in Modahl and Khoo the trends of the results in NEEDS differ between the damage-oriented Eco-indicator and the external cost approach (Impact pathway analysis). Especially the choice of fuel has a big impact on the results. While natural gas shows the worst results in Eco-indicator, it comes best for external costs. Within one fuel group power generation with CCS clearly performs better applying external costs, while the Eco-indicator not always shows considerable advantages. So the choice of weighting and grouping determines different study outcome.

4.3 CCS technologies and their impacts

The fifteen studies present different CCS technologies and their particular environmental impacts. As an example of a typical technology comparison of a post-combustion system Khoo compares 4 different techniques. Figure 4-9 exemplarily shows some results for different impact categories. The environmental profile of the selected capture techniques differs widely. For example, the CO_2 capture by membrane separation has the highest score for GWP, but the lowest one for AP and EP. In contrast to that, the chemical absorption has the lowest GWP, but the three largest scores for AP and EP. Setting all impact categories with the same importance no clear "winner" exists.

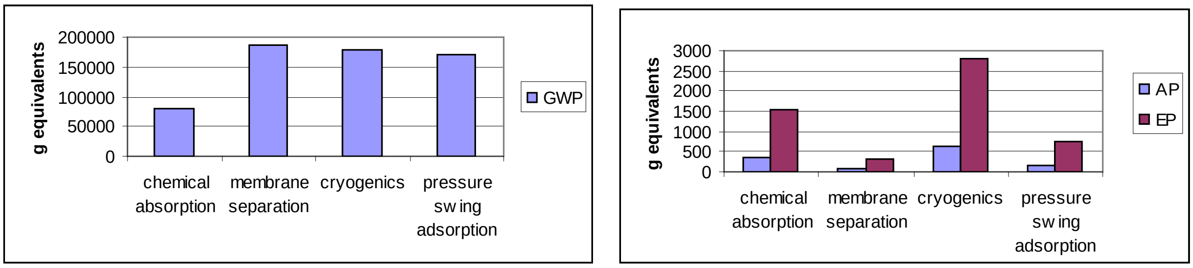


Figure 4-9: Comparison of GWP, AP, EP for different post-combustion techniques (Khoo)

The following results of the studies are compared considering different parameters. Therefore, the figures demonstrate the selected environmental impacts classified into different categories e.g. power plants with and without CCS, type of fuel and capture technique for all studies. The first diagram of a figure always shows the absolute impact equivalents for the presented technology. In the following graphs the relative difference due to CO_2 capture are presented. For Khoo and Lombardi no relative values can be estimated, as both do not indicate the underlying reference system explicitly. In their studies they just compare capture technologies. The figures for the NEEDS study are obtained by personal communication [Bauer 2009]. As described in chapter 3.2.6 a normalisation is highly desirable to benchmark the results obtained. Only three studies have included this step and all using the CML 2001 approach (see also 4.2.4). However, an unreflected presentation of all impact categories in one diagram might overvalue impact categories with big changes but small contribution to the total environment. Therefore, a yearly contribution to a specific region is given as evidence. As the different studies cover different regions the world average values from CML 2001 are chosen as values for the reference system for the different impact categories (Table 4-7), being the latest values available. For the cumulative energy demand no figures for specific regions exists. The normalisation of the related “abiotic depletion potential” in Koornneef shows, that this impact category is of minor importance.

Impact category	**World 2000**	
Global Warming Potential (GWP 100 years)	4.18E+13	kg CO_2 eqv.
Acidification Potential (AP)	2.39E+11	kg SO_2 eqv.
Eutrophication Potential (EP)	1.58E+11	kg phosphate eqv.
Photochemical Oxidation Potential (POCP)	4.01E+10	kg ethane eqv.
Humantoxicity (HTP)	3.63E+13	kg DCB eqv.

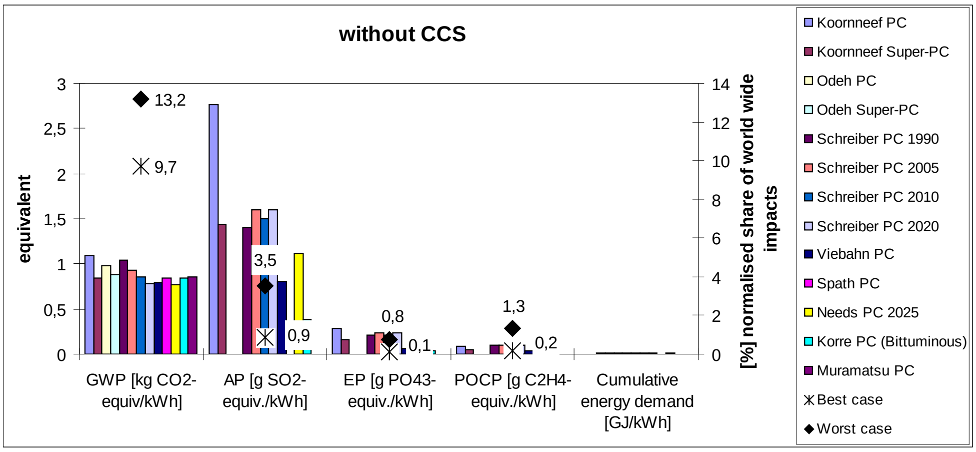
Table 4-7: Normalisation factors world 2000 [Guinèe 2002]

Using the electricity generation figures for coal from 2000 (hard coal: 5296 TWh, lignite: 693 TWh, natural gas: 2676 TWh; [OECD/IEA 2002]) a total production by CCS technology is assumed. For all analysis the technologies with the lowest and the highest values are taken to analyse the effect of the best and worst performance. Hence, in each figure (4.10 – 4.14) the importance of the various impact categories is visible.

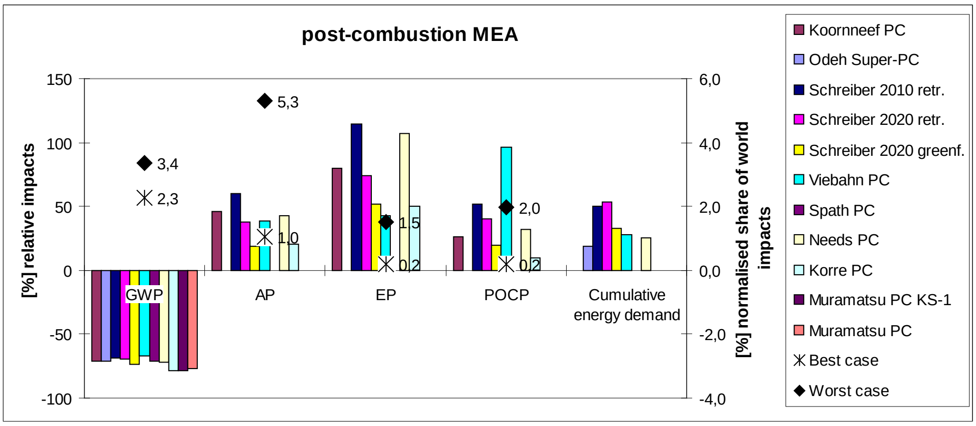
As already described above the number of studies analysing hard coal and post-combustion is large in comparison with studies dealing with oxyfuel and IGCC based on lignite. Therefore, the conclusions which can be drawn have not the same robustness for all the capture technologies.

4.3.1 Hard Coal

a)



b)



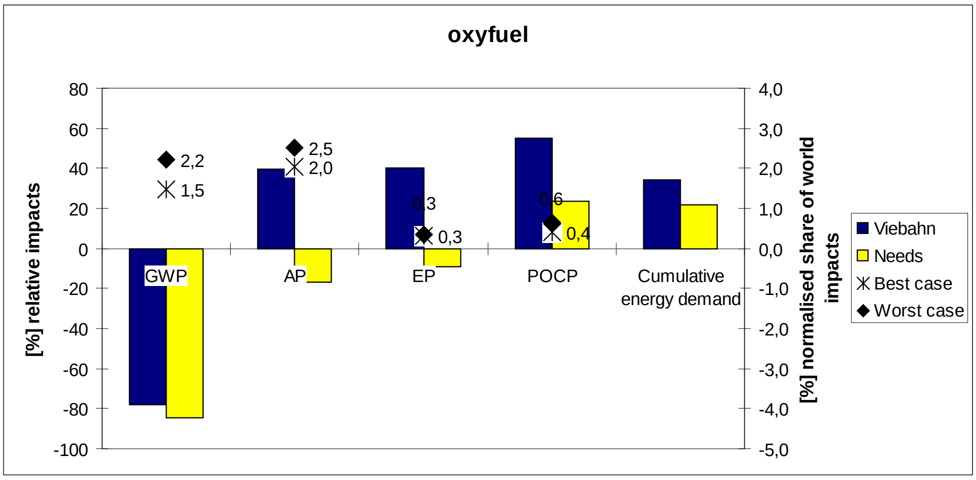


Figure 4-10: ***Environmental impacts of hard coal fired pulverised coal combustion technology a) without capture and b) relative impacts for plants with post-combustion/MEA or oxyfuel capture and normalised values related to the total world production in 2000 calculated for lowest and highest impact values***

The absolute GWP of the pulverised coal combustion technology without capture varies from 765 g CO_2-equivalent/kWh to 1092 g CO_2-equivalent/kWh, depending on the estimated efficiency and the coal used (see Figure 4-10a). The acidification potential values are much more scattered. Koornneef assumes very high 2.76 g SO_2-equivalent/kWh for his “old” average PC plant from 2000, while the lowest value is 0.39 g SO_2-equivalent/kWh in Korre. This is caused by the consideration of different technology representations for SO_2-removal and coal composition. EP, POCP and CED do not vary considerably.

The normalisation shows, that the power generation has a considerable share on the GWP with 13.2 % assuming only plants with low performance and even nearly 10 % if only “modern”, best technology had been used. The share of the worlds AP using only worst case technologies is 3.9 % while best technology would bring that down to about 1 %. Even smaller is the effect on the EP and POCP.

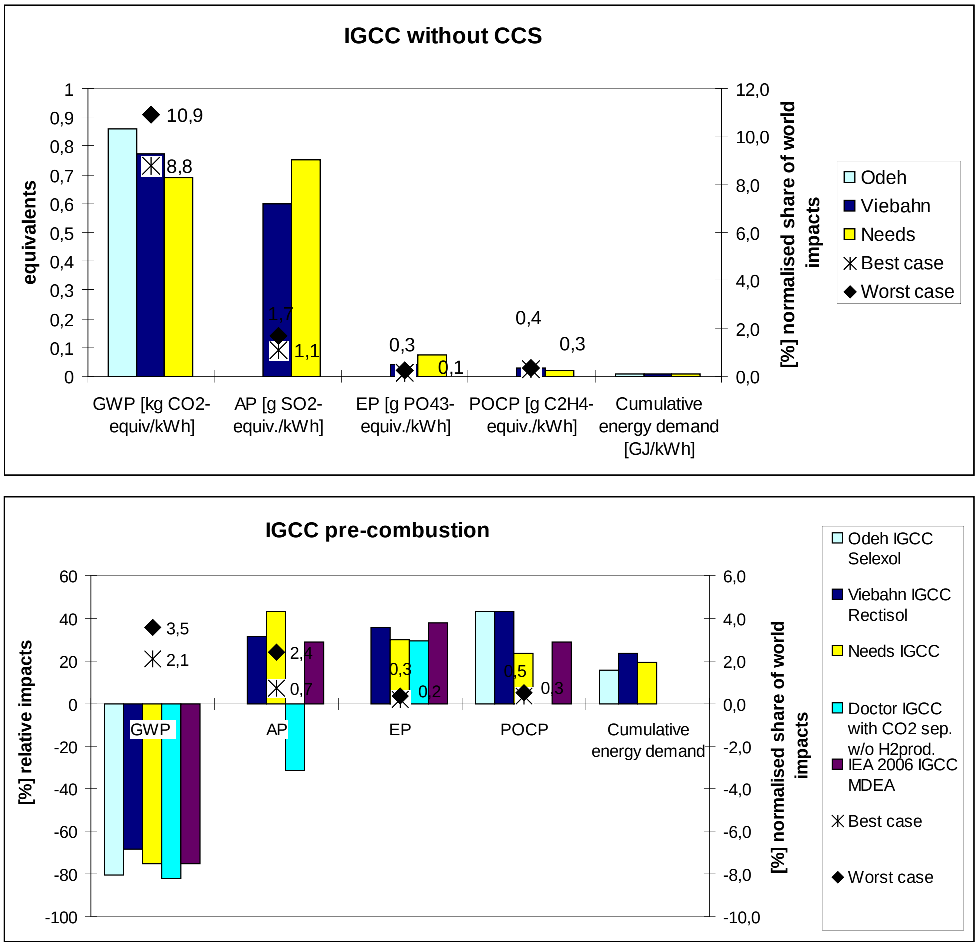


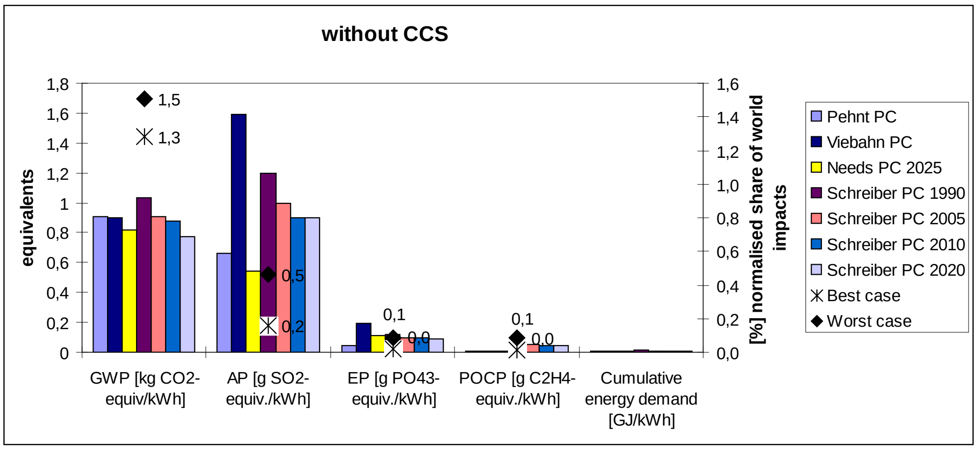
***Figure 4-11:** Environmental impacts of an integrated coal gasification system without capture and relative impacts of systems with pre-combustion capture and normalised values related to the total world production in 2000 calculated for lowest and highest impact values*

As expected, the results of the LCAs of hard coal power generation systems with CCS clearly indicate a substantial reduction in GWP compared with fossil fuel fired power plans without CCS (Figure 4-10b). Furthermore, the LCAs show an increase in all the other considered impact categories (AP, EP, POCP and CED) for post-combustion and IGCC (Figure 4-11). Only Doctor shows a decrease in AP. The increase of AP and CED for post-combustion is smaller than 50 %. However, the share of the world AP increases from 3.5 % (without CCS) to 5.3 % (post-combustion) for the worst case scenario. The importance of AP for post-combustion becomes even higher than for GWP. As stressed before, the acidification is a regional impact category, so the importance will vary in different regions involved in the CCS process chain. As no data and distribution models for all regions exist the average world value indicates, that a close look into this impact category is necessary. In several LCAs EP and POCP increase up to 100 % and even beyond in comparison with the power plants without CCS. Still, the normalisation figure shows a share of 2 % or less for technologies with high EP and POCP and is negligible for best technologies. In contrast to post-combustion, for IGCC with CCS, although all consider different solvents, the increase of AP, EP, POCP and CED in general is smaller than 50 % and stays still rather low in comparison to the world wide EP and POCP. The share of AP doubles from 1.7 % to a maximum of 2.4 %. The main reason for increasing impacts is the loss of efficiency associated with additional fuel demand for CCS power plants. Beside additional fuel supply another main environmental issue is the use of large amounts of amines or other solvents in CO_2 capture processes, their losses into the atmosphere and the disposal of their degradation products. Although Thitakamol postulates that the environmental impacts of adding a post-combustion absorption-based CO_2 capture unit to a power plant is not serious, further efforts are needed to reduce losses of solvents and to develop new solvents which produce lower and less toxic emissions.

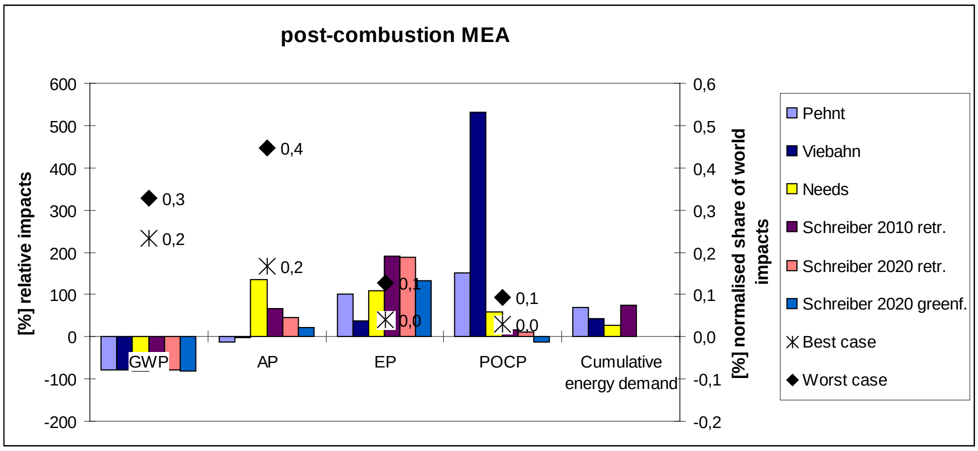
The impact assessments of the two studies analysing hard coal oxyfuel power plants present no consistent results, except for GWP. The values for AP and EP lie between minus 16 % and plus 40 % and minus 9 % and 40 %, respectively, for POCP between 23 % – 54 %. This implicates, that no general conclusions can be draw for the environmental assessment of oxyfuel power plants from two studies.

4.3.2 Lignite

a)



b)



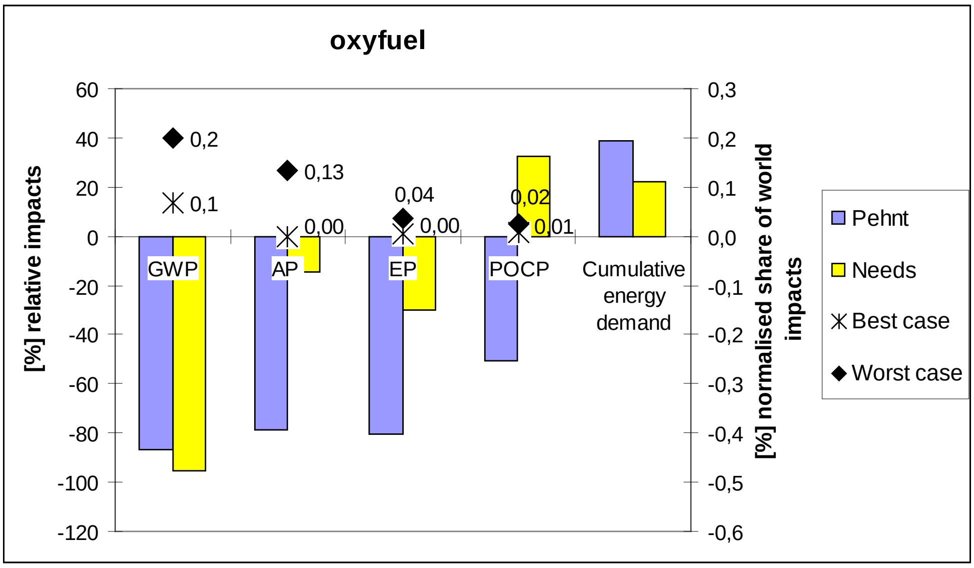


Figure 4-12: Environmental impacts of lignite powered pulverised coal combustion technology a) without capture and b) relative impacts for plants with post-combustion/MEA or oxyfuel capture and normalised values related to the total world production in 2000 calculated for lowest and highest impact values

The results of the LCAs analysing lignite power plants (Figure 4-12a) point in the same direction as those for power plants based on hard coal. The GWP for the base plant without CCS is slightly higher compared to hard coal, as expected. The AP varies between 0.66 and 1.59 g SO_2-equivalent/kWh. This is mainly influenced by the fuel used. All other environmental impacts are within the same range. Due to the much smaller amount of power generation by lignite fired plants world wide, the share of all environmental impacts on the total world impact is much smaller, than for hard coal. For GWP it is maximum 1.5 % without CCS and all other categories are negligible.

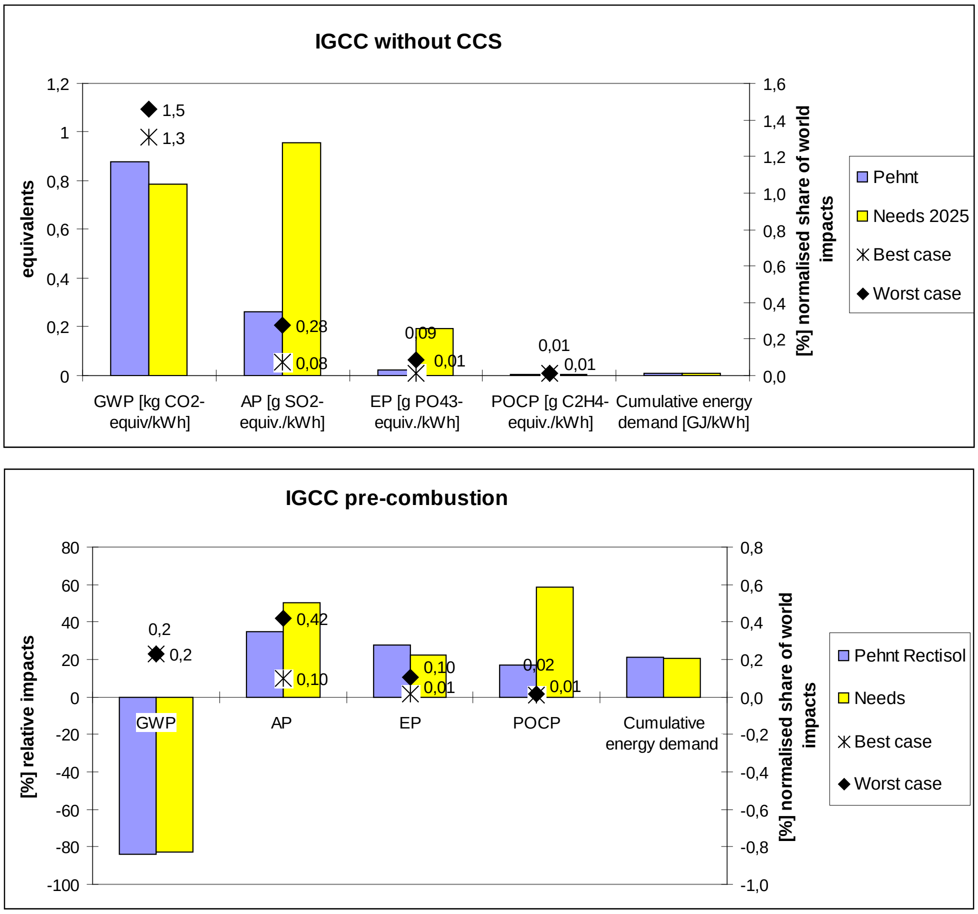


Figure 4-13: Environmental impacts of an integrated coal gasification system without capture and relative impacts of systems with pre-combustion capture and normalised values related to the total world production in 2000 calculated for lowest and highest impact values

For the capture systems GWP is substantially decreasing while AP, EP, POCP and CED are increasing for post-combustion and IGCC. For post-combustion the increase is stronger than for IGCC and rise up to 200 % for EP. One LCA (Viebahn) denotes an increase for POCP even up to 530 % compared to the power plants without CCS, due to the production of monoethanolamine during the capture process. The share on the world wide POCP rises from only 0.01 % to 0.1 % (post-combustion), which is still very small. The absolute figures for the IGCC system are in the same range as for the other studies. Only Viebahn assumes a very small POCP value for the reference plant. For IGCC the increase is 60 % at most (Figure 4-13).

For the oxyfuel system all other categories decrease as well. Only the CED increases due to the energy penalty. The two LCAs for oxyfuel demonstrate values for AP (-15 % up to - 80%) and EP (- 30 up to - 80%). In contrast to hard coal, the studies show the same directions for the results, except for POCP. The obvious decrease of AP and EP compared to hard coal is related to the absence of considerable transport distances for lignite and associated NO_x and SO_2 emissions. Pehnt states in his study that the destiny of pollutions other than CO_2 is the most important uncertainty in an oxyfuel system. He even suggests a real “zero emission power plant” as one case in his study. Nevertheless, the same statement as for hard coal holds, that two studies are not sufficient to draw any conclusions. If the ration of lignite fuelled power plants remains small the impacts will stay negligible. Even an increase of more than 500 % using CCS for POCP will not have a noticeable effect on the total world wide impacts.

4.3.3 Natural Gas

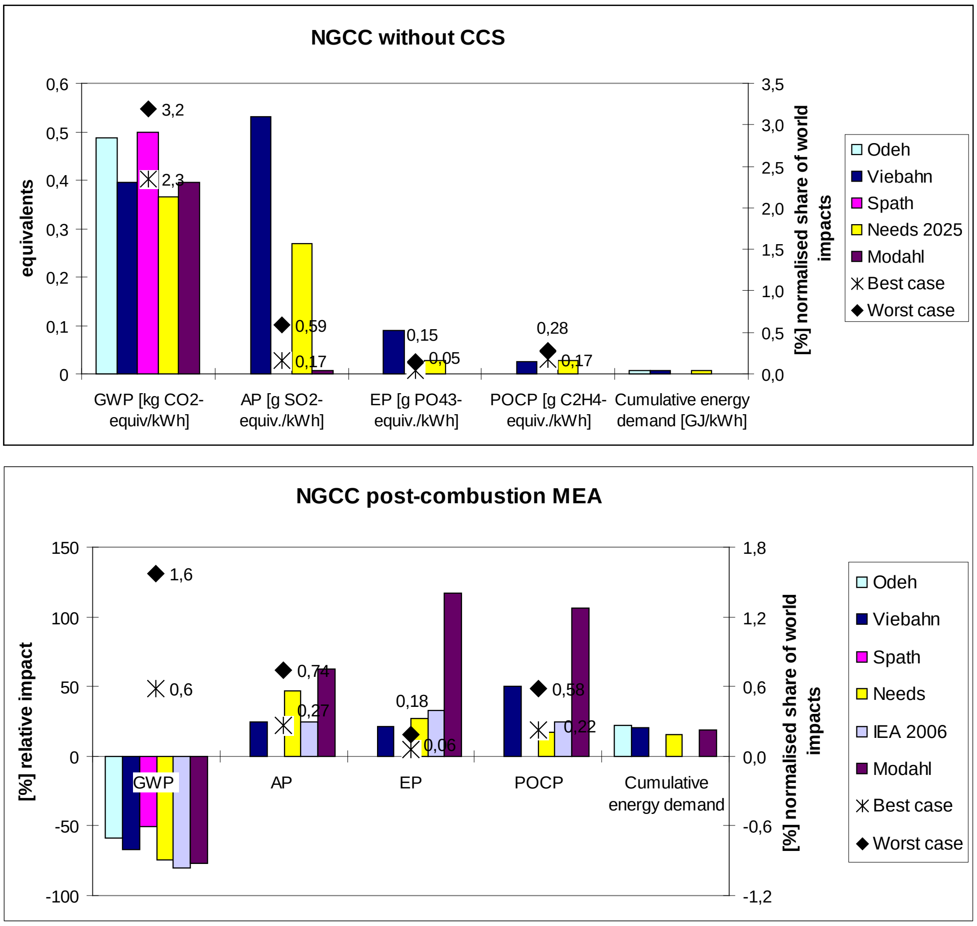


Figure 4-14: Environmental impacts of a natural gas combined cycle without capture and relative impacts of systems with post-combustion capture and normalised values related to the total world production in 2000 calculated for lowest and highest impact values

For natural gas only post-combustion systems are investigated so far. D’Addario considers also a pre-combustion system, but uses a different concept for comparison (functional unit 1 kWh, plus constant CO_2 capture rate, see also 4.2.1) and is therefore not considered in the direct comparison of the studies. According to their efficiency the GWP of natural gas fired power plants is much lower. With a power generation amount of about half of the hard coal fuelled plants the share on the total

GWP is less than a quarter (3.2 %, worst case). With CCS it comes down to 1.5 %. Within the studies no coherent picture concerning the other impact categories is shown, neither for the absolute impacts for systems without CCS nor for the post-combustion systems (Figure 4-14). The increase for AP, EP, POCP and CED is in the range between 15 % and 50 %, except for one LCA (Modahl). All normalised impacts are well below 1 % of the world total, even with the considered increase within the different categories. As well as the other fuels the results for GWP are the most uniform. This constitutes the assumption, that the understanding of future technology parameters is not very clear.

In summary for all fuel types and capture systems only GWP is a very robust impact parameter for comparison of LCAs among each other. For a reliable statement about the environmental impacts the number of studies for oxyfuel power plants, IGCC based on lignite and NGCC is too small anyway. Keeping this in mind, as a first tendency, the oxyfuel power plants show the lowest increase of environmental effects followed by IGCC and NGCC, presumably due to chemicals involved. It appears that the lower the maturity of a technology the fewer consensuses can be found about technical parameter.

Nevertheless, it cannot be expected, that even with a more uniform pattern for study development a clear “winner” can be found. It is most likely, that the technology ranking varies between the impact categories and further discussion about values and weighting is necessary. Therefore, it is important, that the results of the different impact categories are visible and no aggregation into one output figure, as being done by some studies using the eco-indicator or other sum parameters should be performed. At least the score for every impact category should be clearly stated before aggregation and the aggregation procedure should also be fully transparent.

5 Conclusions

As expected, it is difficult to obtain solid information about the environmental impacts of a specific CCS technology by comparing the studies. Especially, as it is impossible to describe all underlying assumptions and data in a paper or even in a report. However that would be necessary to understand all consequences of choices. Though several studies exist, the technology field of CCS is so broad that as yet only some facets are covered. Nevertheless, with these few existing studies it can already be identified which the sensitive parameters are and also which have only a minor impact on the overall results. To some extent methodological differences and their impact on the study outcomes can be identified. Preliminary guidelines and recommendations on how to interpret study outcomes can be formulated but must be confirmed by adding more studies into the comparison.

5.1 Sensitive parameters

Choice of reference system

One important determination at the beginning of every study is the choice of the reference system. The improvement potential of today's technologies is much higher than of enhanced future systems. At the same time the technical understanding becomes less verified for future components and furthermore CCS technology is not expected to be commercial before 2020.

Efficiency and energy penalty

A very important parameter set is the development of efficiency and the energy penalty connected with the capture process. The studies show no common understanding about how future technologies for the different fuels might look like with or without CCS. The expected efficiency varies from 37 % to 54 % for a hard coal system without CCS. The differences for a lignite system and a natural gas system without CCS are 11 %points and 12 %points, respectively. This is caused to some extent by the different time horizons considered, but mostly due to different future technology predictions. As the efficiency has a direct influence on all impact categories, the variation in results can be explained, even without considering the impacts of CCS technology. In addition to that, the inconsistent understanding of energy losses associated with the elements of the capture processes worsens the effect. Energy penalty ranges from 5 %points to 18 %points can be found looking across all capture technologies.

Capture efficiency

Directly associated with the unit operations employed during capture is the technical parameter CO_2 capture efficiency. Odeh shows in his report that the GWP increases by 11.3 % – 25.6 % if the capture efficiency decreases by 5 %. Koornneef states, that removal efficiencies included in the IPCC report of between 85 % and 96 % translate to a change in GWP of +20 % and -20 % respectively in relation to the 90 % he considers.

CO_2 purity

CO_2 purity is also a sensitive parameter for the capture and compression process, which has not attracted much interest in the LCA studies yet. The energy demand for compression, transportation and injection is mostly not explicitly expressed, let alone connectionist relationship with CO_2 purity.

Fuel composition and origin

However the studies outcome is most sensitive to the fuel origin, fuel type and fuel composition. Primarily, this influences the combustion process. Due to the increase in coal demand for CCS processes, the addition of a capture process intensifies this effect drastically as explicitly shown in Odeh and Schreiber. In Odeh the GWP changes from 3.5 % using different coal transport distances without CCS to 17 % when using CCS with its additional coal demand. Schreiber identifies an increase of GWP reduction from – 3 % to -15 %. Beside GWP all other impacts are affected as well. Mills concludes in his report, that when operating a power plant, coal, natural gas or oil may come from different sources at different times during the lifetime of the plant and that the location-specific nature of many LCA studies can make transfer of its findings and conclusions to other locations and situations very difficult. Without all background data it is not possible to answer, which part of the result is related to the technology and which to the fuel composition. For comparison of technologies themselves, this site related linkage is undesirable and the use of an identical fuel composition would be helpful, even though unrealistic. However, to find out where a specific technology can have which affect the regional differences must be considered.

5.2 Insignificant parameters

Transport and storage

There are several parameters which have been proved to be insignificant, mostly connected to the CO_2 transport and storage part of the process chain.

Some authors (Odeh, Schreiber, Wildbolz) conclude that the length of the CO_2 pipeline has only minor effects on the environmental impacts. An increase in transport distance from 300 km to 400 km increases overall GWP by less than 0.1 % (Odeh). Spath considers the largest distances with the share of transport in the total GWP rising from 0.1 % for 300 km to 1 % for 1800 km.

All studies which include transportation and storage into their analysis describe the contribution to the overall system as relatively small, though in a wide range (0.17 % Modahl - 10 % NEEDS, Viebahn), depending on the fuel used and the storage option. Therefore, one might conclude that a change in the storage system does not have a major impact on the overall results. Only Khoo and Wildbolz compare different sequestration options and support this assumption. Thus there are not yet enough studies available to confirm this suggestion.

Construction and dismantling

Typically for power production processes the construction and dismantling of the power plant has only a minor impact on the overall results (<0.2 % on GWP, Koornneef and Pehnt). This contribution will be expanded by adding CCS by up to 2 % for the power plant and up to 5 % (Koornneef) when including third order processes in the analysis.

5.3 Open questions

There are still some open questions for using LCA to analyse CCS. The most prominent in relation to CCS is, that at some point in the future a portion of the stored CO_2 could leak and cause negative environmental effects. This should be included into a full life cycle analysis. Firstly, the prediction of possible leakage for different storage systems is not clear so far. And secondly, the methodological problem, how to deal with long-term emissions in relation to emission reduction today, is not solved.

5.4 Guidelines

Taking the findings above into account, general guidelines can be formulated as to what to consider when comparing results from different studies:

- Despite the number of studies that already exist, it is hard to find studies with roughly the same parameters for comparison. Especially the key parameter sets energy efficiency and penalty, capture efficiency and CO_2 quality, as well as fuel composition should not vary drastically. As the assumptions for these parameter varies, a sensitivity analysis would help to classify the results.
- Statistical fault analyses, such as Monte-Carlo simulation, which is used to judge the robustness of results when dealing with extreme values to assess whether two products differ significantly, need a higher number of integrated studies.
- As many practitioners have a relatively clear picture about the performance of CO_2 capture the GWP results and fuel demand are the most robust figures. Some studies take only these results into account. Also, the understanding of emissions with acidification potential (mostly SO_2) is quite developed. EP and

POCP are considered quite often, too. Nevertheless, the associated emissions are not so well documented or modelled. CCS systems using and disposing solvents also have high toxicity potentials. The discussion on characterisation of toxic-related impact categories is far from being settled. Beside that, normalisation shows, that the absolute values are still quite small compared to other industries.

- Future LCA/CCS studies should consider a harmonised set of impact categories and corresponding indicators to make a comparison more straightforward.
- So far, hardly any weighting and aggregation to one figure is performed regularly. To keep the degree of transparency as high as possible the reporting only of aggregated results without full transparency of the aggregation method should be avoided. The use of more than one valuation method could enhance comparability and decrease uncertainties on the one hand. Otherwise the effort and the complexity increase. Besides it is not out of question that mistakes and misleading interpretations persist.
- Only a few studies have included the normalisation step into the analysis. To classify the results gathered, the figures must be reflected against those of a specific region. This helps to relate the different categories and to set priorities.

When more studies and therefore more robust information about CCS technologies exist a comparison to other mitigation possibilities such as renewable energy systems is desirable.

The results from an LCA can be used to identify weak points in a process chain of a specific technology and help to set benchmarks for the development of a technology. LCA is used to describe environmental aspects in a steady-state situation. For a dynamic situation, e.g. to include shut down periods or varying load factors, LCA is not the appropriate tool. When decisions have to be made about the most appropriate technology in a given situation LCA results must be combined with other assessment systems, which for example consider environmental risks, cost and market aspects, political frameworks or public acceptance.

6 Research recommendations

By comparing the studies, their methodological choices, technical assumptions and the derived results, several fields for further research can be identified.

Although several studies have been performed in the last years, there is still not sufficient data to draw any robust conclusions. To be able to test this robustness, e.g. by Monte-Carlo simulation or other methods, more studies are necessary.

The wide range of possible capture and storage technologies makes it difficult to make a sufficient number of comparable studies available. Especially for the oxyfuel process route, but also for the pre-combustion route, the number of investigations must be increased substantially. Although only two detailed studies looking at transport processes exist an increase in efforts in this area does not seem necessary at the moment. Conclusions by analogy with transportation systems of other gases, e.g. natural gas pipelines or ship transport for LNG, and the findings of the existing studies are sufficient at the moment, especially as transport gives rise to only a small share of the overall impacts.

Although latter is also true for storage, there is still not enough information about this part of CCS. Especially the variety of possible ways to store CO_2 is not yet covered. The existing results for the storage process must be compared, to get a better understanding of the processes. Most often they are not expressed explicitly. Also, there is no agreement on how to estimate and treat possible leakage during storage. These impacts have to be investigated using a sensitivity analysis, at least. That does not however solve the problem of how to value long-term emissions versus today's emission reductions through capture. This is a typical methodological LCA problem that has to be further addressed. As mentioned earlier, the site specific aspects of a storage site, such as geological and hydrological characteristics are important. LCA is not always the appropriate tool to support this discussion.

When performing more LCAs to get a sufficient number of studies, there are some aspects where an advanced common understanding is necessary to draw a clearer picture. First of all it must be clear which type of technologies should be included into the technology comparison. New, second generation, technologies, such as chilled ammonia, membranes or others, should be covered also. However widening the portfolio of technologies to investigate will cause a great demand for new studies. A compromise between representation of different technologies and study numbers must be found.

To guarantee the comparability of the studies, it is helpful to have a set of background or benchmark information about technologies. Here, a common understanding about efficiency development and even more about energy penalty has shown to be one key parameter set for the discussion.

Another discussion, which is in its infancy, is the question about different CO_2 qualities and CO_2 products. Are two processes really comparable if they do have the same functional unit of 1 kWh electricity but also two different CO_2 products with different values, such as properties and prices, and most probably different arrangements to reach them?

There are some upstream and downstream processes which have a high impact on the results. While first preliminary estimations for hard coal or lignite exist, hardly any investigation for natural gas has been performed so far. Nevertheless, the importance of this parameter has been proved. As it cannot be expected, that all practitioners use the same coal input, it would be helpful to present the underlying coal parameters, such as composition, heating value and transport distances, at least. Also the production and waste management of solvent has a major impact on the results. Until now, most studies use data from the data base ecoinvent. As the results are so important, it is worth to have a more detailed look into these upstream and downstream process chains as well.

To reduce the efforts for the LCA it is helpful to have an agreement about impact categories, which have to be considered. Also the commitment of the particular category indicators yields in a higher number of comparable data. To get a better understanding of the results it is highly important to consider them in the context of the impacts for a specific region, in the normalisation step, so that no overestimation of importance takes place.

Once a sufficient number of studies exist and the understanding of the life cycle effects of CCS is quite robust, the comparison of CCS with other GHG emission mitigation measures, particularly renewable energies, will be inevitable. Important in this is the investigation of co-firing with biofuel which is not yet sufficiently investigated and the existing two studies show contrary results. Overall performance benchmarks can be concluded out of this form of comparison and once established can help to identify development targets for CCS. Again, the precise definition of the functional unit will become a subject of discussion which will have to be resolved in order to be able to compare conventional and renewable systems. The different availability of 1 kWh of electricity produced by these alternative systems has to be kept in mind when defining the systems boundaries for a Life Cycle Assessment.

7 Summary

Since the IEA's "Full Fuel Cycle Study" in 1994 the technology of CCS has developed continuously. At the same time the methodology for analysing environmental impacts has been consolidated significantly. Especially in the last 5 years, several studies on life cycle perspectives covering various parts of CCS have been performed. However, the results from the various studies cannot be compared easily. A thorough understanding of the systems considered and their boundaries is indispensable to understand and interpret the various results. Also for practitioners of LCA it is not possible to openly lay out all the assumptions and data sufficiently to provide full transparency.

Fourteen studies have been chosen for comparison. Many of them (8) have a European focus, three consider the US situation, one looks at the Japanese situation and two have a global approach. Unfortunately, no studies for Australia or other Asian Countries could be found, to complete the world-wide scope of the comparison.

Carbon capture and storage is a wide field with various technological options. In almost all studies the main focus is on the capture technology. Most studies investigate the post-combustion route, with MEA scrubbing technology as one option in their analysis. Pre-combustion is investigated less frequently and oxyfuel is considered in only three studies. Except for two studies, all choose hard coal as at least one of the fuel options. The studies with German focus also include lignite fuelled power plants. Natural gas is considered in half of the studies.

Transportation and storage is investigated less sophisticatedly than the capture process. Two studies focus specifically on the life cycles of those two stages. The most prominent option for transport is a pipeline system. Depleted gas fields or saline aquifers are investigated as the storage possibilities. However the percentage on the overall impacts of those two stages on the overall life cycle of CCS is small, between 0.8 % and 10 %.

With CO_2 emission reduction being the focus of CCS all studies analyse the GWP of the technologies based on a very sound understanding of cause, path and fate. Using the LCA approach many studies also widen the environmental aspect to other impact categories, such as AP, EP, HTP or resource consumption etc. Unfortunately, there is no common understanding about what should be considered and what the related category indicator/model is.

All studies show the expected reduction in GWP related to the capture rate, efficiency losses and fuel used. However, all other impact categories increase, due to the energy penalty connected with the capture process and with the associated additional fuel demand. Beside additional fuel supply another main environmental issue is the use of large amounts of amines or other solvents in CO_2 capture processes, their losses into the atmosphere and the disposal of their degradation products. Only the oxyfuel process shows also a reduction for AP and EP in some studies, mostly due to the absence of solvents. As only three studies include oxyfuel, this result is not considered to be robust. The results for gas driven power plants and CCS are the most disperse figures.

Three parameter sets have been identified, which have a significant impact on the results. First there is the understanding of today's and future combustion plant efficiencies and energy penalties associated with the capture process. Differences in the expected efficiencies of 11 %points to 17 %points, depending on the fuel can be found in the studies. The energy penalty due to capture varies between 5 %points and 18 %points. As all impact categories are directly related to these parameters the differences can also be found in the impacts and are intensified when including upstream and downstream processes.

Another group of parameters is related to the capture efficiency and the purity of the CO_2. A decrease in capture efficiency by 5 % results in an increase of GWP of about 20 %. The subject of CO_2 purity is not yet expressed in the studies, although it has a significant impact on efficiency, demand for purification, compression, transport, injection and storage. Additionally the CO_2 storage capacity decreases with increasing impurities.

The third parameter with a very high impact on the results is the fuel composition and its origin. Its impact on the GWP results can be considerable. As most studies consider different fuel compositions a comparison of technologies becomes unfeasible since it is impossible to show which part of the result is to be attributed to differences in technology and which to the fuel. For comparison of technologies themselves the use of an identical fuel composition would be helpful. Sensitivity analyses are a helpful way in which to estimate the impact of important parameters, as it is unlikely, that all studies can use the same core data. For better understanding of the results it is helpful to reflect them against those of specific regions by a normalisation step.

More studies covering the various field of CCS including also new technologies, such as chilled ammonia or membranes, will help to clarify the findings so far. The results can already be used to identify weak points along the process chain and help to formulate research and development targets.

With a clearer picture about the environmental performance of CCS technologies, the comparison can be widened to other CO_2 mitigation options such as the introduction of renewable energy, which is already done in three studies. This helps also to identify benchmarks. Here it is important to look at the same functional unit. If the electricity production of renewable energy system is highly fluctuating due to the weather for example the system has to be expanded with an electricity storage system to provide the same availability as a fossil fuelled power system. However LCA is not an appropriate tool to analyse power availability.

The decision maker has to set priorities, as the studies show no clear winner. They have to combine the results for the environmental performance with other information, such as economic, social or political to make more comprehensive and balanced decisions.

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Appendix A: Study summary

Table 1: Main Process parameters of the investigated plants

Study/Plant	Net generating capacity (MWel)	Net efficiency (%)	Net penalty (%)	SCR efficiency NO_x (%)	ESP/FGD efficiency particulates (%)	FGD efficiency SO_2 (%)	CO_2 capture rate (%)
D'Addario 2003							
NGCC	1.00E+03	5.40E+01	-	-	-	-	-
NGCC/CC (post, MEA)	1.00E+03	4.68E+01	7.20E+00	5.00E+01	9.00E+01	9.00E+01	9.23E+01
NGCC/CC (post, MGA)	1.00E+03	4.63E+01	7.70E+00	-	-	-	8.99E+01
NGCPO/CC (pre, MDEA)	1.00E+03	4.46E+01	9.40E+00	-	-	-	8.78E+01
Doctor 2001							
IGCC Bituminous	4.13E+02						-
IGCC Bituminous/CC (pre, Glycol)	1.10E+02						9.00E+01
(IEA IGCC/CC *)	6.46E+02						-
IEA 2006							
NGCC	7.76E+02	5.56E+01	-				
NGCC/CC (post, MEA)	6.62E+02	4.74E+01	8.20E+00				
POCC	7.85E+02	5.59E+01	-				
POCC/CC (pre, MDEA)	6.94E+02	4.15E+01	1.44E+01				
USCPF Bituminous	7.58E+02	4.40E+01	-				
USCPF Bituminous/CC (post, MEA)	6.66E+02	3.48E+01	9.20E+00				
IGCC Bituminous	7.76E+02	4.31E+01	-				
IGCC Bituminous/CC (pre, MDEA)	6.83E+02	3.50E+01	8.10E+00				
Khoo 2006							
PC Hard coal/CC (post, MEA)				9.00E+01		9.00E+01	9.50E+01
Koornneef 2008							
PC Hard coal	4.60E+02	3.50E+01	-	6.00E+01	9.995E+01	9.00E+01	-
Super-PC Hard coal	6.00E+02	4.60E+01	-	8.50E+01	9.998E+01	9.80E+01	-
Super-PC Hard coal/CCS (post, MEA)	4.55E+02	3.50E+01	1.10E+01	8.50E+01	9.998E+01	9.80E+01	9.00E+01

* not modelled, results only used for comparison

Continuation Table 1: Main Process parameters of the investigated plants							
Study/Plant	**Net generating capacity (MWel)**	**Net efficiency (%)**	**Net penalty (%)**	**SCR efficiency NO_x (%)**	**ESP/FGD efficiency particulates (%)**	**FGD efficiency SO_2 (%)**	**CO_2 capture rate (%)**
Korre 2009							
PC Bituminous							
PC Bituminous/CC (post, MEA)							
Lombardi 2003							
SCGT/CC	2.43E+02	5.16E+01	-				-
SCGT/CC/CC (post, DEA+MDEA)	-	4.60E+01	5.60E+00				8.50E+01
IGCC Hard coal	3.44E+02	4.64E+01	-				-
IGCC Hard coal/CC (pre, DEA+MDEA)	2.88E+02	3.88E+01	7.60E+00				8.50E+01
Modahl 2009							
NGCC	8.32E+02	5.91E+01					-
NGCC/CCS (post, MEA)	7.02E+02	4.48E+01					9.00E+01
Muramatsu 2002							
PC Hard Coal		4.06E+01	-				-
PC Hard Coal/CCS (post, MEA)		3.08E+01	9.80E+00				9.00E+01
PC Hard Coal/CCS (post, KS-1)		3.33E+01	7.30E+00				9.00E+01
NEEDS 2008							
PC Lignite 2025	9.50E+02	4.90E+01	-				-
PC Lignite/CCS (post, MEA)	8.00E+02	4.20E+01	7.00E+00				9.00E+01
PC Lignite/CCS (Oxyfuel)	8.00E+02	4.10E+01	8.00E+00				9.95E+01
PC Hard coal 2025	6.00E+02	4.90E+01	-				-
PC Hard coal/CCS (post, MEA)	5.00E+02	4.20E+01	7.00E+00				9.00E+01
PC Hard coal/CCS (Oxyfuel)	5.00E+02	4.10E+01	8.00E+00				9.95E+01
IGCC Lignite 2025	4.50E+02	5.20E+01	-				-
IGCC Lignite/CCS (pre)	4.00E+02	4.60E+01	6.00E+00				9.00E+01
IGCC Hard coal 2025	4.50E+02	5.40E+01	-				-
IGCC Hard coal/CCS (pre)	4.00E+02	4.80E+01	6.00E+00				9.00E+01

Continuation Table 1: Main Process parameters of the investigated plants							
Study/Plant	**Net generating capacity (MWel)**	**Net efficiency (%)**	**Net penalty (%)**	**SCR efficiency NO_x (%)**	**ESP/FGD efficiency particulates (%)**	**FGD efficiency SO_2 (%)**	**CO_2 capture rate (%)**
Continuation NEEDS 2008							
NGCC 2025	5.00E+02	6.20E+01	-				-
NGCC/CCS (post, MEA)	5.00E+02	5.60E+01	6.00E+00				9.00E+01
Odeh 2008							
PC Hard Coal	4.75E+02	3.53E+01	-	7.50E+01	9.95E+01	9.00E+01	-
Super-PC Hard Coal	4.53E+02	3.96E+01	-	7.50E+01	9.95E+01	9.00E+01	-
Super-PC Hard coal/CCS (post, MEA)	3.35E+02	3.00E+01	9.60E+00	7.50E+01	9.95E+01	9.80E+01	9.00E+01
NGCC	5.00E+02	5.01E+01	-	-	-	-	-
NGCC/CCS (post, MEA)	4.32E+02	4.28E+01	7.30E+00	-	-	-	9.00E+01
IGCC Hard coal	5.00E+02	3.72E+01	-	-	-	-	-
IGCC Hard coal/CCS (pre, Selexol)	4.71E+02	3.20E+01	5.20E+00	-	-	9.50E+01*	9.00E+01
Pehnt 2008							
PC Lignite.	All plants in the Range of 5.00E+02 – 8.00E+02 MW	4.60E+01	-	-	-	9.50E+01	-
PC Lignite/CCS (post, MEA)		2.78E+01	1.82E+01	-	-	9.90E+01	9.00E+01
IGCC Lignite		4.80E+01	-	-	-	9.90E+01	-
IGCC Lignite/CCS (pre, Selexol)		3.87E+01	9.30E+00	-	-	9.90E+01	9.00E+01
Oxyfuel Lignite/CCS		3.34E+01	-	9.20E+01	9.20E+01	9.20E+01	9.20E+01
Schreiber 2009							
Hard coal Pittsburgh No.8							
PC 1990	5.00E+02	3.90E+01	-	7.50E+01	9.98E+01	9.72E+01	-
PC 1990-2008	5.00E+02	4.30E+01	-	7.50E+01	9.98E+01	9.72E+01	-
PC 2008-2020	5.52E+02	4.60E+01	-	7.50E+01	9.98E+01	9.72E+01	-
PC 2020+	6.78E+02	4.90E+01	-	7.50E+01	9.98E+01	9.72E+01	-
PC/CC 1990-2008 (post, MEA)	3.44E+02	2.96E+01	1.34E+01	7.50E+01	9.98E+01	9.72E+01	9.00E+01
PC/CC 2008-2020 (post, MEA)	3.91E+02	3.26E+01	1.34E+01	7.50E+01	9.98E+01	9.72E+01	9.00E+01
PC/CC Greenfield (post, MEA)	5.34E+02	3.75E+01	1.15E+01	7.50E+01	9.98E+01	9.95E+01	9.00E+01
*****: Sulphur recovery efficiency							

Continuation Table 1: Main Process parameters of the investigated plants							
Study/Plant	**Net generating capacity (MWel)**	**Net efficiency (%)**	**Net penalty (%)**	**SCR efficiency NO_x (%)**	**ESP/FGD efficiency particulates (%)**	**FGD efficiency SO_2 (%)**	**CO_2 capture rate (%)**
Continuation Schreiber 2009							
Hard coal Kleinkopje							
PC 1990	5.00E+02	3.90E+01	-	7.50E+01	9.98E+01	8.80E+01	-
PC 1990-2008	5.00E+02	4.30E+01	-	7.50E+01	9.98E+01	8.86E+01	-
PC 2008-2020	5.52E+02	4.60E+01	-	7.50E+01	9.98E+01	8.89E+01	-
PC 2020+	6.98E+02	4.90E+01	-	7.50E+01	9.98E+01	8.89E+01	-
PC/CCS 1990-2008 (post, MEA)	3.44E+02	2.96E+01	1.34E+01	7.50E+01	9.98E+01	8.86E+01	9.00E+01
PC/CCS 2008-2020 (post, MEA)	3.91E+02	3.26E+01	1.34E+01	7.50E+01	9.98E+01	8.89E+01	9.00E+01
PC/CCS Greenfield (post, MEA)	5.34E+02	3.75E+01	1.15E+01	7.50E+01	9.98E+01	9.78E+01	9.00E+01
Lignite Rheinland Garzweiler		.					
PC 1990	4.74E+02	3.60E+01	-	-	9.99E+01	9.08E+01	-
PC 1990-2008	7.59E+02	4.10E+01	-	-	9.99E+01	9.08E+01	-
PC 2008-2020	9.64E+02	4.45E+01	-	-	9.99E+01	9.08E+01	-
PC 2020+	9.64E+02	4.80E+01	-	-	9.99E+01	9.08E+01	-
PC/CC 1990-2008 (post, MEA)	4.87E+02	2.63E+01	1.47E+01	-	9.98E+01	9.09E+01	9.00E+01
PC/CC 2008-2020 (post, MEA)	6.46E+02	2.98E+01	1.47E+01	-	9.98E+01	9.09E+01	9.00E+01
PC/CC Greenfield (post, MEA)	7.09E+02	3.53E+01	1.27E+01	-	9.98E+01	9.82E+01	9.00E+01
Lignite Lausitz							
PC 1990	4.74E+02	3.60E+01	-	-	9.99E+01	9.08E+01	-
PC 1990-2008	7.59E+02	4.10E+01	-	-	9.99E+01	9.08E+01	-
PC 2008-2020	9.64E+02	4.45E+01	-	-	9.99E+01	9.08E+01	-
PC 2020+	9.64E+02	4.80E+01	-	-	9.99E+01	9.08E+01	-
PC/CCS 1990-2008 (post, MEA)	4.87E+02	2.63E+01	1.47E+01	-	9.98E+01	9.01E+01	9.00E+01
PC/CCS 2008-2020 (post, MEA)	6.46E+02	2.98E+01	1.47E+01	-	9.98E+01	9.01E+01	9.00E+01
PC/CCS Greenfield (post, MEA)	7.09E+02	3.53E+01	1.27E+01	-	9.98E+01	9.81E+01	9.00E+01
Spath 2004							
PC Bituminous	6.00E+02	4.10E+01	-				-
PC Bituminous/CCS (post, MEA)	4.57E+02	3.12E+01	9.80E+00				9.00E+01
NGCC	6.00E+02	4.88E+01	-				-
NGCC/CCS (post, MEA)	5.04E+02	-	-				9.00E+01

Continuation Table 1: Main Process parameters of the investigated plants							
Study/Plant	**Net generating capacity (MWel)**	**Net efficiency (%)**	**Net penalty (%)**	**SCR efficiency NO_x (%)**	**ESP/FGD efficiency particulates (%)**	**FGD efficiency SO_2 (%)**	**CO_2 capture rate (%)**
Viebahn 2007							
PC Hard coal	7.00E+02	4.90E+01	-	8.50E+01	9.95E+01	9.00E+01	-
PC Hard coal/CCS (post, MEA)	5.70E+02	4.00E+01	9.00E+00	8.50E+01	9.95E+01	9.00E+01	8.80E+01
PC Hard coal/CCS (Oxyfuel)	5.43E+02	3.80E+01	1.10E+01	-	-	-	9.95E+01
IGCC Hard coal	7.00E+02	5.00E+01	-	-	-	-	-
IGCC Hard coal/CCS (pre, Rectisol)	5.90E+02	4.20E+01	8.00E+00	-	-	-	8.80E+01
PC lignite	7.00E+02	4.60E+01	-	-	-	-	-
PC lignite/CCS (post, MEA)	5.17E+02	3.40E+01	1.20E+01	-	-	-	8.80E+01
NGCC	7.00E+02	6.00E+01	-	-	-	-	-
NGCC/CCS (post, MEA)	6.00E+02	5.10E+01	9.00E+00	-	-	-	8.80E+01

Table 2: Main Input Values of the investigated Studies

Study/Plant	Coal/Gas (g/kWh)	MEA (g/kWh)	Selexol (g/kWh)	NaoH (g/kWh)	Limestone (g/kWh)	Energy for capture proc. (kWh/tCO_2 cap.)	Other (g/kWh)
D'Addario 2003							
NGCC	1.49E+02						
NGCC/CC (post, MEA)	1.71E+02						
NGCC/CC (post, MGA)	1.76E+02						
NGCPO/CC (pre, MDEA)	1.80E+02						
Doctor 2001							
IGCC Bituminous							
IGCC Bituminous/CC (pre, Glycol)							
(IEA IGCC/CC)*							
IEA 2006			MDEA (g/kWh)				
NGCC	1.38E+02	-	-		-		
NGCC/CC (post, MEA)	1.62E+02	6.13E-01	-		-		
POCC	1.37E+02	-	-		-		
POCC/CC (pre, MDEA)	1.84E+02	-	5.03E-03		-		
USCPF Bituminous	3.17E+02	-	-		8.37E+00		
USCPF Bituminous/CC (post, MEA)	4.00E+02	1.31E+00	-		1.16E+01		
IGCC Bituminous	3.23E+02	-	-		-		
IGCC Bituminous/CC (pre, MDEA)	3.997E+02	-	1.114E-02		-		
Khoo 2006							
PC Hard coal/CC (post, MEA)	4.72E+02*[1]				1.03E+02*[1]	3.30E+02	
	direct/total	(kg/t CO_2cap)		(kg/t CO_2cap)			Activated carbon
Koornneef 2008							(kg/t CO_2 capt.)
PC Hard coal	4.41/4.47E+02	-		-	7.73E+00	-	-
Super-PC Hard coal	3.38/3.43E+02	-		-	5.64E+00	-	-
Super-PC Hard coal/CCS (post, MEA)	4.44/4.51E+02	2.34E+00		1.30E-01	7.51E+00	2.46E+02	7.50E-02

* not modelled, results only used for comparison
*[1] value for electricity generation of the power plant without capture

Continuation Table 2: Main Input Values of the investigated Studies

Study/Plant	Coal/Gas (g/kWh)	MEA (g/kWh)	Selexol (g/kWh)	NaoH (g/kWh)	Limestone (g/kWh)	Energy for capture Proc. (kWh/tCO_2 cap.)	Other (g/kWh)
Korre 2009						kW/kWh	Activated carbon
PC Bituminous		-		-		-	-
PC Bituminous/CC (post, MEA)		1.075E+00		4.70E-02		3.40E-02	2.70E-02
Lombardi 2003							
SCGT CC							
SCGT CC/CC (post, DEA+MDEA)							
IGCC Hard coal							
IGCC Hard coal/CC (pre, DEA+MDEA)							
Modahl 2009							
NGCC							
NGCC/CCS (post, MEA)							
Muramatsu 2002							
PC Hard Coal							
PC Hard Coal/CCS (post, MEA)							
PC Hard Coal/CCS (post, KS-1)							
NEEDS 2008							
PC Lignite 2025	8.36E+02						
PC Lignite/CCS (post, MEA)	9.78E+02						
PC Lignite/CCS (Oxyfuel)	1.00E+03						
PC Hard coal 2025	3.91E+02						
PC Hard coal/CCS (post, MEA)	4.60E+02						
PC Hard coal/CCS (Oxyfuel)	4.71E+02						
IGCC Lignite 2025	4.25E+02						
IGCC Lignite/CCS (pre)	4.80E+02						
IGCC Hard coal 2025	3.33E+02						
IGCC Hard coal/CCS (pre)	3.78E+02						
NGCC 2025	1.76E-01*						
NGCC/CCS (post, MEA)	1.99E-01*						
	*(Nm^3/kWh)						

Continuation Table 2: Main Input Values of the investigated Studies							
Study/Plant	**Coal/Gas** (g/kWh)	**MEA** (g/kWh)	**Selexol** (g/kWh)	**NaoH** (g/kWh)	**Limestone** (g/kWh)	**Energy for capture Proc.** (kWh/tCO_2 cap.)	**Other** (g/kWh)
Odeh 2008							NH3
PC Hard Coal	3.30E+02	-	-		1.90E+01		6.80E-01
Super-PC Hard Coal	2.95E+02	-	-		1.69E+01		6.10E-01
Super-PC Hard coal/CCS (post, MEA)	3.90E+02	3.60E+00	-		2.72E+01		8.00E-01
NGCC	1.30E+02	-	-		-		2.00E-01
NGCC/CCS (post, MEA)	1.51E+02	1.33E+00	-		-		2.30E-01
IGCC Hard coal	3.15E+02	-	2.00E-02		-		-
IGCC Hard coal/CCS (pre, Selexol)	3.66E+02	-	3.00E-02		-		-
Pehnt 2008		(kg/t CO_2cap)					
PC Lignite.		-				-	
PC Lignite/CCS (post, MEA)		1.50E+00				-	
IGCC Lignite		-				-	
IGCC Lignite/CCS (pre, Selexol)		-				-	
Oxyfuel Lignite/CCS		-				1.96E+02*[1]	
Schreiber 2009*							NH_3
Hard coal Pittsburgh No.8							
PC 1990	3.11E+02	-		-	2.54E+01	-	7.00E-01
PC 1990-2008	2.82E+02	-		-	2.30E+01	-	6.00E-01
PC 2008-2020	2.63E+02	-		-	2.15E+01	-	6.00E-01
PC 2020+	2.47E+02	-		-	2.02E+01	-	5.00E-01
PC/CC 1990-2008 (post, MEA)	4.09E+02	2.60E+00		1.30E-01	3.34E+01	3.16E+02	9.00E-01
PC/CC 2008-2020 (post, MEA)	3.72E+02	2.30E+00		1.20E-01	3.04E+01	3.16E+02	8.00E-01
PC/CC Greenfield (post, MEA)	3.23E+02	1.30E+00		1.00E-01	2.70E+01	2.53E+02	7.00E-01
Hard coal Kleinkopje							
PC 1990	3.69E+02	-		-	5.80E+00	-	7.00E-01
PC 1990-2008	3.35E+02	-		-	5.30E+00	-	6.00E-01
PC 2008-2020	3.13E+02	-		-	4.90E+00	-	6 00E-01
PC 2020+	2.94E+02	-		-	4.60E+00	-	5.00E-01

***** all data without upstream and downstream processes
*****[1] Energy for oxygen production (kWh/t O_2)

Continuation Table 2: Main Input Values of the investigated Studies							
Study/Plant	**Coal/Gas** (g/kWh)	**MEA** (g/kWh)	**Selexol** (g/kWh)	**NaoH** (g/kWh)	**Limestone** (g/kWh)	**Energy for capture Proc.** (kWh/tCO2 cap.)	**Other** (g/kWh)
Continuation Schreiber 2009*							
Hard coal Kleinkopje							
PC/CCS 1990-2008 (post, MEA)	4.87E+02	2.70E+00		1.40E-01	7.70E+00	3.16E+02	9.00E-01
PC/CCS 2008-2020 (post, MEA)	4.42E+02	2.40E+00		1.20E-01	7.00E+00	3.16E+02	8.00E-01
PC/CCS Greenfield (post, MEA)	3.84E+02	1.30E+00-		1.10E-01	6.70E+00	2.53E+02	7.00E-01
Lignite Rheinland Garzweiler							
PC 1990	8.75E+02	-		-	8.00E+00	-	-
PC 1990-2008	7.68E+02	-		-	7.00E+00	-	-
PC 2008-2020	7.07E+02	-		-	6.50E+00	-	-
PC 2020+	6.56E+02	-		-	6.00E+00	-	activated carbon
PC/CC 1990-2008 (post, MEA)	1.197E+03	3.00E+00		1.50E-01	1.09E+01	3.16E+02	9.00E-02
PC/CC 2008-2020 (post, MEA)	1.057E+03	2.60E+00		1.40E-01	9.70E+00	3.16E+02	8.00E-02
PC/CC Greenfield (post, MEA)	8.92E+02	1.40E+00		1.20E-01	8.80E+00	2.53E+02	7.00E-02
Lignite Lausitz							
PC 1990	9.68E+02	-		-	8.20E+00	-	-
PC 1990-2008	8.50E+02	-		-	7.20E+00	-	-
PC 2008-2020	7.83E+02	-		-	6.60E+00	-	-
PC 2020+	7.26E+02	-		-	6.20E+00	-	activated carbon
PC/CCS 1990-2008 (post, MEA)	1.325E+03	3.30E+00		1.70E-01	1.12E+01	3.16E+02	1.00E-01
PC/CCS 2008-2020 (post, MEA)	1.169E+03	2.90E+00		1.50E-01	9.90E+00	3.16E+02	9.00E-02
PC/CCS Greenfield (post, MEA)	9.87E+02	1.60E+00		1.30E-01	9.10E+00	2.53E+02	7.00E-02
Spath 2004							
PC Bituminous							
PC Bituminous/CCS (post, MEA)							
NGCC							
NGCC/CCS (post, MEA)							

***** all data without upstream and downstream processes

Continuation Table 2: Main Input Values of the investigated Studies							
Study/Plant	**Coal/Gas** (g/kWh)	**MEA** (g/kWh)	**Selexol** (g/kWh)	**NaoH** (g/kWh)	**Limestone** (g/kWh)	**Energy for capture Proc.** (kWh/tCO2 cap.)	**Other** (g/kWh)
Viebahn 2007		(kg/t CO_2cap)		(kg/t CO_2cap)			
PC Hard coal		-		-		-	
PC Hard coal/CCS (post, MEA)		2.25E+00		1.52E-01		2.36E+02	
PC Hard coal/CCS (Oxyfuel)		-		-		2.25E+02*	
IGCC Hard coal		-		-		-	
IGCC Hard coal/CCS (pre, Rectisol)		-		-		2.03E+02	
PC lignite		-		-		-	
PC lignite/CCS (post, MEA)		2.25E+00		1.52E-01		1.77E+02	
NGCC		-		-		-	
NGCC/CCC (post, MEA)		1.76E+00		1.52E-01		5.31E+02	

***** Energy for oxygen production (kWh/t O_2)

Table 3: Main output Values of the investigated Studies

Study/Plant	CO_2 (g/kWh)	CH_4 (g/kWh)	SO_2 (g/kWh)	NO_x (g/kWh)	Particulates (mg/kWh)	Other (g/kWh)	Other (g/kWh)
D'Addario 2003						SOx	CO
NGCC	4.02E+02	7.20E-01		3.00E-01		5.50E-03	1.42E-01
NGCC/CC (post, MEA)	5.80E+01	8.30E-01		1.80E-01		5.30E-03	1.64E-01
NGCC/CC (post, MGA)	7.00E+01	8.50E-01		1.90E-01		5.00E-03	1.68E-01
NGCPO/CC (pre, MDEA)	8.00E+01	8.40E-01		3.10E-01		8.70E-03	1.70E-02
Doctor 2001							
IGCC Bituminous							
IGCC Bituminous/CC (pre, Glycol)							
(IEA IGCC/CC)*							
IEA 2006				NO_2		MEA	
NGCC	3.79E+02		3.27E-03	6.63E-02		-	
NGCC/CC (post, MEA)	6.67E+01		-	6.53E-02		1.80E-02	
POCC	3.71E+02		-	-		-	
POCC/CC (pre, MDEA)	7.20E+02		-	-		-	
USCPF Bituminous	7.39E+02		7.97E-01	7.97E-01		-	
USCPF Bituminous/CC (post, MEA)	1.17E+02		4.00E-02	8.08E-01		1.10E-02	
IGCC Bituminous	7.72E+02		3.76E-03	3.76E-02	3.76E-02	-	
IGCC Bituminous/CC (pre, MDEA)	1.36E+02		7.05E-03	5.18E-01	3.51E-02	-	
Khoo 2006						SO_x	
PC Hard coal/CC (post, MEA)	9.50E+02*1 (977 with mining and Transport)	8.50E-03 (0.91 with mining and transport)		3,12E+00*1	9.18E+03*1	6,53E+00*1	
Koornneef 2008					(mg/kWh)	MEA	NH3
PC Hard coal	1.05E+03	1.47E+00	1.41E+00	1.94E+00	9.78E+1 1.51E+3	2.63E-07	6.30E-02
Super-PC Hard coal	8.05E+02	1.13E+00	7.10E-01	1.03E+00	6.73E+1 1.11E+3	1.99E-07	4.70E-02
Super-PC Hard coal/CCS (post, MEA)	2.00E+02	1.51E+00	8.40E-01	1.39E+00	8.49E+1 1.46E+3	1.23E-02	2.49E-01
					<10µm >10µm		

* not modelled, results only used for comparison
*1 value for electricity generation of the power plant without capture

Continuation Table 3: Main output Values of the investigated Studies							
Study/Plant	**CO2** (g/kWh)	**CH4** (g/kWh)	**SO2** (g/kWh)	**NOx** (g/kWh)	**Particulates** (g/kWh)	**Other** (g/kWh)	**Other** (g/kWh)
Korre 2009	Only the values for the modul coal combustion and carbon capture are listed in the paper. Values for the complete chain are not listed.						
PC Bituminous							
PC Bituminous/CC (post, MEA)							
Lombardi 2003							
SCGT CC	3.88E+02						
SCGT CC/CC (post, DEA+MDEA)	6.50E+01						
IGCC hard coal	7.25E+02						
IGCC hard coal/CC (pre, DEA+MDEA)	1.30E+02						
Modahl 2009							
NGCC							
NGCC/CCS (post, MEA)							
Muramatsu 2002							
PC Hard Coal							
PC Hard Coal/CCS (post, MEA)							
PC Hard Coal/CCS (post, KS-1)							
NEEDS 2008					PM2.5		
PC Lignite 2025	8.08E+02	2.15E-01	1.20E-01	6.41E-01	5.54E-02		
PC Lignite/CCS (post, MEA)	1.40E+02	3.21E-01	1.54E-01	8.03E-01	6.93E-02		
PC Lignite/CCS (Oxyfuel)*	2.70E+01	2.76E-01	1.23E-01	3.02E-01	6.79E-02		
PC Hard coal 2025	7.05E+02	2.17E+00	5.24E-01	7.26E-01	4.65E-02		
PC Hard coal/CCS (post, MEA)	1.41E+02	2.59E+00	3.70E-01	8.94E-01	5.86E-02		
PC Hard coal/CCS (Oxyfuel)*	4.49E+01	2.61E+00	3.49E-01	5.94E-01	5.74E-02		
IGCC Lignite 2025	7.77E+02	1.21E-01	5.76E-01	3.94E-01	2.55E-03		
IGCC Lignite/CCS (pre)	1.29E+02	1.93E-01	7.50E-01	5.30E-01	5.50E-03		
IGCC Hard coal 2025	6.42E+02	1.85E+00	3.54E-01	4.18E-01	9.31E-03		
IGCC Hard coal/CCS (pre)	1.20E+02	2.12E+00	4.41E-01	5.19E-01	1.26E-02		
NGCC 2025	3.67E+02	7.71E-01	1.31E-01	1.82E-01	7.18E-03		
NGCC/CCS (post, MEA)	9.50E+01	8.87E-01	1.60E-01	1.85E-01	9.78E-03		
* for oxyfuel Transport distance 200km, 800km aquifer storage, all other plants 400 km transport distance and storage in 2500m depleted gas field.							

Continuation Table 3: Main output Values of the investigated Studies							
Study/Plant	CO_2 (g/kWh)	CH_4 (g/kWh)	SO_2 (g/kWh)	NO_x (g/kWh)	Particulates (g/kWh)	Other (g/kWh)	Other (g/kWh)
Odeh 2008						NH3	
PC Hard Coal			-	-	-		
Super-PC Hard Coal			1.25E+00	4.10E-01	5.80E-02	5.00E-03	
Super-PC Hard coal/CCS (post, MEA)			9.00E-03	5.90E-01	3.00E-02	4.70E-01	
NGCC			-	1.40E-01	-	-	
NGCC/CCS (post, MEA)			-	1.60E-01	-	-	
IGCC Hard coal			3.00E-01	1.20E-01	4.00E-03	-	
IGCC Hard coal/CCS (pre, Selexol)			3.30E-01	1.00E-01	4.00E-03	-	
Pehnt 2008				Kg/TJ fuel		MEA(g/t CO_2 cap)	NH_3(g/t CO_2 cap)
PC Lignite.				4.18E+01		-	-
PC Lignite/CCS (post, MEA)				4.18E+01		1.00E+01	1.94E+02
IGCC Lignite				2.37E+01		-	-
IGCC Lignite/CCS (pre, Selexol)				2.37E+01		-	-
Oxyfuel Lignite/CCS				4.18E+01		-	-
Schreiber 2009*						Gypsum	
Hard coal Pittsburgh No.8							
PC 1990	8.32E+02		5.00E-01	6.10E-01	2.00E-02	4.36E+01	
PC 1990-2008	7.55E+02		4.50E-01	5.50E-01	2.00E-02	3.96E+01	
PC 2008-2020	7.06E+02		4.10E-01	5.10E-01	2.00E-02	3.70E+01	
PC 2020+	6.62E+02		3.90E-01	4.80E-01	2.00E-02	3.48E+01	
PC/CC 1990-2008 (post, MEA)	1.09E+02		3.00E-02	7.90E-01	1.00E-02	5.75E+01	
PC/CC 2008-2020 (post, MEA)	9.90E+01		3.00E-02	6.90E-01	1.00E-02	5.22E+01	
PC/CC Greenfield (post, MEA)	8.60E+01		5.00E-03	6.10E-01	1.00E-02	4.65E+01	
Hard coal Kleinkopje							
PC 1990	8.86 E+02		5.10E-01	6.30E-01	5.00E-02	1.00E+01	
PC 1990-2008	8.04E+02		4.60E-01	5.70E-01	4.00E-02	9.10E+00	
PC 2008-2020	7.52E+02		4.20E-01	5.20E-01	4.00E-02	8.50E+00	
PC 2020+	7.06E+02		4.00E-01	4.90E-01	4.00E-02	8.00E+00	
PC/CCS 1990-2008 (post, MEA)	1.17E+02		3.00E-02	8.00E-01	3.00E-02	1.32E+01	
PC/CCS 2008-2020 (post, MEA)	1.06E+02		3.00E-02	7.10E-01	3.00E-02	1.20E+01	
PC/CCS Greenfield (post, MEA)	9.20E+01		5.00E-03	6.20E-01	2.00E-02	1.16E+01	
* all data without upstream and downstream processes							

Continuation Table 3: Main output Values of the investigated Studies							
Study/Plant	**CO_2** (g/kWh)	**CH_4** (g/kWh)	**SO_2** (g/kWh)	**NO_x** (g/kWh)	**Particulates** (mg/kWh)	**Other** (g/kWh)	**Other** (g/kWh)
Continuation Schreiber 2009						Gypsum	
Lignite Rheinland Garzweiler							
PC 1990	9.66E+02		5.30E-01	6.50E-01	1.00E-02	1.12E+01	
PC 1990-2008	8.48E+02		4.60E-01	5.70E-01	1.00E-02	9.80E+00	
PC 2008-2020	7.82E+02		4.30E-01	5.30E-01	1.00E-02	9.10E+00	
PC 2020+	7.25E+02		4.00E-01	4.90E-01	1.00E-02	8.40E+00	
PC/CC 1990-2008 (post, MEA)	1.32E+02		4.00E-02	8.90E-01	1.00E-02	1.80E+01	
PC/CC 2008-2020 (post, MEA)	1.17E+02		3.00E-02	7.80E-01	1.00E-02	1.66E+01	
PC/CC Greenfield (post, MEA)	9.90E+01		1.00E-02	6.60E-01	1.00E-02	1.52E+01	
Lignite Lausitz							
PC 1990	1.01E+03		5.70E-01	7.00E-01	1.00E-02	1.16E+01	
PC 1990-2008	8.90E+02		5.00E-01	6.20E-01	1.00E-02	1.02E+01	
PC 2008-2020	8.60E+02		4.80E-01	5.90E-01	1.00E-02	9.30E+00	
PC 2020+	7.60E+02		4.30E-01	5.30E-01	1.00E-02	8.70E+00	
PC/CCS 1990-2008 (post, MEA)	1.45E+02		4.00E-02	1.01E+00	2.00E-02	1.93E+01	
PC/CCS 2008-2020 (post, MEA)	1.28E+02		4.00E-02	8.90E-01	1.00E-02	1.70E+01	
PC/CCS Greenfield (post, MEA)	1.08E+02		6.00E-03	7.50E-01	1.00E-02	1.57E+01	
Spath 2004							
PC Bituminous	8.00E+02						
PC Bituminous/CCS (post, MEA)	1.00E+02						
NGCC	-						
NGCC/CCS (post ,MEA)	-						
Viebahn 2007							
PC Hard coal	7.10E+02						
PC Hard coal/CCS (post, MEA)	1.60E+02						
PC Hard coal/CCS (Oxyfuel)	6.00E+01						
IGCC Hard coal	6.95E+02						
IGCC Hard coal/CCS (pre, Rectiso)l	1.51E+02						
PC lignite	8.95E+02						
PC lignite/CCS (post, MEA)	1.95E+02						
NGCC	3.70E+02						
NGCC/CCC (post, MEA)	1.02E+02						

Table 4: Impact Assessment Results

Study/Plant	Impact Category						
	GWP ( )/kWh$_{el}$	**CED** ( )/kWh$_{el}$	**POCP** ( )/kWh$_{el}$	**EP** ( )/kWh$_{el}$	**AP** ( )/kWh$_{el}$	**ODP** ( )/kWh$_{el}$	**HTP** ( )/kWh$_{el}$
D'Addario 2003	(gCO_2-eq)		(gC2H4-eq)	(gPO_4-eq)	(gH+-eq)		
NGCC	4.19E+02		3.22E-02	7.1E-06	6.7E-03		
NGCC/CC (post, MEA)	7.70E+01		3.72E-02	8.3E-06	4.2E-03		
NGCC/CC (post, MGA)	9.00E+01		3.79E-02	8.4E-06	4.2E-03		
NGCPO/CC (pre, MDEA)	1.00E+02		2.60E-02	9.8E-06	7.0E-03		
Doctor 2001	(gCO_2-eq)	*[1]	(gozone form.)	(gPO_4-eq)	(gSO_2-eq)		*[1]
IGCC Bituminous	1.56E+03	5.66E-03	8.52E-02	8.72E+02	5.03E-01		1.11E-02
IGCC Bituminous/CC (pre, Glycol)	4.90E+02	5.53E-03	7.83E-02	9.43E+02	3.19E-01		1.08E-02
(IEA IGCC/CC)*	2.80E+02	3.64E-03	1.08E-01	1.13E+03	3.46E-01		1.05E-02
IEA 2006							
NGCC							
NGCC/CC (post, MEA)							
POCC							
POCC/CC (pre, MDEA)							
USCPF Bituminous							
USCPF Bituminous/CC (post, MEA)							
IGCC Bituminous							
IGCC Bituminous/CC (pre, MDEA)							
Khoo 2006	(gCO_2-eq)	*[1]		(gNO_3-eq)	(gSO_2-eq)		Air (m^3/g)
PC Hard coal/CC (post, MEA)	7.87E+01	1,65E-03		1,53E+00	3.42E-01		7.24E+01
Koornneef 2008	(gCO_2-eq)	(gSb-eq)*[2]	(gC_2H_4-eq)	(gPO_4-eq)	(gSO_2-eq)	(gCFC-11-eq)	(g1,4 DB-eq)
PC Hard coal	1.09E+03	8.25E+00	9.06E-02	2.88E-01	2.76E+00	8.52E-06	1.06E+02
Super-PC Hard coal	8.37E+02	6.32E+00	5.13E-02	1.61E-01	1.44E+00	6.41E-06	5.84E+01
Super-PC Hard coal/CCS (post, MEA)	2.43E+02	8.45E+00	6.49E-02	2.90E-01	2.10E+00	9.93E-06	1.64E+02

* not modelled, results only used for comparison
*[1] Unit not clear or not specified
*[2] Name of Impact category: Abiotic depletion (ADP)

Continuation Table 4: Impact Assessment Results							
Study/Plant	**Impact Category**						
	GWP ( )/kWh$_{el}$	**CED** ( )/kWh$_{el}$	**POCP** ( )/kWh$_{el}$	**EP** ( )/kWh$_{el}$	**AP** ( )/kWh$_{el}$	**ODP** ( )/kWh$_{el}$	**HTP** ( )/kWh$_{el}$
Korre 2009	(gCO_2-eq)	(gSb-eq)*	(gC_2H_4-eq)	(gPO_4-eq)	(gSO_2-eq)		(g1,4-DB-eq)
PC Bituminous	8.46E+02	3.96E+00	1.39E-02	4.00E-02	3.90E-01		2.99E+01
PC Bituminous/CC (post, MEA)	1.79E+02	6.06E+00	1.52E-02	6.00E-02	4.70E-01		2.12E+01
Lombardi 2003	(gCO_2-eq)						
SCGT CC	-						
SCGTCC/CC (post, DEA+MDEA)	1.04E+02						
IGCC Hard coal	-						
IGCC Hard coal/CC (pre, DEA+MDEA)	3.58E+02						
Modahl 2009	(gCO_2-eq)	(kWh LHV)	(gC_2O_4-eq)	(gPO_4-eq)	(gSO_2-eq)		
NGCC	3.95E+02	1.62E+00	4.23E-02	2.66E-02	1.48E-01		
NGCC/CCS (post, MEA)	9.10E+01	1.93E+00	8.74E-02	5.78E-02	2.40E-01		
Muramatsu 2002							
PC Hard Coal							
PC Hard Coal/CCS (post, MEA)							
PC Hard Coal/CCS (post, KS-1)							
NEEDS 2008	(gCO_2-eq)	(MJ-eq)	(gC_2H_4-eq)	(gPO_4-eq)	(gSO_2-eq)		
PC Lignite 2025	8.19E+02	8.44E+00	1.05E-02	1.15E-01	5.40E-01		
PC Lignite/CCS (post, MEA)	1.56E+02	1.07E+01	1.68E-02	2.41E-01	1.27E+00		
PC Lignite/CCS (Oxyfuel)*[1]	4.10E+01	1.03E+01	1.39E-02	8.02E-02	4.61E-01		
PC Hard coal 2025	7.65E+02	8.03E+00	2.42E-02	1.11E-01	1.11E+00		
PC Hard coal/CCS (post, MEA)	2.13E+02	1.01E+01	3.20E-02	2.30E-01	1.58E+00		
PC Hard coal/CCS (Oxyfuel)*	1.17E+02	9.80E+00	2.99E-02	1.01E-01	9.24E-01		
IGCC Lignite 2025	7.88E+02	7.98E+00	6.50E-03	1.94E-01	9.57E-01		
IGCC Lignite/CCS (pre)	1.38E+02	9.63E+00	1.03E-02	2.37E-01	1.44E+00		

* Name of Impact category: Abiotic depletion (ADP)
*[1] for oxyfuel Transport distance 200km and 800km aquifer storage, all other plants 400 km transport distance and storage in 2500m depleted gas field

Continuation Table 4: Impact Assessment Results							
Study/Plant	**Impact Category**						
	GWP ( )/kWh$_{el}$	**CED** ( )/kWh$_{el}$	**POCP** ( )/kWh$_{el}$	**EP** ( )/kWh$_{el}$	**AP** ( )/kWh$_{el}$	**ODP** ( )/kWh$_{el}$	**HTP** ( )/kWh$_{el}$
Continuation NEEDS 2008	(gCO_2-eq)	(MJ-eq)	(gC_2H_4-eq)	(gPO_4-eq)	(gSO_2-eq)		
IGCC Hard coal 2025	6.92E+02	7.27E+00	2.13E-02	7.63E-02	7.54E-01		
IGCC Hard coal /CCS (pre)	1.71E+02	8.69E+00	2.63E-02	9.93E-02	1.08E+00		
NGCC 2025	3.66E+02	6.86E+00	2.83E-02	2.67E-02	2.69E-01		
NGCC/CCS (post, MEA)	9.30E+01	7.94E+00	3.31E-02	3.39E-02	3.95E-01		
Odeh 2008	(gCO_2-eq)	(MJ)					
PC Hard Coal	9.84E+02	8.40E+00					
Super-PC Hard Coal	8.79E+02	8.40E+00					
Super-PC Hard coal/CCS (post, MEA)	2.55E+02	1.00E+01					
NGCC	4.88E+02	6.40E+00					
NGCC/CCS (post, MEA)	2.00E+02	7.80E+00					
IGCC Hard coal	8.61E+02	8.20E+00					
IGCC Hard coal/CCS (pre, Selexol)	1.67E+02	9.50E+00					
Pehnt 2008*	(gCO_2-eq)	(MJ)	(gC_2H_4-eq)	(gPO_4-eq)	(SO_2-eq)		($x10^{-6}$Yoll)
PC Lignite.	9.10E+02	8.00E+00	9.50E-3	4.60E-02	6.60E-01		5.50E-02
PC Lignite/CCS (post, MEA)	1.90E+02	1.35E+01	2.38E-2	9.20E-02	5.80E-01		6.80E-02
IGCC Lignite	8.80E+02	7.75E+00	5.80E-3	2.50E-02	2.60E-01		3.60E-02
IGCC Lignite/CCS (pre, Selexol)	1.40E+02	9.40E+00	6.80E-3	3.20E-02	3.50E-01		4.60E-02
Oxyfuel Lignite/CCS	1.20E+02	1.11E+01	4.70E-3	9.00E-03	1.40E-01		4.20E-02
Schreiber 2009	(gCO_2-eq.)	(gSb-eq)	(gC_2H_4-eq)	(gPO_4-eq)	(gSO_2-eq)	(gCFC-11-eq)	(gDCB eq)
Hard coal Pittsburgh No.8							
PC 1990	9.48E+02	6.08E+00	9.50E-02	1.60E-01	1.30E+00	2.90E-06	5.30E+01
PC 1990-2008	8.61E+02	5.52E+00	8.70E-02	1.50E-01	1.20E+00	2.70E-06	4.90E+01
PC 2008-2020	8.05E+02	5.16E+00	7.90E-02	1.40E-01	1.10E+00	2.50E-06	4.60E+01
PC 2020+	7.55E+02	4.84E+00	7.50E-02	1.30E-01	1.00E+00	2.40E-06	4.30E+01
PC/CC 1990-2008 (post, MEA)	2.72E+02	8.09E+00	9.70E-02	2.90E-01	1.50E+00	4.00E-06	1.76E+02
PC/CC 2008-2020 (post, MEA)	2.47E+02	7.34E+00	8.70E-02	2.60E-01	1.40E+00	3.70E-06	1.58E+02
PC/CC Greenfield (post, MEA)	2.11E+02	6.34E+00	7.40E-02	2.20E-01	1.20E+00	2.90E-06	9.70E+01
* values are taken from bar chart							

Continuation Table 4: Impact Assessment Results							
Study/Plant	**Impact Category**						
	GWP ( )/kWh$_{el}$	**CED** ( )/kWh$_{el}$	**POCP** ( )/kWh$_{el}$	**EP** ( )/kWh$_{el}$	**AP** ( )/kWh$_{el}$	**ODP** ( )/kWh$_{el}$	**HTP** ( )/kWh$_{el}$
Continuation Schreiber 2009	(gCO_2-eq.)	(gSb-eq)	(gC_2H_4-eq)	(gPO_4-eq)	(gSO_2-eq)	(gCFC-11-eq)	(gDCB eq)
Hard coal Kleinkopje							
PC 1990	1.04E+03	7.18E+00	1.00E-01	2.10E-01	1.40E+00	2.70E-06	1.05E+02
PC 1990-2008	9.27E+02	6.11E+00	1.10E-01	2.30E-01	1.60E+00	3.70E-06	9.90E+01
PC 2008-2020	8.53E+02	5.72E+00	9.90E-02	2.10E-01	1.50E+00	3.50E-06	9.20E+01
PC 2020+	7.86E+02	5.03E+00	1.10E-01	2.30E-01	1.60E+00	4.10E-06	8.90E+01
PC/CCS 1990-2008 (post, MEA)	2.66E+02	8.50E+00	1.50E-01	4.50E-01	2.40E+00	8.10E-06	2.61E+02
PC/CCS 2008-2020 (post, MEA)	2.41E+02	7.71E+00	1.40E-01	4.00E-01	2.20E+00	7.40E-06	2.36E+02
PC/CCS Greenfield (post, MEA)	2.07E+02	6.68E+00	1.20E-01	3.50E-01	1.90E+00	6.20E-06	1.74E+02
Lignite Rheinland Garzweiler							
PC 1990	9.83E+02	5.07E+00	5.20E-02	1.10E-01	1.00E+00	6.10E-07	2.10E+01
PC 1990-2008	8.63E+02	4.45E+00	4.60E-02	9.00E-02	9.00E-01	5.40E-07	1.80E+01
PC 2008-2020	7.95E+02	4.10E+00	4.20E-02	8.00E-02	8.00E-01	4.90E-07	1.70E+01
PC 2020+	7.37E+02	3.80E+00	3.90E-02	8.00E-02	8.00E-01	4.60E-07	1.60E+01
PC/CC 1990-2008 (post, MEA)	1.67E+02	7.06E+00	4.30E-02	2.50E-01	1.30E+00	1.80E-06	1.52E+02
PC/CC 2008-2020 (post, MEA)	1.47E+02	6.23E+00	3.80E-02	2.20E-01	1.10E+00	1.60E-06	1.34E+02
PC/CC Greenfield (post, MEA)	1.21E+02	5.23E+00	3.10E-02	1.80E-01	9.00E-01	1.10E-06	8.00E+01
Lignite Lausitz							
PC 1990	1.04E+03	5.61E+00	5.70E-02	1.20E-01	1.20E+00	6.70E-07	2.70E+01
PC 1990-2008	9.06E+02	4.93E+00	5.00E-02	1.00E-01	1.00E+00	5.90E-07	2.30E+01
PC 2008-2020	8.74E+02	4.54E+00	4.60E-02	1.00E-01	9.00E-01	5.40E-07	2.20E+01
PC 2020+	7.74E+02	4.21E+00	4.30E-02	9.00E-02	9.00E-01	5.10E-07	2.00E+01
PC/CCS 1990-2008 (post, MEA)	1.94E+02	7.89E+00	5.40E-02	2.90E-01	1.50E+00	2.50E-06	1.79E+02
PC/CCS 2008-2020 (post, MEA)	1.71E+02	6.96E+00	4.70E-02	2.60E-01	1.30E+00	2.30E-06	1.58E+02
PC/CCS Greenfield (post, MEA)	1.41E+02	5.84E+00	3.80E-02	2.10E-01	1.10E+00	1.60E-06	9.60E+01
Spath 2004	(gCO_2-eq.)	(MJ)					
PC Bituminous	8.47E+02	1.25E+01					
PC Bituminous/CCS (post, MEA)	2.47E+02	1.46E+01					
NGCC	4.99E+02	8.40 E+00					
NGCC/CCS (post, MEA)	2.45E+02	9.70 E+00					

Continuation Table 4: Impact Assessment Results

Study/Plant	Impact Category						
	GWP ( )/kWh$_{el}$	**CED** ( )/kWh$_{el}$	**POCP** ( )/kWh$_{el}$	**EP** ( )/kWh$_{el}$	**AP** ( )/kWh$_{el}$	**ODP** ( )/kWh$_{el}$	**HTP** ( )/kWh$_{el}$
Viebahn 2007	(gCO_2-eq)	(MJ)	(gC_2H_4-eq)*[1]	(gPO_4-eq)*[1]	(gSO_2-eq)*[1]		(gPM10-eq)
PC Hard coal	7.92E+02	7.74E+00	3.10E-02	6.30E-02	8.10E-01		2.37E-01
PC Hard coal/CCS (post, MEA)	2.62E+02	9.88E+00	6.10E-02	8.50E-02	7.30E-01		2.42E-01
PC Hard coal/CCS (Oxyfuel)	1.76E+02	1.04E+01	4.80E-02	9.13E-02	1.13E+00		
IGCC Hard coal	7.74E+02	7.68E+00	2.80E-02	4.20E-02	6.00E-01		
IGCC Hard coal/CCS (pre, Rectiso)l	2.44E+02	9.50E+00	4.00E-02	5.70E-02	7.90E-01		
PC lignite	8.97E+02	6.67E+00	6.50E-03	1.90E-01	1.59E+00		3.60E-01
PC lignite/CCS (post, MEA)	1.98E+02	9.60E+00	4.10E-02	2.60E-01	1.54E+00		4.60E-01
NGCC	3.96E+02	6.97E+00	2.60E-02	9.00E-02	5.30E-01		
NGCC/CCC (post, MEA)	1.32E+02	8.37E+00	3.90E-02	1.09E-01	6.60E-01		

*[1] Basic value is taken from bar chart

Legend

CC	carbon capture	power Plants:		Impact categories:	
CCS	carbon capture and storage	PC	pulverized coal	GWP	global warming potential
pre	pre combustion capture	NGCC	natural gas combined cycle	CED	cumulative energy demand
post	post combustion capture	NGCPO	natural gas catalytic partial oxidation	POCP	photochemical oxidation potential
MEA	monoethanolamine	IGCC	Integrated combined cycle	EP	eutrophication potential
DEA	diethanolamine	SCTG CC	semi closed gas turbine combined cycle	AP	acidification potential
MDEA MEA	methyldiethanolamine	USCPF	ultra super critical pulverized fuel	ODP	ozone layer depletion potential
KS-1	hindered Amine	POCC	natural gas partial oxidation combined cycle	HTP	human toxicity potential
MGA	MEA based membrane gas contactor				

Appendix B: LCA impact categories

Impact category	Abbre-viation	Scale	Example of relevant LCI data	characterisation factor [Guinée 2002]
Global Warming Potential	GWP	Global	Carbon Dioxide CO_2 Nitrous Oxide N_2O Methane CH_4 Sulphure hexafluoride SF6 Chloroform $CHCL_3$ Tetraflouromethane Chlorofluorocarbons CFCs Hydrochlorofluorocarbons HCFCs Methyl Bromide CH_3Br	kg CO_2-equivalents
Acidification Potential	AP	Regional Local	Sulphur oxides SOx Nitrogen oxides NOx Hydrochloric acid HCl Hydrofluoric acid HF Ammonia NH_3 Nitric acid HNO_3 Sulphuric acid H_2SO_4 Phosphoric acid H_3O_4P	kg SO_2-equivalents
Eutrophication Potential	EP	Local	Phosphate PO_4^{3-} Nitrogen Nitrogen dioxide NO_2 Nitric acid HNO_3 Ammonia NH_3 Phosphoric acid H_3PO_4 Chemical oxygen demand COD	kg PO_4^{3-}equivalents
Photochemical Oxidation Potential	POCP	Local	Alkanes Alkenes Alkine Aromatic hydrocarbones	kg ethylene-equivalents
Stratospheric Ozone Depletion Potential	ODP	Global	CFCs HCFCs Halons Methyl Bromide Methylchloride CH_3CL	kg CFC-11-equivalents
Human Toxicity Potential	HTP	Regional Local	Arsenic Benzene Chromium IV Hexachlorbenzene	kg 1,4-DCB-equivalents

Fresh Water Aquatic Ecotoxicity Potential	FAETP	Local	Arsenic Chromium IV	kg 1,4-DCB-equivalents
Marine Aquatic Ecotoxicity Potential	MAET P	Local	Arsenic Chromium IV	kg 1,4-DCB-equivalents
Terrestrial Ecotoxicity Potential	TEP	Local	Arsenic Chromium IV	kg 1,4-DCB-equivalents
Cumulative energy Demand/ Abiotic Depletion Potential	CED/ ADP	Global Regional Local	Quantity of energy used/ Quantity of minerals used Quantity of fossil fuels used	MJ/ kg antimony-equivalent