Life Cycle Assessment of Selected Technologies for CO_2 Transport and Sequestration

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Departement Bau, Umwelt und Geomatik

Institute of Environmental Engineering (IfU)

Caroline Wildbolz

Supervisor: Roberto Dones, Senior Scientist, Technology Assessment, PSI Villigen

Diploma Professor: Prof. Dr. Stefanie Hellweg, Institut of Envirnmental Engineering (IfU)

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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Credit picture title page: http://www.ieagreen.org.uk/march81.htm Access Date: 18.Juni 07. Weyburn Project.

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Caroline Wildbolz

Abstract

A life cycle assessment (LCA) of selected transport and storage options of supercritical carbon dioxide for European conditions is conducted in this study. The onshore pipeline – with and without recompression unit – as possible transport option and the deep saline aquifer as well as the depleted gas field as feasible storage options are analyzed. The focus lies on the determination of the life cycle inventory (LCI) data. An own model is built and the model parameters are compared to values found in literature for existing CO_2 transport and storage projects. The comparison of the options is done at the impact assessment (LCIA) level by using the Eco-indicator 99 as well as the CO_2 equivalent (IPCC 2001) method with 100 year time horizon. Furthermore, the entire CCS chain is covered by application of data for the post-combustion capture process to a current best pulverized coal power plant, available from the ongoing PSI research.

As expected, with increasing transport distance and increasing injection depth the overall environmental burdens increase. The key factor thereby is the energy required for injection of the CO_2 into the reservoir formation which in turn depends highly on the required injection pressure. The estimation of the injection pressure is very uncertain. Another important factor is the construction and material effort of the pipeline.

The calculation of the overall environmental burdens and the CO_2 equivalents along the whole process chain show that the CCS technology in particular can reduce the CO_2 emissions by approximately 80 % per kWh, against a 90% reduction postulated at the power plant, for which the goal of “near-zero emission” technology is more distant than desired. Therefore, it is here calculated that the CCS technology emits about the same amount of CO_2 equivalent per kWh as the power plant it complements. The share of the transport and storage system on the entire CCS chain is less important compared to the capture process and the operation of the power plant.

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List of Acronyms and Abbreviations

CCS	Carbon dioxide capture and storage
CO_2-ECBM	CO_2-enhanced coal bed methane recovery
DIN	Deutsches Institut für Normierung
EGR	Enhanced gas recovery
EI'99	Eco-indicator 99
EOR	Enhanced oil recovery
FP	Framework Programme
GHG	Greenhouse Gas
GWP	Global Warming Potential
(H,A)	EI'99 method, "A" refers to average weighting set, "H" to Hierarchist perspective
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LNG	Liquefied natural gas
LNP	Liquefied petroleum gas
n.a.	Not available
n.s.	Not specified
OD	Outside Diameter
ppm	Parts per million
UCTE	Union for the Co-ordination of Transmission of Electricity

1 Introduction

Carbon capture and storage (CCS) technology importance is gaining momentum considering the highest priority of the energy policy agenda today. It is a viable option within the scope of climate protection. “Near-zero emissions” fossil technologies power plants could then be more competitive with renewable energy technologies on environmental performance grounds, especially in view of likely continuing installation of future fossil power plants world-wide as well as in Europe and maybe in Switzerland.

Global warming is a topical theme today. The increase in the world’s average temperature is correlated to the increase in the CO_2 concentration in the atmosphere. Over the past 150 years the CO_2 concentration has been increasing significantly mainly due to combustion processes for electricity production, transportation and heating systems.

In particular, as coal is a major strategical energy carrier with resources estimated to last for a couple of centuries at the current rate of consumption, the option of CCS is being discussed. The disadvantage of the coal power plant is the high amount of CO_2 emission that is produced. Therefore the goal is to design and operate a CO_2 poor power plant. The technology of carbon capture and storage (CCS) captures the CO_2 at the plant, transports it to a suitable storage site where the CO_2 will be isolated from the atmosphere.

Sooner or later the question of the environmental impacts arises. Does it make sense to mitigate the CO_2 in this way? The substantial reduction of CO_2 by CCS is somewhat negatively compensated by the substantial extra energy and the increased material use which cause additional environmental burdens compared to the technology without CCS. Therefore the name “near-zero emission” technology may be misleading. Until now only preliminary, limited research has been done on the environmental impacts of the CCS technology. Moreover, only a few rather simplified LCA studies have been conducted on the subject. The present study aims at using the current knowledge and applying an own, yet simplified, model for average European conditions in order to estimate total environmental burdens.

This study is organized as follows: Chapter 2 gives a brief introduction of the of CO_2 capture and storage technology and briefs on recent research projects. Chapter 3 defines the research objectives and the scope of the study. Chapter 4 outlines the methods as well as the approach applied in this study. Chapter 5 presents and discusses the model results. The study closes with conclusions given in Chapter 6.

2 The Technology of Carbon Capture and Storage

Carbon capture and storage (CCS) is a viable option to reduce global warming by isolating the most important greenhouse gas (GHG) CO_2 from the atmosphere. The CO_2 will be captured at the site of origin, transported to a suitable storage site and there be stored for geological time scale. The process chain consists of three elements: capture, transport and storage of CO_2, each described in the following.

2.1 Capture of CO_2

In principle there exist three basic processes to capture the incidental CO_2 at the power plant:

- CO_2 post-combustion capture
- CO_2 pre-combustion capture
- Oxyfuel combustion

In Figure 1 these three options are schematically shown as well as a further one, namely the industrial separation. The separated CO_2 will then be compressed, then transported and stored in each option.

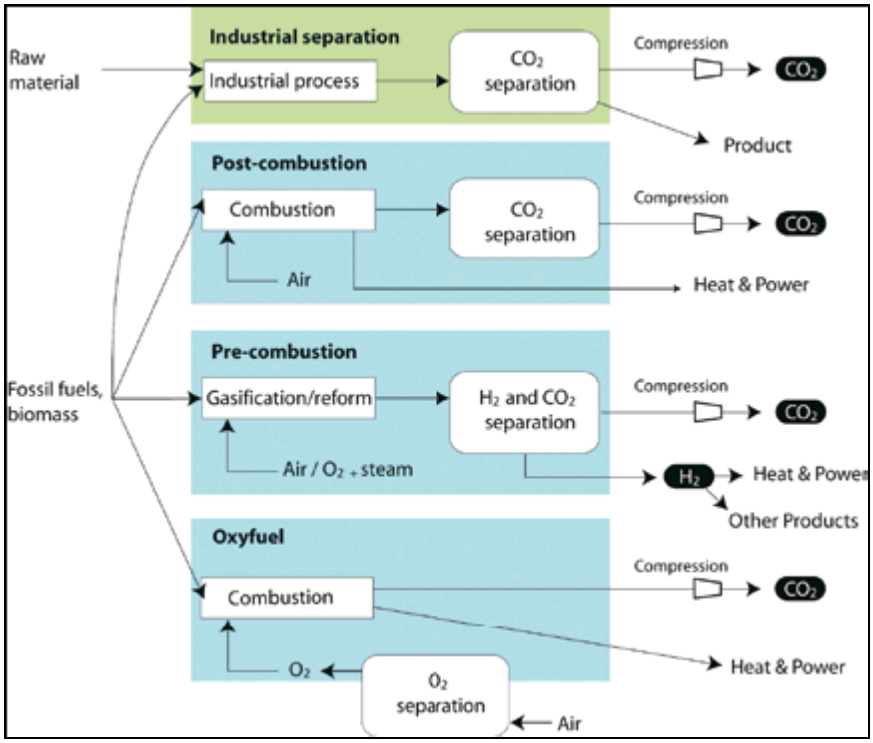

Figure 1 Scheme of the different processes for the capture of CO_2 (Source: IPCC 2005).

Post-combustion

The carbon dioxide is captured after the combustion process. The flue gases produced by combustions in air of fossil fuels and/or biomass consist mainly of nitrogen and carbon dioxide. To capture the CO_2 the flue gas has to pass through equipment which separates most of the CO_2 from the fuel gas. The most common procedure today is the amine-

scrubbing. It is similar to the procedure in the flue gas scrubber for sulphur removal. The remaining flue gas is released into the atmosphere (IPCC 2005, Germanwatch 2004).

Pre-combustion

The capture of carbon dioxide follows adequate processing of the fuel before combustion. The fuel reacts with oxygen or air, in some cases with steam, to produce a mixture consisting mainly of carbon monoxide and hydrogen. The carbon monoxide passes into a reactor referred to as a shift converter where it is forced to react with steam to produce CO_2 and hydrogen. The produced mixture can be separated into CO_2 and hydrogen. The hydrogen will be further burned to fuel a combined cycle power plant. (IPCC 2005, Germanwatch 2004)

Oxyfuel combustion

The combustion of the fuel will occur with pure oxygen or a mixture of oxygen, water and carbon dioxide (the latter species to control the combustion temperature level). This results in a flue gas containing high concentrations of CO_2 of about 80% compared to 4 -14% (Germanwatch 2004) for a combustion with air (Germanwatch 2004). Hence the separation of the CO_2 is easier requiring less energy. However, the process to separate the oxygen in the required high purity is an energy consuming process. The oxyfuel combustion system is still in the demonstration phase, but Vattenfall is building a test plant in Germany. (IPCC 2005, Germanwatch 2004)

2.2 Transport of CO_2

The captured CO_2 can normally not be stored directly at the point of origin but has to be transported to a suitable storage site. Howeever, for the existing pilot projects different examples can be found, e.g. CO_2 stored directly at the capture site like in Sleipner or in In Salah or the CO_2 is transported to the injection site by a pipeline like in the Weyburn Project. The transport is the necessary intermediate step between CO_2 capture and storage. Among the possible transportation options are the CO_2transport by pipeline, ship, railway or truck. Figure 2 shows the different possible means of transport of CO_2.

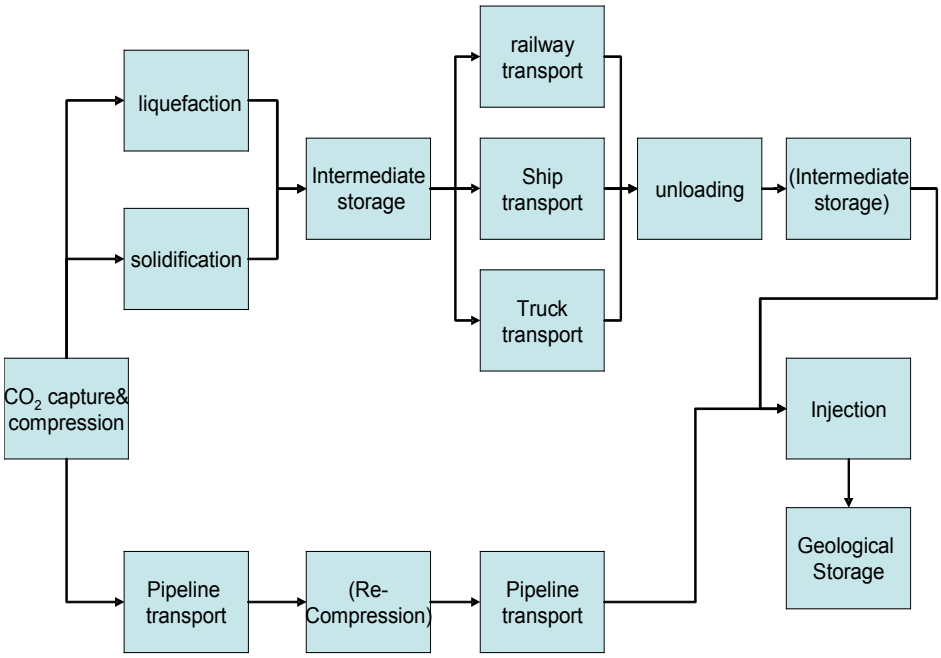

Figure 2 The process chains of the different options for the transport of CO_2.

The transport costs depend on distance and CO_2 flow. According to FZ Jülich (2006), the selection of a transport option not only depends on the costs and capacities but also on geographic conditions, security and type of ultimate storage.

In principle the CO_2 can be transported in different physical conditions. However, carbon dioxide transported at pressure near the atmospheric pressure occupies enormous volumes being in gaseous state. To transport higher mass flows the CO_2 is usually compressed before transportation. Also liquefaction, solidification or hydration are common options to reduce the volume of CO_2. Liquefaction is a well known technology from the gas transport by ship as liquefied petroleum gas (LPG) and liquefied natural gas (LNG) and can be taken over to liquid CO_2 transport. Solidification is a very energy consuming process but reduces volume furher. (IPCC 2005)

Only pipelines and ships are cost-effective options due to the enormous volumes involved in CCS projects (IEA 2004).

2.2.1 Pipeline

The transportation of CO_2 by pipeline is a proven technology. Besides, there is a high degree of experience and know-how especially in the field of natural gas and oil pipelines that can be transferred to CO_2 transport. At present there are globally about 3100 km of CO_2 pipelines, especially in the USA & Canada, with a transport capacity of 44.7 Mio t CO_2 per year (FZ Jülich 2006). Table 1 shows a list of existing pipelines in North Amercia.

Table 1 Existing CO_2 pipelines in North America (after IPCC 2005).

Name	Operator	Origin of CO_2	Length [km]	diameter [mm]	Capacity [$MtCO_2$/year]	Year start-up
Cortez	Kinder Morgan	McElmoDome	808	762	19.3	1984
Sheep Mountain	BP Amoco	Sheep Mountain natural	660	610	9.5	-
Bravo	BP Amoco	Bravo Dome natural	350	508	7.3	1984
Canyon Reef Carriers	Kinder Morgan	Gasification plants	225	n.a.	5.2	1972
Val Verde	Petrosource	Val Verde Gas Plants	130	n.a.	2.5	1998
Bati Raman (Turkey)	Turkish Potroleum	Dodan Field	90	n.a.	1.1	1983
Weyburn	North Dakota Gasification Co.	Gasification Plant	328	356/305	5	2000

To design a pipeline several physical and environmental factors have to be considered and determined. The physical state of CO_2 transported gives the optimal size and pressure for the pipeline. Beside the piping with high quality carbon steel, coated against external corrosion and mechanical damaging, other elements as initial compressor station, intermediate pumping or recompression stations, section and security valves, cathodic corrosion protection and stations for corrosion monitoring must be considered (UBA 2006). Another important factor is the topography along the pipeline route. Environmental considerations such as annual variation in temperature, frost heave and seismic activity, permafrost, biological growth and other factors have also to be studied (IPCC 2005).

The previous considerations give the input to the conceptual design. This includes the following points after (IPCC 2005):

- Mechanical design
- Stability design
- Protection against corrosion
- Trenching and backfilling
- Fracture arresters

The selection of the pipeline material is influenced by the quality of CO_2 transported. The pipelines for CO_2 transport are usually constructed using corrosionless low-alloyed carbon steel. During 12 years of operating a carbon steel pipeline with dry CO_2, the corrosion rate amounts to 0.25-2.5 µm/yr (IPCC 2005). But it is unlikely to transport wet CO_2 in low-alloy steel pipelines to its higher (0.7 mm/yr) corrosion rate (IPCC 2005). To avoid corrosion the CO_2 should not contain water vapour or sulphur compounds. In (UBA 2006) a threshold value of 580 ppm for H_2O is recomended.

An important aspect in the design of a pipeline should be the consideration of the pressure that has always to be above the critical point of 73.9 bar with a temperature of 31.1 °C (cf. Annex A.I). In literature (UBA 2006) a minimal pressure of 80 bar is often required to keep some margin. During transportation of CO_2 a pressure drop along the pipeline occurs caused by the friction due to the roughness of the pipe. To compensate this pressure loss recompressor stations may be necessary over long distances or a higher initial pressure has to be chosen. In the literature recompressor stations are said to be needed for distance over 150 km (Heddle et al. 2003), in practice also greater distances of 400 km or even more (IPCC 2005) without recompression are said to be feasible. The main factors influencing the pressure drop are the roughness of the pipe, the mass flow and the inner diameter of the pipe.

In principle there exists the possibility of transporting the CO_2 in gaseous state at low pressures operating with a maximum pressure of 4.8 MPa. This option is less adapted due to its lower density and capacity which also causes higher costs. So carbon dioxide is preferably transported in supercritical state at high pressures where it has a high density as liquids but a viscosity similar to the one of gases. CO_2 always has to remain above the critical point to avoid two-phase system that can induce a sharp and sudden pressure increase. (IPCC 2005, UBA 2006, BMU 2007)

After (UBA 2006) the capacity of a pipeline not only depends on the density of CO_2 but also on other properties of CO_2, on pipeline system parameters as roughness, section length between two compressor station and on the slope of the terrain.

During operation the pipelines are monitored from inside by “pigs” and from outside by corrosion monitoring and leak detection system as well as by patrols on foot and by aircraft (IPCC 2005).

Potential risks during the transportation process are leakages or even breaches of the pipeline, where CO_2 can escape into the air. Leakage can be caused by corrosion. Major causes for externally caused failures are construction works. Due to the higher density of CO_2 compared to air, the CO_2 will probably accumulate in depressions, thus presenting a potential risk for humans and animals. If the route of a CO_2 pipeline is selected along topographical exposed positions the risk of CO_2 accumulations after a pipe break can be reduced. The incidence of CO_2 pipeline failure is very small and roughly in the same range as the corresponding for natural gas pipelines. Because carbon dioxide is not flammable the consequences of the accidences are less severe than by transportation of natural gas or other dangerous liquids. (Mazzotti 2006, IPCC 2005)

2.2.2 Ship

The transport option by ship is a flexible alternative for bringing the CO_2 to the injection site. But due to its discontinuous feature, intermediate storage is needed to handle the continuously captured CO_2 at the plant. Hence additional area, material and energy are required for intermediate storage. The longer the distance the more economic is the ship transport. In (IPCC 2005) the break-even distance is about 1000 km for a system with 6 Mt/yr transport capacity. Nevertheless, the transportation of larger amounts of CO_2 shifts the break-even point towards longer distances.

The transportation by ship shows similarities to LPG transportation by ship. The development of the design of the ship, tank, operation and onshore loading system can

be based on the existing technology for the transport of LPG. Moreover, novel concepts have to be developed for the unloading process and the liquefaction plant.

For the construction of CO_2 tankers the International Gas Carrier Code is applied. The technology of ships for transporting CO_2 is still under development.

The transport conditions of CO_2 are an important factor for the design of the transport system. In order to transport high quantities of CO_2 efficiently the gas must be transformed into a form with higher density. The CO_2 can be transported in liquid, solid and supercritical state. In Figure 3 the density of CO_2 as a function of pressure and temperature is shown as well as the optimal conditions for fully refrigerated ship, the semi-pressurized ship, and the fully pressurized ship types.

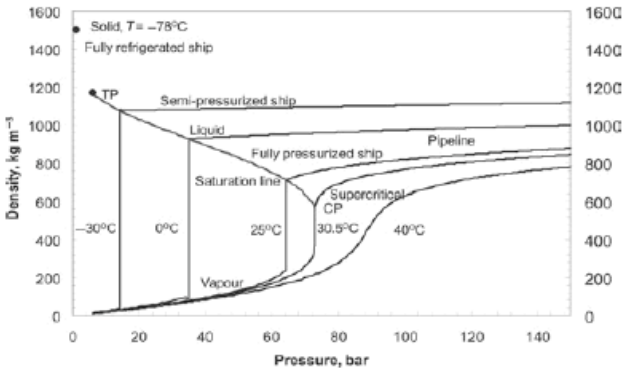

Figure 3 Density as a function of pressure and temperature (Source: Aspelund et al. 2006).

Three types of CO_2 transport ships exist:

- pressure type/ fully pressurized operating at high pressure to prevent gas from boiling under ambient temperature conditions;
- low temperature type / fully refrigerated ship operating at a sufficiently low temperature to keep gas as a liquid (or) under atmospheric pressure a solid;
- semi-refrigerated type / semi-pressurized combined conditions of temperature and pressure necessary for gas to be kept as a liquid.

At atmospheric pressure CO_2 can only exist in gas or solid state according to its temperature. By lowering the temperature at atmospheric pressure the CO_2 can only be transferred into solid, so called dry ice state. Liquid CO_2 can only exist at a combination of low temperature and pressures well above atmospheric pressure (see Fig. 3 and Annex A.I).

The transport condition of CO_2 is an optimization between its temperature and its pressure. The lower the pressure is designed the thinner the vessel or pipe will be, therefore the lower the material consumption and costs for transportation. If the pressure is lower the temperature also has to be lower for CO_2 to be in a state with adequate density for reasonable transport capacities. But the lower the temperature the more energy for cooling is required.

The semi-pressurized ship transports the CO_2 in liquid phase at temperature lower than ambient temperature and pressures higher than atmospheric pressure. This type is

preferred by ship designers. The design parameter is around -54°C per 6 bar to -50 °C at 7 bar for transporting a volume of approximately 22 000 m^3 (IPCC 2005). The fully refrigerated ship transports CO_2 in solid phase as dry ice with very high density. But this option does not seem economically feasible because of the complex loading and unloading procedures as well as the high energy requirement for refrigeration.

The processes which are included in the transport chain according to (Aspelund et al. 2006) are the liquefaction, the intermediate storage, the loading, the dedicated CO_2 ships and the offshore unloading systems. Figure 4 shows the chain of the main processes for a system of CO_2 transportation by ship.

Figure 4 Main processes in the chain of ship transport of CO_2 (Source: Aspelund et al. 2006).

The captured CO_2 will first be liquefied at the liquefaction plant and then be intermediately stored in tanks. The intermediate storage can occur in underground caverns or semi-pressurized, cylindrical storage tanks.

The loading system can consist of two parallel product pipes between the tanks and the loading arm. One line to export the CO_2 and a return line for CO_2 vapour generated on board. The equipment and material has to be resistant to corrosion and low temperature.

The semi-pressurized ships are working at a pressure between 5 to 7 bara and temperatures around -50°C (Aspelund et al. 2006). Figure 5 illustrates a ship with a carrying capacity of 20 000 m^3 which is the most frequent type for LPG transport. Without appropriate measures, the CO_2 would eventually boil and the pressure in the cargo tank would increase by heat transfer from the environment through the wall. To compensate this pressure rise, CO_2 boil-off gas has to be discharged to the atmosphere. By recondensation on board these CO_2 emissions of boil-off CO_2 can be avoided but it will result in a higher energy demand. The liquid CO_2 is unloaded at the destination site. Depending on the destination site and on the required state of CO_2 different unloading systems are possible. The ship will be refilled with dry gaseous CO_2 to avoid contamination of the tanks by humid air. The tanker will return to the harbour and be filled with CO_2 gas after being dried purged the tanks for the next trip.

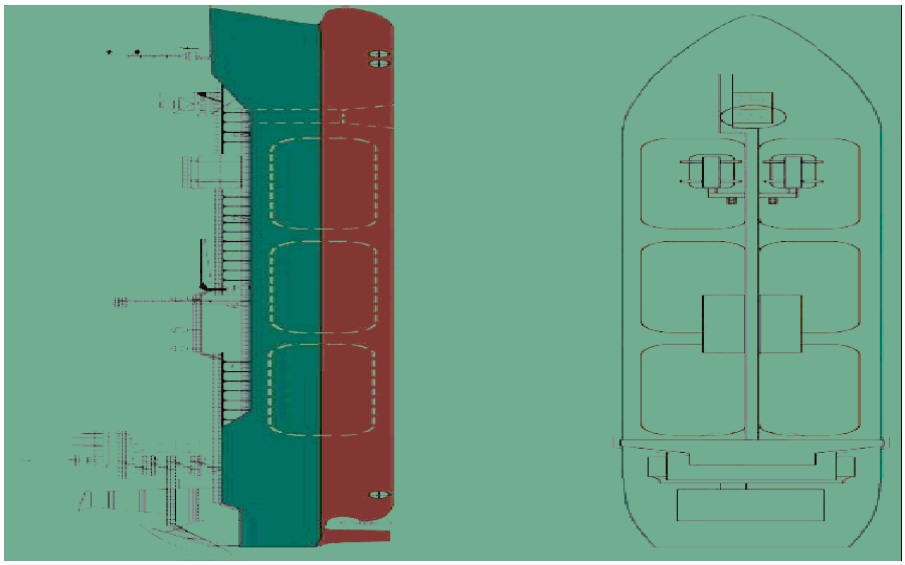

Figure 5 Semi-cooled ship with a capacity of 20 000 m^3 for CO_2 or LPG transportation (Source: Mazzotti 2006).

According to (Aspelund et al. 2006) the liquefaction plant is the most important process in the chain of CO_2 transport by ship because it requires 77% of energy needed for the whole transport chain. The storage and unloading system have a small energy requirement. The ship is the second most important part in this chain.

The ship transportation has established and a good safety record as well as pipelines. However, the ship system can fail in various ways like collision, foundering, stranding and fire.

The whole section on ships is mainly based on reference (IPCC 2005) and (Aspelund et al. 2006).

2.2.3 Truck and railway

Transport by truck or railway provides much lower transport capacities than pipelines or ships. Technically the CO_2 transportation is a feasible option where CO_2 gets transported as liquid at a temperature of -20 °C and at 2 MPa pressure. In context of long distance and large amounts of CO_2 transportation for CCS, these options are not attractive options and uneconomical in comparison to other options like ship or pipeline. Only on a very small scale or where flexibility plays an important role these options may be an alternative. (IPCC 2005, UBA 2006)

2.3 Storage of CO_2

There are two main possible options to store the separated carbon dioxide:

- geological storage
- ocean storage

On the other hand, also rather different options such as mineral carbonation or industrial use of CO_2 exist.

2.3.1 Geological Storage

Among the geological storage options being considered as a possible option for CO_2 storage are depleted or depleting oil and gas reservoirs, unminable coal beds (enhanced coal bed recovery (ECBM)), deep saline aquifers and caverns and salt domes. Table 2 shows the different options with some qualitative characterization. This report focuses on deep saline aquifers, depleted gas fields and unminable coal beds. In all cases the CO_2 will be injected in dense, supercritical phases, due to the storage of a substantially greater amount of CO_2 than it would be possible in gas-phase. At depth below about 800 m to 1000 m the ambient temperature and pressure conditions will usually result in CO_2 to be in supercritical phase. Only storage of pure or nearly pure CO_2 will be considered. (IPCC 2005)

Table 2 Qualitative comparison of different geological storage options (Source: Ploetz 2003).

Storage Option	Relative Capacity	Relative costs	Storage Integrity	Technical Feasibility
Oil field (EOR)	small	very low	good	high
Deep coal seems	unknown	low	unknown	unknown
Depleted oil and gas fields	modest	low	good	high
Deep saline aquifers	large	unknown	unknown	unknown
Cavern and salt dome	large	very high	good	high

General storage sites characterisations

Suitable sites for CO_2 storage need to provide sufficient storage capacity and injectivity, an adequate sealing cap rock with low-permeability and stable geological conditions. The location of the storage site on the continental plate is also decisive. Locations in tectonically active regions are less suitable for CO_2 storage sites due to the potential risk of leakage.

The storage efficiency will be greater if the CO_2 is denser, due to the increased quantity of stored CO_2 per unit of volume. Also the storage safety will increase because the buoyancy forces are lower than for lighter fluids. However, the porosity of the rock is usually smaller at greater depth because of compaction and cementations, which results in a lower storage capacity and efficiency. The increase of the CO_2 density with depth is shown in Figure 6. At a depth greater than approximately 1000 m an increase of depth will not change the CO_2 density as significantly as for the first 800 m of depth. At a depth of 1500 m the CO_2 density will remain almost constant.

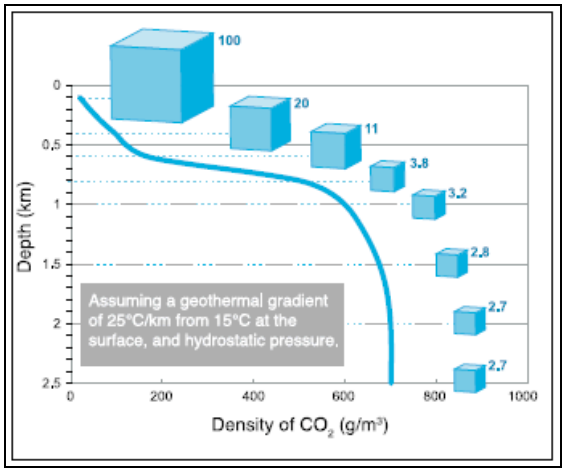

Figure 6 Variation of the density with depth for a geothermal gradient of 25 °C/km (Source: IPCC 2005).

Trapping mechanisms in geological formations

The carbon dioxide injected into the underground will be stored by physical and geochemical trapping mechanisms. Physical trapping of CO_2 occurs below a cap rock, a layer of low-permeability, such as shale or clay rock situated above the storage formation. The carbon dioxide will also remain in the pore spaces by capillary forces. By the geochemical trapping process, the CO_2 dissolves in the in-situ water. The carbon dioxide containing water sinks down due to its density higher than the surrounding water. A chemical reaction between the dissolved CO_2 and the rock minerals occurs, where CO_2 converts to solid carbonate minerals over a potential time of thousandsof years or longer. Another trapping mechanism is the adsorption of CO_2 onto coal or organic-rich shales, where the CO_2 replaces gases such as methane due to its higher adsorption affinity. This process is reversible, thus only if the pressures and temperature remain stable the CO_2 will remain trapped. (IPCC 2005)

Frequently more than one type of trapping mechanism would be present in a single geological sink. Most trapping mechanisms however, do not permanently immobilize the CO_2. The leakage of CO_2 to the surface can potentially occur from all types of geological storage reservoirs. (Nelson et al. 2005)

Saline aquifers

“Sandstone aquifers rich in clay minerals and low in carbonates would be the most favourable geologic sinks for mineral trapping of CO_2.” (Nelson et al. 2005).

Saline aquifers are globally widespread and occur in most of sedimentary basins, offshore as well as onshore. In various literature saline aquifers are said to provide an enormous storage capacity, much higher than all other options.

Saline aquifers are deep underground, porous rock formations which contain formation water or brines with high salinity. Due to its high salinity the water is not suitable for human use as irrigation water for agriculture or as drinking water. Only in very arid regions, deep saline formation water might be considered as a future drinking water source. Saline aquifers can be a potential source for geothermal energy.,Therefore, competition may occur between geothermal energy and CO_2 storage at some sites.

However, generally storage sites with good geothermal potential may not be suitable for CO_2 storage due to the acute increase of the temperature with depth and the high degree of faulting and fracturing. (IPCC 2005)

Saline aquifers – suitable for CO_2 storage – have to provide a high porosity and permeability because they should be such to store sufficiently large amounts of CO_2. The potential storage volume of an aquifer is estimated at a little over 30 % of the total rock volume. Furthermore, they should be overlain by an impermeable layer, known as the cap rock, to prevent buoyant movement of CO_2 in upper layers. According to (Nelson et al. 2005) the most common reservoir lithologies are sandstone and dolomite and the predominant sealing cap rock lithologies are anhydrite and shale. There exist two types of aquifer formations, a dome structure and a cap rock without faulting structure. In the first type the lighter CO_2 accumulates at the highest point within the reservoir, where it will be trapped by the impermeable cap rock. In the second type the CO_2 will migrate along the sealing layer as a separate phase. (IPCC 2005, UBA 2006)

Multiple mechanisms are responsible for the storage process in saline aquifers including physical trapping, dissolution and mineralization. Therefore the estimation of potential storage capacity of saline aquifers is very difficult and uncertain. A deeper understanding of the geological structure and the physical properties of saline aquifers is still required. (IPCC 2005, UBA 2006)

The advantages of saline aquifers are their large estimated storage capacity and the low number of existing wells compared to oil and gas fields, for these wells present a possible leakage path,. But on the other hand there is not so much information on the storage site as for oil and gas reservoirs and no by-product like oil or gas available. (NETL 2006)

Depleted or depleting oil and gas reservoirs

Oil or gas reservoirs are formations of porous rock that has trapped crude oil or natural gas for millions of years. Therefore oil and gas reservoirs (securing appropriate sealing of wells) provide ideal storage sites for CO_2 sequestration due to the demonstration of their suitability and safety over geological time scales. The geological structure and physical properties of the reservoir are well-known thanks to many studies which have been conducted and the developed computer models.

The potential storage capacity of oil and gas reservoirs can be derived from the databases of the reserves and production of oil and gas reservoirs. Anyhow it has to be considered that it is limited by a maximum pressure that is below the pressure that damages the cap rock of the formation. The injection of CO_2 can either occur in depleted reservoirs or enhance the oil and gas recovery in depleting fields. Enhanced gas recovery is so far only conducted at pilot scale.

The advantages of oil and gas reservoirs are their potential economic gain due to enhanced oil (EOR) and gas recovery (EGR), the reuse of some of the already existing infrastructure and wells and the great knowledge about the storage site characteristics. The challenge is the earlier drilled wells, which have not been sealed to the state of the art technology standard. These wells represent a potential leakage path way of the stored CO_2. (NETL 2006, IPCC 2005)

Unminable coal beds

Another option to store CO_2 in the underground is to adsorb it on coal in deep coal seams. Most of the global coal resources are economically unmineable with today's technology. But these coal beds can contain significant amounts of methane-rich gas that is mainly adsorbed on the surface of the coal. So besides the storage of CO_2 coal beds provide possibility for recovery of methane. Coal has a greater affinity to adsorb CO_2 than CH_4. For one molecule of CH_4 the coal can adsorb two molecules of CO_2. Even if the desorbed CH_4 will be used as a fuel and completely burned producing one molecule of CO_2 per molecule of CH_4, there would remain a net-storage of CO_2 in the coal seam. The CO_2 will replace the CH_4 and will be stored in the underground. (UBA 2006, Nelson et al. 2005)

Potential CO_2 storage sites are coal beds, where a later production of coal is very unlikely, to prevent that a subsequent mining of the coal would result in the release of the stored CO_2 back to the atmosphere. Moreover, the coal gas has to provide a sufficient permeability to store enough CO_2. The adsorption process is reversible, so for permanent storage of CO_2 in coal seams the pressures and the temperatures have to remain stable.

Enhanced coal bed methane recovery is still in the demonstration phase. A better understanding of injection process and storage mechanisms in deep coal seams is required. (IPCC 2005, Nelson et al. 2005)

Risk of leakage

Once the CO_2 is stored underground several potential leakage pathways exist as injection well failures, leakage up abandoned wells, through undetected faults, fractures or through leaking wells. Also seismicity, ground movement, CH_4 leakage by replacing by CO_2 and saline brine displacement represent potential risks of CO_2 storage. In Figure 7 these potential risks of CO_2 storage are illustrated.

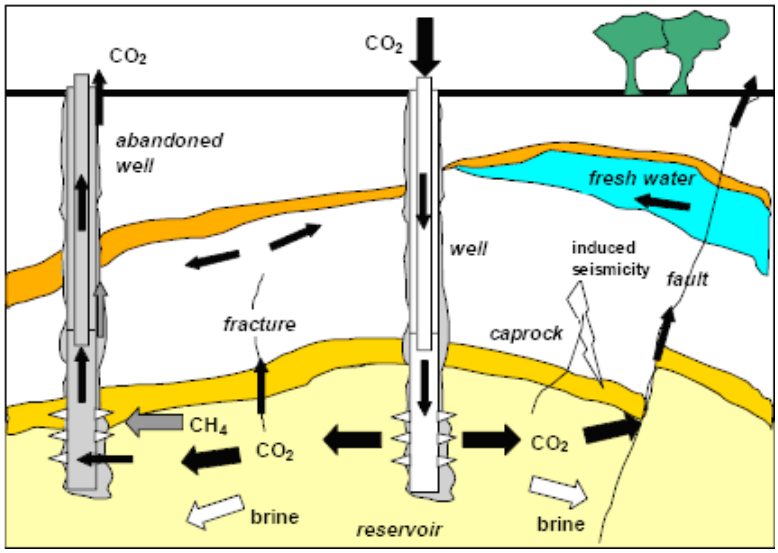

Figure 7 Risks of underground CO_2 storage (Source: CO_2NET 2004).

2.3.2 Ocean Storage

A further measure for mitigating climate change is the storage of the captured CO_2 in the deep ocean. The captured, liquefied CO_2 will be injected directly into the deep ocean (> 3000/4000 m (UBA 2006)), where it will remain isolated. It is estimated that the storage of CO_2 in depths greater than 1000 m will be isolated from the atmosphere for an order of magnitude of 1000 years (UBA 2006). Another method is to inject the CO_2 in shallower depths up to about 1000 m (UBA 2006), where it would dissolve and disperse into the surrounding sea water. CO_2 can also be injected in solid phase, where blocks of dry ice will be unloaded from a ship and sink into the deep sea. There also exists a rather different method: the fertilisation of the ocean with algae to increase the production of biomass and therewith the consumption of CO_2 near the oceans surface. (UBA 2006, BMU 2007)

The ocean is the biggest natural carbon dioxide storage reservoir. Since CO_2 is soluble in water natural exchanges of CO_2 between the atmosphere and ocean surface occur. The natural absorption and desorption of CO_2 is a slow process. Over long time scales this exchange has reached its equilibrium. Due to the increase of atmospheric concentration of CO_2 the oceans take up about 7 Gt additional CO_2 per year and act as a natural mitigation for climate change (IPCC 2005, UBA 2006). As a consequence of the increasing CO_2 concentration in the atmosphere, the composition in the upper ocean is adversely changing. So far, the pH has decreases on the average by about 0.1 at the ocean's surface (IPCC 2005).

The potential of additional storage of anthropogenic CO_2 is enormous. So it is likely that ocean storage will be considered as a potential storage option. But this option is still in the research phase and has not yet been conducted or demonstrated in pilot projects so far.

The possible risks of CO_2 storage in the oceans are not predictable with today's knowledge. However, the injection of CO_2 would generate a measurable change in the ocean's chemistry in the area where the injection occurred.

Experiments show that injection of CO_2 would have adverse effects of marine organisms, such as reduced rates of calcification, reproduction, growth, circulatory oxygen supply, mobility and increased mortality over time. The chronic effects have not yet been investigated. Today it is still not clear how the ecosystem or individual species would adapt to chemical changes. (IPCC 2005)

Due to the lack of knowledge about the processes in the oceans, it is impossible to draw a conclusion about the influence of CO_2 storage on the oceans. In Europe the ocean storage option is not investigated intensively so far and also in this thesis it will not be further considered as a potential storage option.

2.3.3 Other Storage Options

Mineral carbonation

The process of mineral carbonation deals with the fixation of CO_2. Chemical reactions between CO_2 and alkaline and alkaline-earth oxides, such as magnesium oxide (MgO) and calcium oxide (CaO), produce carbonates and silica, which fix the CO_2 in their

chemical structure. The process of mineral carbonation also takes place in nature as chemical weathering of rocks. Since the carbonates and silica are stable over long time scale, the storage can assume to be permanent and the associated risks are very low. The global reserves of silicates are said to be adequate, but there is still need of research. In nature the process of mineral carbonation is very slow. Therefore a big technical challenge exists to accelerate the process of mineral carbonation to become a viable storage option for sequestrated CO_2. Another critical point in addition to the extreme slow reaction is the huge silicate demand and the resulting effects on the local environment by the surface mining and the landfilling of the produced carbonate (if not used). (IPCC 2005, UBA 2006)

Industrial use of CO_2

An industrial use of CO_2 involves chemical and biological processes as well as numerous technological utilizations that use CO_2 directly. Today about 120 Mt CO_2 per year is used worldwide in industrial processes. Compared to the emissions from anthropogenic activities, it is only a very small amount. Also the time of storage is a limiting factor of this potential storage option. Most industrial processes using CO_2 last only days or month. To be a potential storage option the quantity and the duration of CO_2 stored in industrial uses have to be significant and also a net reduction of CO_2 is required. Considering all these requirements the contribution of industrial uses of sequestrated CO_2 is assumed to be small. (IPCC 2005)

2.4 Current Research Projects on CCS

2.4.1 World

On international level in particular the USA, Japan, Canada and Australia as well as the projects of the global operating crude oil and natural gas companies as BP, Statoil, Shell, Texaco, Chevron and others, all play an important role. The projects for storage are often combined with enhanced recovery of fossil fuels (EOR, EGR, ECBM).

The international CO_2 capture and storage projects listed below are only a selection according to (UBA 2006) as there exist plenty of projects. To specify them here exceed the frame of this work.

- IPCC: Special Report on Carbon Dioxide Capture and Storage:

  The IPCC (International Panel on Climate Change) is one of the most important institutions in the field of the GHG problem. It was founded in 1988 by the *World Meteorological Organisation* and the *United Nations Environmental Programme.* IPCC Reports on climate change are regularly published. The most recent one on technology is the IPCC Special Report on Carbon Dioxide Capture and Storage published in 2005.

Projects in the USA

- Carbon Capture Project (CCP)
- FutureGen
- Shady Point Power plant and Warrior Run Power plant

- Great Plains Synfuel Plant
- Advanced CO_2 Separation and Geological Storage
- CO_2 Separation Using Thermally Optimized Membranes
- Oxy-fuel Boiler Concept
- Coal Seq
- Teapot Dome Test Centre
- NACS: Natural Analogs for Geologic CO_2 Sequestration
- Large Scale CO_2 Transportation and Deep Ocean Sequestration
- Carbon Sequestration form Flue gas
- Development of Superior Sorbents
- Development of a carbon management geographic information system (GIS) for the United States
- Sequestration of CO_2 in Depleted Oil Reservoirs

Projects in Canada

- International Test Centre for CO_2 (ITC)
- Alberta ECBM
- The Capture and Storage of Carbon Emissions

Projects in Japan

- RITE R&D Geological Sequestration of Carbon Dioxide
- CO_2 sequestration in unminable Coal Seams in Japan
- Sea-Cosmic

Projects in Australia

- CO_2CRC cooperative research centre for GHG technologies

Projects in Algeria

- In Salah

Until now only a few researches have been performed on the integration of CCS in energy systems, impacts on the environment of the CO_2-storage, impacts to the environment by the technology used for CO_2-capture and in the area of technical acceptance (UBA 2006).

2.4.2 Europe

The European CO_2 capture and storage projects are an important topic within the European energy research in the context of sustainable development. The Framework Programmes (FP) are the funding mechanism for research, technological development and demonstration. It is implemented through calls for proposals. (EU 2004)

Table 3 shows the projects in the FP5.

Table 3 The Current portfolio of FP5 (1999-2002) funded research projects modified after (EU 2004) and (UBA 2006).

European project acronym	Topic	Coordinator
AZEP	Advanced Zero Emission Power Plant, advanced membrane cycles	Siemens
GRACE	Capture in processes	BP
GESTCO	Geological Storage Potential of CO_2 from Fossil Fuel Combustion	GEUS
CO_2STORE	SACS2 follow up on land	Statoil
NASCENT	Natural Analogues for the Storage of CO_2 in the Geological Environment	BGS
RECOPOL	Reduction of CO_2 emission by means of CO_2 storage in coals seams in the Silesian Coal Basin of Poland	TNO
WEYBURN	Weyburn CO_2 monitoring	BGS
SACS2	Monitoring of Sleipner	Statoil
CO_2NET	European Carbone Dioxide Thematic Network	Technology Initiatives
CO_2-ECBM	Investigation into the Basic Scientific Phenomena of CO_2 Injection and Retention in Coal for CO_2 Storage and ECBM Recovery	Imperial College
NGCAS	Development of Next Generation Technology for the Capture and Geological Storage of CO_2 from Combustion Processes	BP

Table 4 shows the ongoing projects in the FP6.

Table 4 Projects funded after the first call in FP6 (2002-2006) modified after (EU 2004).

Project acronym	Topic	Coordinator
ENCAP	Enhanced capture of CO_2	Vattenfall
CASTOR	CO_2 from capture to storage	Institut Français du Pétrole
CO_2SINK	In-situ laboratory for capture and storage of CO_2	GeoForschungs-Zentrum Potsdam
CO_2GeoNet	Network of excellence on geological sequestration of CO_2	British Geological Survey
ISSC	Innovative in-situ CO_2 capture technology for solid fuel gasification	University of Stuttgart

UBA(2006) also includes the following two projects which were performed before the fifth and sixth FP.

- The underground disposal of Carbon Dioxide (Joule II)

  This project was coordinated by the British geological office between 1993 and 1995. The result was a first overview of the distribution of potential CO_2 storage possibilities and capacities in various European countries.

- SACS (Saline Aquifer CO_2 Storage)

  The Norwegian company Statoil is worldwide the first company which stores CO_2 with the goal of mitigating the climate change. Statoil produces natural gas from the Sleipner Field in the Norwegian part of the North Sea. In advance to the delivery to the user, CO_2 has to be separated from the extracted natural gas. This separation occurs on the offshore platform and the separated CO_2 gas is re-injected and stored in an aquifer (Ustria Sand) at a depth of about 800 m below the sea ground. An essential goal of the project is the investigation of the dispersal of the gas in the underground. The project started in 1997.

3 Research Methodology, Objectives and Scope

The aim of this diploma thesis is to conduct a life cycle inventory analysis (LCI) on selected technologies for the CO_2 transport and storage, focussing on European conditions. The comparison between the selected transport and storage options is accomplished using selected life cycle impact assessment (LCIA) methods. Furthermore, the full CCS technology will be modelled using CO_2 capture data available from the ongoing PSI research and compared to a currently operational, best available technology reference hard coal power plant.

The leading questions thereby are the following:

- What is the required energy and material consumption for the transport and storage of CO_2?
- What are the overall environmental burdens associated with the transport and the storage of CO_2?
- Which is the best CO_2 transport and storage option relating to the ecological aspect?
- Which elements of the investigated CO_2 transport and storage processes cause the most significant contributions to the total environmental burdens?
- To what extent is the concept of „near-zero emission“ achieved by the assessed transport and storage options (including capture)?
- Which part of the whole hard coal chain for electricity production has the most significant environmental impact?

The selected options analyzed in this study are the onshore pipeline – with and without recompression unit – for transport on the one hand, and the deep saline aquifer and the depleted gas field for storage of CO_2 on the other hand.

For the selected options an original model has been built which represents a typical case for European conditions. The chosen model parameters are compared to the values found in the literature. The focus lies on the energy and material consumption associated with the transport and storage of CO_2. The capture process has not been defined as a part of the system to model in this thesis, but its data are integrated with transport and storage when assessing the whole energy chain associated with the coal power plant with CCS. The SimaPro (Pré Consultions 2006) LCA software tool has been applied, featuring the most updated version of the Swiss LCI database ecoinvent currently available (v1.3). The comparison of the selected transport and storage options will be done using the Eco-indicator 99 as well as the CO_2 equivalents methods. The EI'99 has been chosen due to its wide acceptance, the CO_2 equivalents due to the context of the thesis as far as CO_2 emissions are concerned.

The comparison of the power plant with complete CCS vs. a conventional power plant without CO_2 capture will also be done using the same two LCIA methods.

The interpretation of the results will consider overall environmental burdens and the CO_2 equivalents for the combination of the selected transport and storage options as well as for the whole CCS technology chain. In addition the contribution of the different processes on the whole process chain will be analyzed. The results will give a first

estimation of the CCS technology in comparison with conventional power plants. This study will allow further extension of the depth of the analysis as well as possibility of comparison with other energy supply systems.

4 Analytical Approach

4.1 System Modelling

4.1.1 System Boundaries and Functional Unit

The focus of this study lies on the processes transport and storage of CO_2. The capture process is herewith not modelled, so it is located outside the system boundary. The intersection between the transport process and the capture process is the given CO_2 flow rate. The capture process delivers the CO_2 in a defined physical state. The compression of CO_2 is assumed to take place at the power plant (as it wil be done in the real case) therefore it is not defined as a part of the transport and storage system. The central point is the energy and material requirement associated with the transport and storage processes. Figure 8 shows a simplified schematic with the system boundary and the inputs of interests from outside. The leakage of CO_2 during the transport process is not indicated.

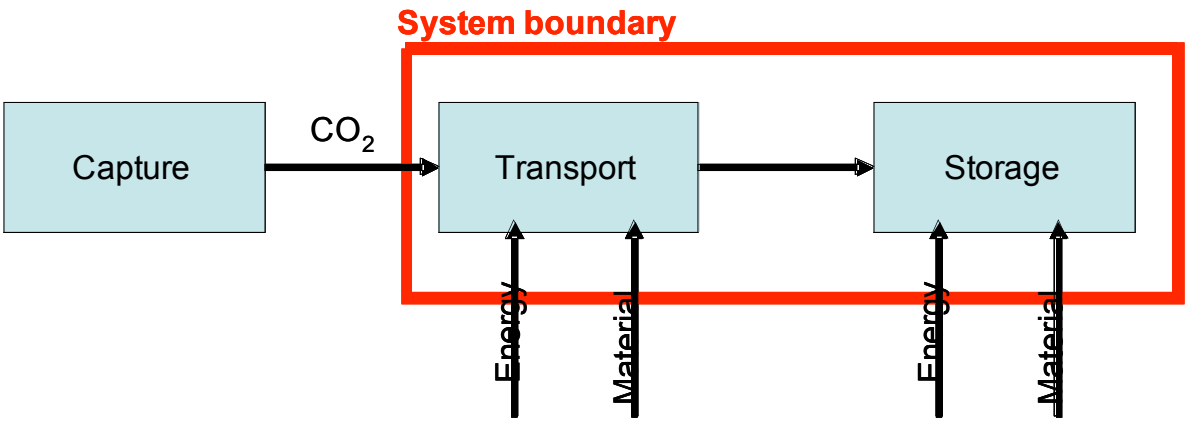

Figure 8 System boundary of the modelled system for the transport and storage.

The chosen functional unit is “kg stored CO_2”. For later comparison of the full carbon capture and storage option with a power plant without CCS option the additional functional unit “kWh” (net) is utilized.

For the system it is assumed that no CO_2 emissions from the storage reservoir will be taken into account. (This is a precondition for the implementation of CO_2 storage.) Furthermore, the assumption is made that only pure or nearly pure CO_2 is considered for modelling of the processes transport and storage.

The model using first assumptions is referred to as the reference case. Later in section 5.3 sensitivity cases are defined.

Managing the state of CO_2, specifically keeping it supercritical in the pipeline, down the injection well, and in the storage formation, is an important part of the system design. The key value therefore is the density of CO_2 depending on the temperature and the pressure. The accurate determination of this value is crucial for the entire system design.

4.1.2 Power Plant Technology

The reference power plant (Dones et al. 2007) is a pulverized hard coal power plant with a net power of 600 MW_{el}, best technology operational today. The CO_2 emissions without capture of CO_2 amount to 738 g CO_2/kWh. The net efficiency is 45 %. Through the installation of the CO_2 post-combustion capture technology the net efficiency of the power plant will decrease to approximately 35 %. This results in a lower net power of approximately 470 MW_{el}. The installed technology is assumed to capture 90 % (854 g per kWh net) of the accruing CO_2 production of the reference plant (with capture), while 95 g per kWh net are ultimately released to the atmosphere. The modelled processes transport and storage are assumed to handle the emissions of three of these power plants (see Figure 9) with a full load hour of 75 %. This gives a constant net power of approximately 1060 MW_{el} and an equivalent, constant flow of captured CO_2 of 7.9 Mt CO_2 per year. When one unit is in maintenance, the other two units are hypothesized to operate at full power, thus providing 940 MW_{el}. Therefore, oscillations in the flow of CO_2 should be limited to 10-20% around the average value mentioned above.

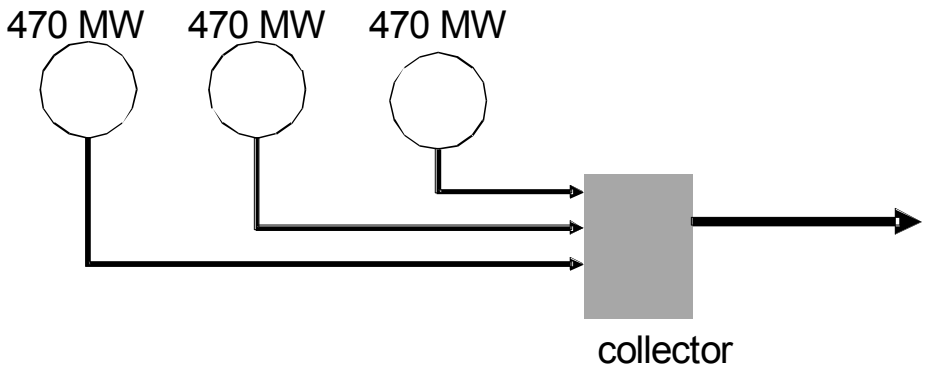

Figure 9 Modelled system of three reference power plants. The pipeline between each plant and the collector is negligible in comparison to the whole pipeline from the collector to the suitable storage site.

4.2 Selection of Parameters for Transport of CO_2

The only economically feasible transport options for transport of such enormous volumes as involved in the CCS are the CO_2 transport by ship or pipeline (IEA 2004), where the ship offers a more flexible option. In order to approximate average conditions in Europe the options to take into account are the pipeline – onshore and offshore – as well as the ship. In this study only the onshore pipeline is analyzed.

The CO_2 is herewith assumed to be transported in supercritical state. Supercritical CO_2 transportation is the general practice for transport of CO_2 in pipelines (UBA 2006). As a first step values found in the literature were chosen and a preliminary model was built to estimate the order of magnitude of the system parameters. In a further step the overall calculation has been refined. The optimization of the parameters is an iterative process. In Table 5 the selection of the parameters for the CO_2 transport is shown. In Table 5 the uncertainty to the assumed values is given. It is based on the knowledge of the different parameters. If the calculation of the parameter depends on other parameters and several

assumptions the uncertainty is considered higher. In the following section each parameter will be explained.

Table 5 Some selected parameters with range and uncertainty for the CO_2 transport process.

Parameter	Unit	Data	Range	Uncertainty to assumed value
CO_2 mass flow rate	Mt CO_2 / yr	7.9	2-30	given value
Inlet pressure	bar	110	100 - 200	low
Average temperature	°C	45	31.1 < T < 50	modest
Average density	kg/m^3	446	200-800	modest, small variation of T and p causes high change
CO_2 velocity	m/s	2.17	1-5	modest
Pipeline outer diameter	m	0.609	0.350-0.750	low, US standard pipe 24 OD
Wall thickness	m	0.018		low
pressure drop per 200 km	bar	30	10-50	high

4.2.1 Assumed CO_2 Properties for Transportation

Mass Flow rate of CO_2

The mass flow rate of CO_2 is given by the above made assumption of modelling a system of three reference power plants. Consequently the process transport of CO_2 has to deal with a constant CO_2 mass flow rate of 7.9 Mt/year.

Temperature

In first approximation the transport temperature of the CO_2 has been modelled assuming an average temperature over the whole distance. The temperature always has to stay over the critical temperature of 31.1 °C for CO_2 to remain in supercritical state. The inlet temperature is assumed to be 50 °C because according to (Mazzotti 2006, BMU 2007) the temperature should not exceed this value. The minimum temperature is set to 40 °C in order to have a sufficient margin for CO_2 to always remain in supercritical state. This results in first approximation of an average temperature of 45°C with a rock wool insulation of 0.03 m over the whole transport distance (see insulation in Section 4.2.2 and the calculation reported in Annex A.II.2). Additionally for the case with recompression a little increase in temperature occurs by the recompression process in the gas turbine. In this study this problem is not exactly modelled, but also for the 400 km distance case with recompression an average temperature of 45 °C over the whole distance is assumed as a first simplification.

Pressure

The inlet pressure in the pipeline is assumed at 110 bar as a consequence of the required minimum pressure of 80 bar and a pressure drop of 30 bar over a distance of 200 km (see pressure drop in Section 4.2.3). The required minimum pressure is fixed at 80 bar according to (UBA 2006, IPCC 2005). With this pressure safely high enough

above the critical pressure of 73.9 bar the CO_2 always stays in supercritical state, thus a two phase system, which is technically very difficult to handle, is avoided.

Density

The density of CO_2 depends on its temperature and pressure. Just a small variation in pressure or temperature causes a high change of the CO_2 density or some temperature/pressure ranges. In Table 6 the density is tabled for different selected conditions of interest in this study. In all conditions the CO_2 is in supercritical state. Where no value is tabled an interpolation between tabled values for the missing condition is conducted. The density of the transported CO_2 is a key factor for the transport system.

Table 6 Density of CO_2 for different conditions in the pipeline (after VDI 2002).

Case	Temperature	Pressure	Density
Unit	°C	bar	kg/m^3
Initial condition	50	110	447.5
mean condition	45	95	446
outlet condition	40	80	277.9

4.2.2 Infrastructure Parameters

Transport Distance

The selection of a typical distance takes into account the distance between two compressor stations. After (IPCC 2005) in general practice the distance between two compressor stations is about 160 km, but some long pipelines have greater distances. Heddle et al. (2003) give a distance of 150 km after which a recompression is required. In (NREL 2004) the distance between two compressor stations amounts to 300 km. Therefore, this study assumes a distance of 200 km without compressor station and 400 km with one compressor station in the middle. By doing so, the effect of additional energy requirement for recompression of the CO_2 can be analyzed.

Pipe Dimensions

The inner diameter of the pipe depends on the given capacity of 7.9 Mt/yr and the velocity of the CO_2 to be transported (see Equation 1). As a first assumption the diameter is calculated with a velocity of 2 m/s.

Equation 1 Continuity equation

$$Q = \vec{v} \cdot A = \vec{v} \cdot \pi \cdot \left(\frac{D_i}{2} \right)^2$$

Q volume flow

v velocity

A Area

D_i inner diameter

Over the resulting inside diameter the outside diameter is calculated with Equation 2. The safety factor S_k of 1.5 for steel (Dialer 2007) takes into account the uncertainty of the yield factor σ that amounts to 2.3E+8 N/m_2 for carbon steel (DIN 17100). For the pressure the mean of 95 bar over the whole pipe is used. With a resulting thickness of t = 18.5 mm the outer diameter is calculated to 634 mm assumed constant throughout the pipe. This means that for the initial section with highest pressure S_k = 1.3. Comparing to existing tabled US-pipes (TEMA 1999) the pipe suitable for a capacity of 7.9 Mt/yr and a velocity of around 2 m/s it the OD 24 (corresponds to 609 mm outside diameter).

Equation 2 Wall thickness

$$t = \frac{p \cdot D_i}{2 \cdot \sigma} \cdot S_k$$

t	wall thickness
p	pressure
Di	inner Diameter
σ	Yield Strength
S_k	safety factor

On the basis of this chosen outside diameter the wall thickness t is recalculated to 17.8 mm, the corresponding inner diameter to 573 mm and the velocity to 2.17 m/s. Table 7 shows the characteristic of the pipe dimensions.

Table 7 The characteristic of the pipe dimensions.

Parameter		Unit	Value	Reference
Mean pressure in tube	p	Pa	9.5E+06	
Yield strength	σ	N/m^2	2.30E+08	C-steel, type R St 37-2, material number 1.0114 after DIN 17100
Safety factor	S_k	-	1.5	for steel, Dialer 2007
Inner diameter	D_i	m	0.573	
Wall thickness	s	m	0.0178	
Outer diameter	D_a	m	0.609	Tabled standard US-pipe 24” (TEMA 1999)
Velocity		m/s	2.17	

Insulation

Since there is lack of data on the type and thickness of the pipeline insulation used in practice in this study a rock wool insulation of 30 mm is assumed as a first approximation. The thickness of 30 mm is calculated over a simplified static heat loss estimation assuming an allowed temperature drop of 10°C per 200 km (see Annex A.II.2). It has to

be kept in mind that this calculation is very rough and the uncertainty is high. Especially the value for the isobaric heat capacity c_p is very sensitive for the whole calculation. In practice a coating with decreasing thickness over the distance is conceivably, but not done in this study.

Buried Depth

The pipeline is assumed to be buried within trench, at a minimum of about 0.9 m (distance from top of pipe to the surface) (IPCC 2005).

Lifetime

In the literature values for lifetime of 30 years (Johnson et al. 2006) and 25 years (McCollum et Odgen 2006) can be found. As a first assumption 30 years are assumed for this study. However, one has to keep in mind the high influence of the CO_2 conditions on this value. It is unlikely to transport wet CO_2 in carbon steel due to the high corrosion rate caused by the acid character. When CO_2 meets water acid is produced. The CO_2 transportation in this study only consider the transport in dry condition. However, contact with water due to leakage or damage of the pipeline might occur at a later stage of its lifetime.

4.2.3 Operation parameters

Corrosion

The corrosion rate is not considered in this study because it is very low for transportation operating with dry supercritical CO_2. From the literature, for X-60 carbon steel pipeline the corrosion rate amounts to less than 0.5 µm/yr (IPCC 2005) at a temperature of 22 °C, a pressure of 140 bar and 1000 ppm H_2S. Another measurement for AISI 1080 results in a corrosion rate of 0.01 mm/yr (Mazzotti 2006) at 90-120 bar and 160 – 180 °C for 200 days. A relative humidity less than 60 % (Mazzotti 2006) does not corrode meaningfully the carbon steels usually used for CO_2 pipelines.

Velocity

The typical velocity in a pipeline transporting CO_2 is 1 to 5 m/s (IPCC 2005, BMU 2007). As a first value a velocity of 2 m/s has been assumed. The exact velocity is recalculated after fixing the inner diameter by choosing the dimension of the pipe out of tabled, existing pipe diameters (TEMA 1999). The final velocity amounts to 2.17 m/s, as shown in the previous Section.

Pressure Drop

The main factors influencing the pressure drop are the roughness of the pipe, the mass flow and the diameter of the pipe. The pressure drop in the pipe over the distance of 200 km is calculated with Equation 3.

Equation 3 Pressure drop in pipe

$$\Delta p = \lambda \frac{L}{D_i} \cdot \rho \cdot \frac{v^2}{2}$$

Δp	pressure drop
λ	dimensionless roughness number
L	length
ρ	density of the fluid
Di	inside Diameter
v	velocity

Table 8 Used values for the parameters to calculate the pressure drop.

Parameter	Unit	Value	Remark and Source
Temperature	°C	50	Inlet temperature, Mazzotti et al. 2006
Pressure	bar	110	Inlet pressure, assumed
Kinematic viscosity	m^2/s	7.52E-08	at 50 °C and 110 bar, Vauck et Müller 2000
Density	kg/m^3	447.48	at 50 °C and 110 bar, Vauck et Müller 2000
Reynolds number	-	1.66E+07	> 2300, turbulent flow, calculated
Length	m	200'000	given by the model
Pipe diameter	m	0.573	calculated (TEMA 1999)
Velocity	m/s	2.17	calculated

The values used for the calculation are shown in Table 8.

The dimensionless roughness number λ (see Table 9) depends on the absolute roughness k of the pipe (see Annex A.II.1).

Table 9 Resulting pressure drop as function of different absolute roughness k for rough pipes and for smooth pipes.

Material	Absolute roughness k [mm]	Roughness number λ [-]	Pressure drop Δp [bar]	Source
rough pipes				
new steel	0.02	0.0067	25	Vauck et Müller 2000
welded, used, cleaned steel	0.15	0.0126	46	VDI 2002
steel, no more precise information given	0.046	0.0087	32	Bock et al. 2001
commercial steel	0.000045	0.0010	4	efunda engineering fundamentals

smooth pipes	-	0.0024	9	Vauck et Müller 2000

The resulting pressure drop for different values of the absolute roughness k is also shown in Table 9. The pressure drop varies between about 5 and 50 bar depending on the used absolute roughness k of the pipe. These values are compared to values found in the literature (see Table 10). A pressure drop of 0.001 MPa/100 m corresponding to 20 bar per 200 km is given by (NREL 2004). In (Heddle et al. 2003) a pressure of 16 Pa/m for 300 km transport is given. This results in a pressure drop of 32 bar per 200 km, but one has to keep in mind that (Heddle et al. 2003) deduced this pressure drop over the inlet pressure and the required minimum pressure at the outlet. The pressure drop found in (Bock et al. 2001) is 25 Pa/m that is equivalent to a pressure drop of 50 bar per 200 km. In this study a pressure drop of 30 bar is assumed for the reference case.

The pressure drop will define the required inlet pressure and also the required energy for recompression is determined by this value.

Table 10 Pressure drop in pipe according to various references.

Pressure drop	Pa/m	Distance [m]	Pipe diameter [mm]	per 200 km [bar]
Heddle et al. 2000	16	300	350	32
NREL 2004	10	n.s.	n.s.	20
Bock et al. 2001	25	100	323	50
This study	15	200	573	30

Energy for Recompression

The energy required for recompression is calculated with Equation 4 for a pressure drop of 30 bars and an assumed gas turbine efficiency η= 85 % (Dialer 2007). The resulting value for the system is 0.011 kWh/tkm. In (NREL 2004) the electric energy required for recompression over a pipeline distance of 300 km is given as 1 MW that corresponds to approximate 0.014 kWh/tkm.

Equation 4 Power and efficiency

$$P = \Delta p \cdot \dot{V} \cdot \frac{1}{\eta} \qquad \eta = \frac{P_{ideal}}{P_{real}}$$

It is assumed that the required energy is provided by a gas turbine with 10 MW power. 60 MW for six compressor stations is reported in (IPCC 2005) for the SACROC project. The gas turbine is only used to model the infrastructure for recompression process. The required energy of 0.011 kWh/tkm corresponds to 2 MW for a mass flow rate of 7.9 Mt CO_2/yr and a distance of 200 km. Compared to the 10 MW power provided by the gas turbine, the model is overestimated.

Leakage

The leakage of CO_2 during pipeline transportation is said to be very low according to various sourcs (IPCC 2005, UBA 2006, BMU 2007), but no values are given. The frequency of incidents occurring during CO_2 transport by pipeline is about in the same range as the one for transportation of natural gas in pipelines. Therefore in this study the leakage rate of natural gas of 0.026 % per 1000 km transport from the process "Transport, natural gas, pipeline, long distance/RER U" (Faist Emmenegger et al. 2003) is assumed also for CO_2 transport.

Except from the assumed leakage the security of the pipeline is not further studied in this paper because the pipelines have an established and good safety record according to (IPCC 2005).

4.3 Selection of Parameters for Storage of CO_2

The possible storage options in Germany are after (BMU 2007) selected depleted gas fields and deep saline aquifers. BMU (2007) also considers deep coal seams as a viable option even if there is still substantial research required.

The German gas fields are considered as an important storage option. The capacity is said to be available to store enough CO_2 to contribute significantly to the CO_2 emission reduction. Saline aquifers are said to provide the largest storage potential which is however, difficult to estimate. The deep coal seams are seen as a less suitable option for Germany. (UBA 2006)

In order to reflect average conditions in Europe as possible storage options depleted gas fields, deep saline aquifers and deep coal seams with production of methane (ECBM) are considered. In this study only deep saline aquifers and depleted gas fields are analyzed.

The intersection between the transport and the storage process is the delivered CO_2 at the end of the pipeline. The CO_2 has the characterization shown in Table 11 at the delivery point.

Table 11 Characterization of the carbon dioxide at the end of the pipeline.

Pressure	p	bar	80
Temperature	T	°C	40
Density	ρ	kg/m^3	277.9
Mass flow rate CO_2	M	kg/s	2.50E+02

The CO_2 is supposed to be injected and stored in supercritical state. In Table 12 the selection of the parameters for the CO_2 storage is shown. In the following section the selection of each parameter will be discussed.

Table 12 Some selected parameters with range and uncertainty for the CO_2 storage process.

Parameter	Unit	Aquifer	Gas Field	Range	Uncertaintyto assumed value
Depth	m	800	2500	700 - 4000	low
Reservoir pressure	bar	78	172	100 - 200	high

Pressure difference to overcome for injection	bar	28	122		high
Injection rate	kg/s	125	125	1-120	modest

4.3.1 Storage Site Characterization

Depth

Suitable storage sites are located at a minimum depth of 800 m as given in the literature (IPCC 2005, IEA 2004). At this depth CO_2 will remain in its supercritical state which is the preferred state to store the CO_2 due to the relatively high density.

The depth of a deep saline aquifer can vary from site to site. In Table 13 some depths for existing projects are shown. In this study a depth of 800 m is selected. This depth may provide the most suitable storage site in terms of LCI because less energy is required for the injection of the CO_2.

Table 13 Depth of deep saline reservoirs according to various projects.

Project	Storage site	Depth [m]	Reference
Sleipner	North sea, Norway	800-1000	IPCC 2005
CO_2 SINK	Ketzin Germany	700	CO_2SINK 2007
Snovhit	North Sea, Norway	2500	NETL 2006
Thaynes formation	Uinita county, Utha, USA	900	Nelson et al. 2005

The location of depleted gas fields in 2-4 km below ground is reported in (IEA 2004). In Table 14 depths of gas fields are shown for existing projects. The depth of the reference depleted gas field assumed in this study is 2500 m.

Table 14 Depth of gas fields for various projects.

Project	Storage site	Depth	Reference
CASTOR	Lindach Austria	850	Le Thiez et al. 2007
CASTOR	K12B, Gaz de France, The Netherlands	3500-4000	Le Thiez et al. 2007
In Salah	Algeria	1800	IPCC 2005
CASTOR	Atzbach-Schwanendstadt (Rohoel, Austria)	1600	Le Thiez et al. 2007

Reservoir Pressure

The pressure in the reservoir can vary in a wide range, with large uncertainty. From one specific site to another a great variability of reservoir pressures can be found.

In (Kaszuba et al. 2003) is reported that the reservoir pressure conditions vary widely between approximately 200 bar and 1000 bar. Sedimentary basins can have abnormal pressure systems according to (Nelson et al. 2005). Any pressure/depth gradients outside of the common gradient of 9.8 kPa/m are considered abnormal. Often abnormal pressures are over-pressured, but also under-pressured basins exist.

The reservoir pressure in this study is assumed over a hydrostatic pressure gradient of 9.8 kPa/m (Nelson et al. 2005). For the depleted gas fields the reference reservoir pressure is assumed to be only 70 % of the calculated hydrostatic pressure, under the assumption of lower reservoir pressure due to gas extraction.

Storage Capacity

For storage capacities of deep saline aquifers any size is likely to be found. Holloway et Lindeberg (2004) report 1.5 Gm^3 volumes in accessible traps from the Utsira Formation in Norway. This corresponds to approximately 944 Mt CO_2 with a CO_2 density of 629 kg/m^3 (for T=40°C and p=100 bar).

For depleted gas fields it is important that the potential capacity is available. According to (Mazzotti et al. 2007) it is expected that in about 20 years from now CCS technology will provide a significant CO_2 sink. Therefore enough storage capacity has to be at hand within the next 15 to 20 years. A storage capacity of 410 Mt for the biggest depleted gas field in Germany is reported in (BMU 2007).

The existence of large suitable deposits would simply mean that the storage capacity of the reservoir might not be limited by the lifetime of the reservoir but by the lifetime of the materials used in the injection well unless several injection points were used (which would likely increase the probability of leak). So the assumption is made that the total flow into the reservoir throughout the lifetime of the modelled system will not exceed the total capacity of the reservoir.

Reservoir Temperature

The reservoir temperature can be calculated using a geothermal gradient. A common geothermal gradient of 4 °C to 29.5 °C/km is given in (Nelson et al. 2005). In this study the temperature is not important for the system because the storage mechanisms in the underground are not modelled. Therefore it is assumed that the temperature of the CO_2 over the injection process remains more or less constant.

4.3.2 Infrastructure Parameters

Deep Drilling and Injection Well

The technology used for drilling is the rotary drilling (CO_2SINK 2007). In this study the injection well technologies are not modelled but the deep drilling LCI dataset modelled for the geothermal energy LCI (Bauer et al. 2007) is used with some adjustments (see 4.4.2.1). The diameter of 200-400 mm for the drilling used in (Bauer et al. 2007) is justifiable as a first assumption since (CO_2SINK 2007) reports for lower flow rate a diameter of 600 mm for the standpipe up to 30 m depth and 89 mm for the injection string up to 680m.

In (IPCC 2005) is reported that horizontal and extended reach wells can be good options for improving the rate of CO_2 injection from individual wells. In this study also horizontal and extended reach wells are considered. Therefore the assumption is made that the length of deep drilling is double the depth of the storage site.

Besides the two (see Number of Wells in Section 4.3.3) injection wells a monitoring (CO_2SINK 2007) well with thinner diameter is modelled. To somewhat account for these,

the monitoring well is modelled along the main wells but using half of the depth to storage. This length is then added to the total length of the injection wells.

Already existing infrastructure facilities for depleted gas fields are not considered in this study. One may further have to prove if existing boreholes or other infrastructure facilities can be reused for CO_2 injection. In this way a decrease in the material and energy consumption for the storage process may be achieved.

The lifetime of the injection well is herewith assumed to 15 years, taking into account the value of 12 years reported in (Johnson et al. 2006) for a CO_2 injection well and 30 years given by (Bauer et al. 2007) for wells used for geothermal energy. This value is highly influenced by the CO_2 conditions. It is unlikely to inject wet CO_2 due to the high corrosion rate caused by the acidity. When CO_2 meets water acid is produced. In (GreenPrices 2007) it is reported that the Norwegian carbon storage project at the Draugen oilfield is aborted due to unexpected corrosion problems.

4.3.3 Operating Parameters

Overpressure and Injection Pressure

The injection pressure results from the actual reservoir pressure and the overpressure required for the injection of the CO_2 into the storage reservoir. In (IEA 2004) it is reported that the injection pressure is a function of the injection depth and the pressure profile found in the underground. Other factors influencing the injection process are the permeability of the reservoir and the injection rate. The exact modelling of the injection process is very complex and the data availability inadequate. In this study this process is not modelled into detail, but only a first assumption according to the values found in literature is done.

In the Sleipner project an injection pressure of 66 bar (Statoil 2007) is enough to inject the CO_2 into underground. For enhanced oil recovery an overpressure of 118 bar is reported in (IPCC 2005) for the Weyburn project. In the seconde case, probably there is a higher pressure required to gain an enhanced oil production. In (IEA 2004) an overpressure of up to 17 kPa/m depth for gas projects in USA is given. This corresponds to an overpressure of 136 bar for a depth of 800 m. However, the same reference also report that for CO_2 projects such high additional pressures are not proposed, for which the potential cap rock fracture may be less of problem. An overpressure of 2 MPa for the Sleipner area is reported in (SINTEF 2003). In (Bock et al. 2001) overpressures of 1.4 MPa for an oil reservoir, 12 MPa for a gas reservoir and 7 MPa for an aquifer are reported. However, the value given for the aquifer is just a mean between the oil and gas reservoir and the value for the gas reservoir is not very plausible. The reservoir pressure can vary widely from site to site (see Annex A.III.1).

In this study as a first assumption for the required overpressure 30 bar is selected based on the literature, so shown in Table 15.

Table 15 Overpressures for injection according to various studies.

Reference	Overpressure [Mpa]	Depth [m]	Storage formation	Remark
IPCC 2005	12	n.s.	Weyburn EOR	
IEA 2004	14	800	gas projects	calculated over value of 17kPa/m, but such high pressures not proposed for CO_2
SINTEF 2003	2	850	Sleipner area	
Bock et al. 2001	12	1524	gas reservoir	reservoir pressure of 3.45 Mpa at a depth of 1524 m
	1.4	1554	oil reservoir	
	7	1539	aquifer	mean of gas and oil
this study	3	800	aquifer	
	3	2500	gas field	

The injection pressure is the sum of the reservoir pressure and the required overpressure. For the aquifer the injection pressure adds up to 108 bar, for the depleted gas field to 202 bar. The pressure difference that is to overtake for injection results from the delivery pressure at the end of the pipeline and the required pressure for injection at the bottom hole. In Table 16 the different pressures are shown for the deep saline aquifer and the depleted gas field modelled in this study.

Table 16 Pressures at different stages of the process storage in an aquifer or a depleted gas field.

Parameter	Unit	Aquifer	Gas field
Depth	m	800	2500
Surface pressure of CO_2 at the well head	bar	80	80
Hydrostatic pressure in the reservoir	bar	78.4	171.5
Pressure required at bottom hole	bar	108.4	201.5
Δp required for injection	bar	28.4	121.5

The reservoir pressure will increase in the area where the CO_2 injection occurs. To prevent potential cap rock fracture the maximum safe injection pressure is estimated to be 1.35 times the hydrostatic pressure for a depth down to 1000 m and 2.4 times for depth of 1000 – 5000 m (IPCC 2005). In this study this is assmued to be adhered to.

Injection Rate

According to the Table 17 in this study each modelled well is assumed to be capable of handling up to 125 kg CO_2/s. This value is selected as it describes the upper limit of the injection rates found in literature (all test cases, no real application to CCS yet available). It is to prove further if higher injection rates are technologically feasible.

Table 17 CO_2 injection rate in kg/s for different storage sites.

Project	Country	Injection rate [kg/s]	Reservoir
Weyburn	Canada	46	CO_2-EOR
Salt Creek	USA	64	CO_2-EOR
Sleipner	Norway	35	Aquifer
In Salah	Algeria	41	depleted gas field
Snovhit	Norway	23	saline formation
Gorgon	Australia	116	saline formation

Number of Wells

In (IPCC 2005) is reported: “The number of wells required for a storage project will depend on a number of factors, including total injection rate, permeability and thickness of the formation, maximum injection pressures and availability of land-surface area for the injection wells.”

Under the constraint of data availability the number of wells is only assumed over the selected injection rate of 125 kg CO_2 per second and well. With a given constant mass flow of approximately 250 kg/s correspoding to 7.9 Mt CO_2/yr this results in the requirement of two wells for the modelled case.

Pressure Drop

The pressure losses in the wells over the injection depth is negligible in comparison to the required pressure to overtake for injection and not considered in this study.

Energy for Injection

The energy required for the injection of CO_2 is calculated with Equation 4 also used for the calculation of the required recompression energy for the transport in pipelines. The energy is calculated for the required pressure difference (see Table 16) and the injection rate of 125 kg/s per well. The assumed gas turbine efficiency η is 85 % (Dialer 2007). The resulting values for the aquifer as well as for the gas field are shown in Table 18.

Table 18 Parameters for energy requirement calculation for injection of CO_2 per well and for the whole system.

Parameter	Unit	Aquifer	Gas field
required Δp	bar	28.4	121.5
efficiency η	-	85%	85%
volume flux at ρ = 277.9 kg/m^3	m^3/s	0.45	0.45
Power P per well	MW	1.5	6.4
Electricity needed, 2 wells	kWh/kg	6.68E-03	2.86E-02

4.4 Life Cycle Inventory (LCI)

The modelled system for transport and storage is implemented into the SimaPro LCA software tool. Figure 10 shows the scheme of the transport and storage chain as it is organized in SimaPro. The datasets of deep drilling and well infrastructure are taken from the modelling of geothermal energy “electricity at geothermal power plant, Basel, 2030” (Bauer et al. 2007). The dataset “drilling deep borehole for HDR”, which is applied for the modelling of the drilling, is not reproduced here. The dataset “well triplett, Basel, 2030” is used for the modelling of the injection well, with some adaptions to the CO_2 storage case.

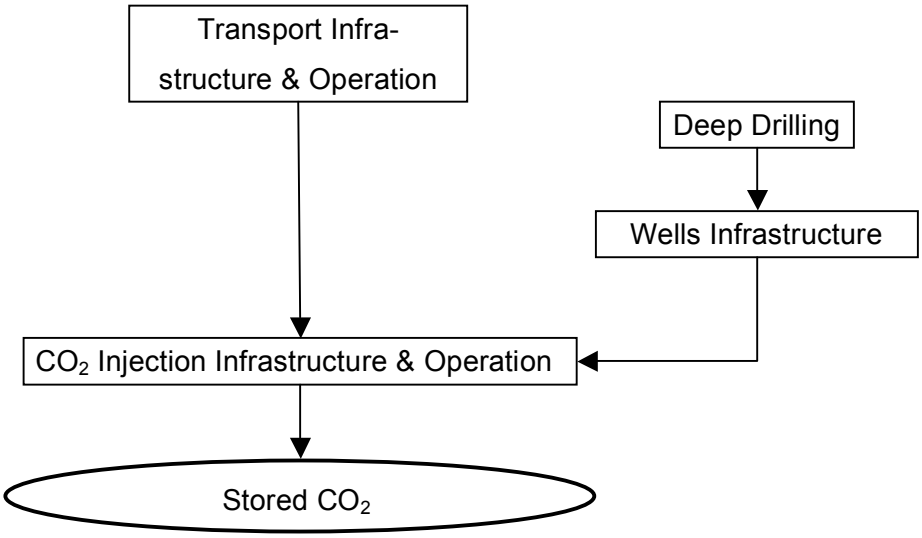

Figure 10 Scheme of the transport and storage chain.

4.4.1 LCI for Transport

4.4.1.1 Infrastructure

Material

The pipelines used for CO_2 transport are made of carbon steel. Steel grades of X-60 and X-65 are reported in (IPCC 2005) for steels generally used for pipelines. The required material for steel pipe is determined over the defined dimensions of the pipe (see section 4.2.2) with a diameter of 609 mm. The calculation is shown in Annex A.II.3.1. The resulting steel demand per km pipeline amounts to 270 t/km including a surcharge of 3 %. The surcharge is a first assumption for considering valves, flanges etc. and likley somewhat overestimated. In (IPCC 2005) block valves within every 16 km are reported and considered included in the surcharge.

The pipelines are coated (IPCC 2005) for protection and for keeping the heat loss small. As a first assumption the insulation is assumed 30 mm thick on the bases of a simplified calculation (see Annex A.II.2). The selected material is rock wool. Other coatings as poly ethylene casings are neglected in this study. The resulting rock wool requirement per km pipeline comes up to 5119 kg (see Annex A.II.3.2).

The pipelines are buried to a minimum of 0.9 m (IPCC 2005). The trench is assumed to be approximately 1.5 m wide and 1.7 m deep according to (Faist Emmenegger et al. 2003). The volume not occupied by the pipe including the coating is assumed to be filled with sand. The resulting sand requirement amounts to 4.4E+06 kg per km pipeline (see Annex A.II.3.3).

The average lifetime of the pipelines is assumed 30 years (see 4.2.2).

The transport distances of the materials to and away from the construction site are calculated according to (Frischknecht et al. 2004).

Construction and Land Use

For the effort required for pipeline construction the values from the process “Pipeline, natural gas, long distance, low capacity, onshore/GLO/I U” (Faist Emmenegger et al. 2003) are assumed. The land use is also adopted from the same process.

Dismantling and Disposal

The effort to remove the pipelines out of the soil is assumed to be part of the construction of the new pipeline. The sand removed from the soil is believed to count as inert material to the landfill. Also the rock wool is assumed to be deposited. The steel is assumed to be half recycled and half left on site. (The Final desicion on digging the pipe out depending on economics.)

Monitoring per Helicopter

Pipelines in operation have to be monitored at regular interval. According to (IPCC 2005) the monitoring is done internally by”pigs” and externally by corrosion monitoring and leak detection systems as well as by patrols on foot and by aircraft. In this study only monitoring by aircraft is considered as a first assumption. Therefore the calculations made for the process “Pipeline, natural gas, long distance, low capacity, onshore/GLO/I U” (Faist Emmenegger et al. 2003) are adopted.

Assembly Drawing

Table 19 shows the resulting LCI data for the construction and the disposal of CO_2 pipelines.

Table 19 LCI data per km of pipeline assumed in this study.

Pipeline, supercritical CO2		**Unit/km**
Resources		
Occupation, construction site	3330	m2a
Transformation, from forest	2000	m2
Transformation, to heterogeneous, agricultural	2000	m2
Water, unspecified natural origin/m3	187	m3
Materials/fuels		
Sand, at mine/CH U	4.40E+06	kg
Diesel, burned in building machine/GLO U	3.31E+06	MJ
Steel, low-alloyed, at plant/RER U	2.70E+05	kg
Drawing of pipes, steel/RER U	2.70E+05	kg
Rock wool, packed, at plant/CH U	5119	kg
Transport, helicopter/GLO U	26	hr
Transport, helicopter, LTO cycle/GLO U	10.4	p
Transport, lorry 32t/RER U	3.15.E+05	tkm
Transport, freight, rail/RER U	5.51.E+04	tkm
Waste to treatment		
Disposal, inert waste, 5% water, to inert material landfill/CH U	4.40E+06	kg
Disposal, steel, 0% water, to inert material landfill/CH U	1.35E+05	kg
Disposal, mineral wool, to final disposal/CH U	5.12E+03	kg

4.4.1.2 Operation

For the operation of the pipelines transporting supercritical CO_2 two cases are distinguished:

- Transport without recompression over 200 km
- Transport with one recompression stage over 400 km

The schematic of the transport system is shown in Figure 11. For the transport over 200 km no recompression is required due to the pressure head is still high enough for injection. For the transport over 400 km a recompression is required which has to compensate the pressure drop of 200 km transport. The first compression of the CO_2 is done at the power plant and not part of the transport system.

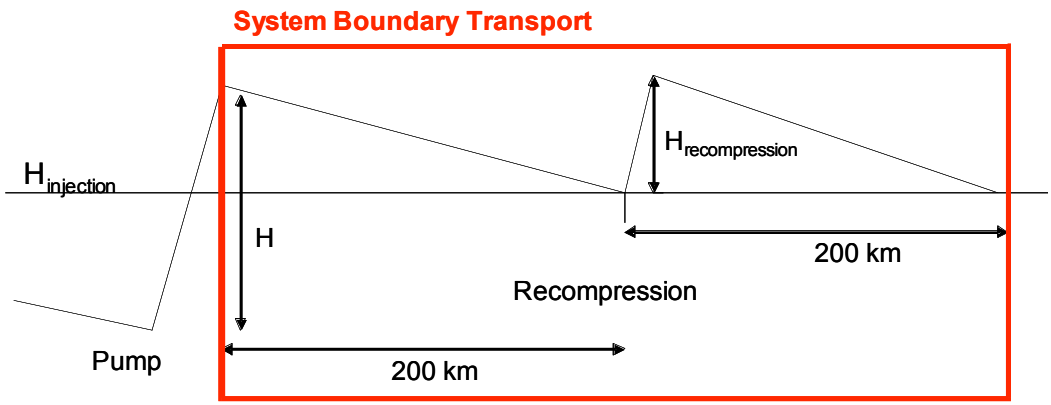

Figure 11 Schematic of the recompression for the transport process.

For the case without recompression besides the required pipeline infrastructure only the losses of CO_2 have to be considered in the inventory. The leakage rate is assumed to be equal to the one for natural gas in the dataset "Transport, natural gas, pipeline, long distance/RER U" (Faist Emmenegger et al. 2003). For the CO_2 emissions this results to 2.6E-04 kg carbon dioxide, fossil per tkm transport of CO_2 with a almost negligible leakage rate of 0.026 % per 1000 km.

The LCI data for the transport of supercritical CO_2 without recompression is shown in Table 20.

Table 20 LCI data per tkm transportation of CO_2 in pipeline without recompression assumed in this study.

Transport, pipeline, supercritical CO2, w/o recompression		**Unit/tkm**
Resources		
Pipeline, supercritical CO2	6.34E-09	km
Emission to air		
Carbon dioxide, fossil	2.60E-04	kg

The pipeline transport of supercritical CO_2 with recompression is based on the same assumptions as the transport without recompression but additionally it requires energy for the recompression process. The calculation of the energy requirement is done in section 4.2.3 and results to 0.011 kWh per tkm transport of CO_2. The required energy is assumed to be provided as electricity of the Western Europe mix UCTE. The process "Electricity, medium voltage, production UCTE, at grid/UCTE U" from the ecoinvent database is representative for the year 2000. The data provided by UCTE give a composition of 16 % hydro power, 37 % thermal nuclear and 47 % conventional thermal power for the year 2000. In (NREL 2004) also a mixture, the generation mix of the mid-continental United States, is assumed to be used for recompression of CO_2 in pipelines.

For the required machine for recompression as first assumption the "Gas turbine, 10 MWe, at production plant/RER/I U" from ecoinvent database is selected.

The LCI data for the transport of supercritical CO_2 with recompression is shown in Table 21.

Table 21 LCI data per tkm transportation of CO_2 in pipeline with recompression assumed in this study.

Transport, pipeline, supercritical CO2, w recompression		**Unit/tkm**
Resources		
Electricity, medium voltage, production UCTE, at grid/UCTE U	0.011	kWh
Pipeline, supercritical CO2	6.34E-09	km
Gas turbine, 10 MWe, at production plant/RER/I U	6.97E-10	p
Emission to air		
Carbon dioxide, fossil	2.60E-04	kg

The material requirement and the construction effort play an important role in the process transport. In the SimaPro Sankey-diagramm with 12 % cut-off for the case transport with recompression (see Figure 12) the importance of the steel input and the construction effort can be seen clearly.

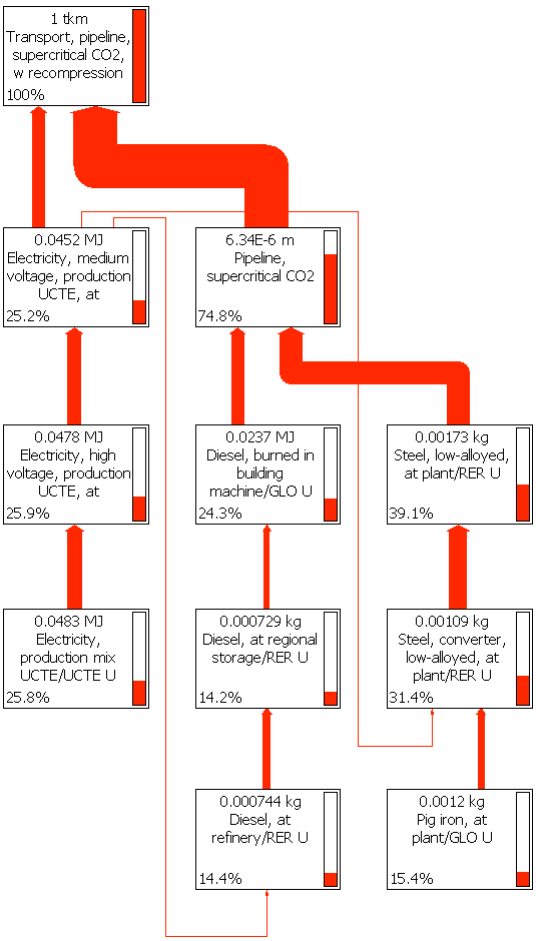

Figure 12 Sankey-diagramm of the process „Transport pipeline, supercritical CO2 w compression" with 12 % cut-off using the Eco-indicator 99 method.

4.4.2 LCI for Storage

4.4.2.1 Infrastructure

Material and Drilling

The material used for the double well is adopted from the process “well triplett, Basel 2030” from (Bauer et al. 2007) with some adjustments. All materials and efforts needed for the stimulation of the deep heat filed are obviously omitted, the land use is adjusted and the needed length of drilling is set according to the selected storage depth. The total drilling length is combined in Table 22. For the aquifer the required drilling amounts to 3.6E+03 m including the two injection wells with a length of 1600 m per well as well as with the monitoring well with a selected length of 400 m to compensate the assumed thinner diameter in order to balance the material use. For the depleted gas fields the value come up to 1.13E+04 m for two wells of 5000 m length per well and for the monitoring well of 1250 m length.

Table 22 The different elements to the total drilling length.

	Aquifer [m]	depleted gas field [m]
Depth well	800	2500
Length borehole	1600	5000
Number of wells	2	2
Assumed monitoring well	400	1250
Total drilling length	3600	11 300

The data set representing the deep drilling for the injection well coincides with the process “drilling, deep borehole for HDR” from (Bauer et al. 2007) except for the change of the kind of steel from “Reinforcing steel, at plant/RER U” to “Steel, low-alloyed, at plant/RER U" to account for the use of cabon steel.

The transport distances of the materials are recalculated over the standard distances in (Frischknecht et al. 2004).

Land Use

The occupation of the area for injection is assumed to be 600 m^2 as a first approximation. Anyway from the LCIA point of view this factor changes only marginally the total environmental burdens. For the depleted gas fields “Transformation from unknown” is selected because it is not known if already existing industrial area or if former pasture and meadow will be occupied.

Assembly Drawing

Table 23 and Table 24 show the resulting LCI dataset describing the construction of the double well for the aquifer and the depleted gas field respectively.

Table 23 LCI data for the construction of the double well for the geological storage in deep saline aquifers.

well double, aquifer		per unit
Resources		
Occupation, industrial area	900	m2a
Occupation, industrial area, vegetation	8100	m2a
Transformation, from pasture and meadow	600	m2
Transformation, to industrial area	60	m2
Transformation, to industrial area, vegetation	540	m2
Materials/fuels		
drilling, deep borehole for HDR	3.60E+03	m
Cement, unspecified, at plant/CH U	1.26E+05	kg
Gravel, unspecified, at mine/CH U	1.32E+06	kg
Transport, lorry 28t/CH U	2.89E+04	tkm
Transport, freight, rail/CH U	1.26E+04	tkm

Table 24 LCI data for the construction of the double well for the geological storage in depleted gas fields.

well double, depleted gas field		per unit
Resources		
Occupation, industrial area	900	m2a
Occupation, industrial area, vegetation	8100	m2a
Transformation from unknown	600	m2
Transformation, to industrial area	60	m2
Transformation, to industrial area, vegetation	540	m2
Materials/fuels		
drilling, deep borehole for HDR	1.13E+04	m
Cement, unspecified, at plant/CH U	1.26E+05	kg
Gravel, unspecified, at mine/CH U	1.32E+06	kg
Transport, lorry 28t/CH U	2.89E+04	tkm
Transport, freight, rail/CH U	1.26E+04	tkm

4.4.2.2 Operation

Electricity

To inject the CO_2 into the storage reservoir it has to be pumped underground. The pressure difference between the delivery pressure at the well head and the required bottom hole pressure gives the energy required for the injection (see 4.3.3). For deep saline aquifers the required reference energy amounts to 6.68E-03 kWh/kg CO_2, for depleted gas fields to 2.86E-02 kWh/kg CO_2.

The required energy is assumed to be provided as electricity by the Western Europe mix UCTE. The process “Electricity, medium voltage, production UCTE, at grid/UCTE U” from the ecoinvent database is representative for the year 2000. The data provided by UCTE give a composition of 16 % hydro power, 37 % thermal nuclear and 47 % conventional thermal power for the year 2000.

Upstream datasets

The upstream datasets “transport …” and “well double …” are discussed above.

Assembly drawing

Table 25 and Table 26 show the resulting LCI data for the storage with 200 km transport for the aquifer and the depleted gas field per kg stored CO_2, respectively.

Table 25 LCI data per kg stored CO_2 in a deep saline aquifer with 200 km transport by pipeline.

Storage, CO2, aquifer, 200 km pipeline		**Unit/kg**
Resources		
well double, aquifer	2.54E-11	p
transport, pipeline, supercritical CO2, w/o recompression	0.2	tkm

Table 26 LCI data per kg stored CO_2 in a depleted gas field with 200 km transport by pipeline.

Storage, CO2, depleted gas field, 200 km pipeline		**Unit/kg**
Resources		
well double, aquifer	2.54E-11	p
transport, pipeline, supercritical CO2, w/o recompression	0.2	tkm

Table 27 and Table 28 show the show the resulting LCI data for the storage with 400 km transport for the aquifer and the depleted gas field per kg stored CO_2, respectively.

Table 27 LCI data per kg stored CO_2 in a deep saline aquifer with 400 km transport by pipeline.

Storage, CO2, aquifer, 400 km pipeline		**Unit/kg**
Resources		
well double, aquifer	2.54E-11	p
transport, pipeline, supercritical CO2, w/o recompression	0.2	tkm
transport, pipeline, supercritical CO2, w compression	0.2	tkm
Electricity, medium voltage, production UCTE, at grid/UCTE U	6.68E-03	kWh
Gas turbine, 10 MWe, at production plant/RER/I U	8.92E-10	p

Table 28 LCI data per kg stored CO_2 in a depleted gas field with 400 km transport by pipeline

Storage, CO2, depleted gas field, 400 km pipeline		**Unit/kg**
Resources		
well double, depleted gas field	2.54E-11	p
transport, pipeline, supercritical CO2, w/o recompression	0.2	tkm
transport, pipeline, supercritical CO2, w compression	0.2	tkm
Electricity, medium voltage, production UCTE, at grid/UCTE U	2.86E-02	kWh
Gas turbine, 10 MWe, at production plant/RER/I U	8.92E-10	p

4.5 Life Cycle Impact Assessment (LCIA)

The comparison of the conducted LCI data of the analyzed transport and the storage options will be done using only two selected life cycle impact assessment methods. The applied methods are the “Eco-indictor 99” (EI’99) and the “CO_2 equivalents” IPCC 2001 (100a).

The EI‘99 as a damaged-oriented method is focused on several environmental damage categories as global warming, ozone depletion, acidification etc. (Goedkoop et al. 2000) with relatively high weight given on fossil energy resources Table 29 shows the damage categories for the EI’99. As cultural perspective only the Hierarchist with an average weighting is shown in the table and herewith applied for the discussion of results. However, final ranking of the discussed alternatives may generally change due to different aspects.

The method “CO_2 equivalents” is a measure for estimate the global warming potential (GWP 100). All GHG emissions the most important one carbon dioxide, methane, and N_2O, weighted with the CO_2-equivalent factors 1, 21 and 310, respectively (IPCC 2001).

Table 29 Most important items (resources use and emissions to air, ground, and water), damage analysis midpoint and final categories, and weighting scheme for Hierarchist for Eco-indicator 99 (after Felder et Dones 2007).

Life cycle inventory	Damage analysis midpoint categories	Damage categories	Hierarchist (average; %)
Land use: occupation and transformation	regional effect on vascular plant species	Ecosystem quality	40
	Local effect on vascular plant species		
NO_x, SO_x, NH_3	Acidification/eutrophication		
Pesticides, heavy metals	Ecotoxicity		
CO_2, CH_4, N_2O, HCFC	Climate change	Human health	40
H/CFC, halons	Ozone layer depletion		
Nuclides	Ionizing radiation		
NO_x, SO_x, VOC, particulates	Respiratory effects		
Heavy metals, PAH, dioxins, etc.	Carcinogenesis		
Extraction of minerals and fossil fuels	Surplus energy for future extraction	Resources	20

Results using both methods are directly provided by the SimaPro LCA software tool. The results of the comparisons will be shown and discussed in the following chapter.

5 Results and Discussion

5.1 Transport and Storage

The four cases of the selected transport and storage options described in Table 25 through Table 28 are compared with each other. In Figure 13 the results for the LCIA method Eco-indicator 99 are plotted. The first and second bar show the storage option with a pipeline transport of 200 km and 400 km, respectively; the third and fourth bars represent the storage option depleted gas fields with a pipeline transport of 200 km and 400 km, respectively.

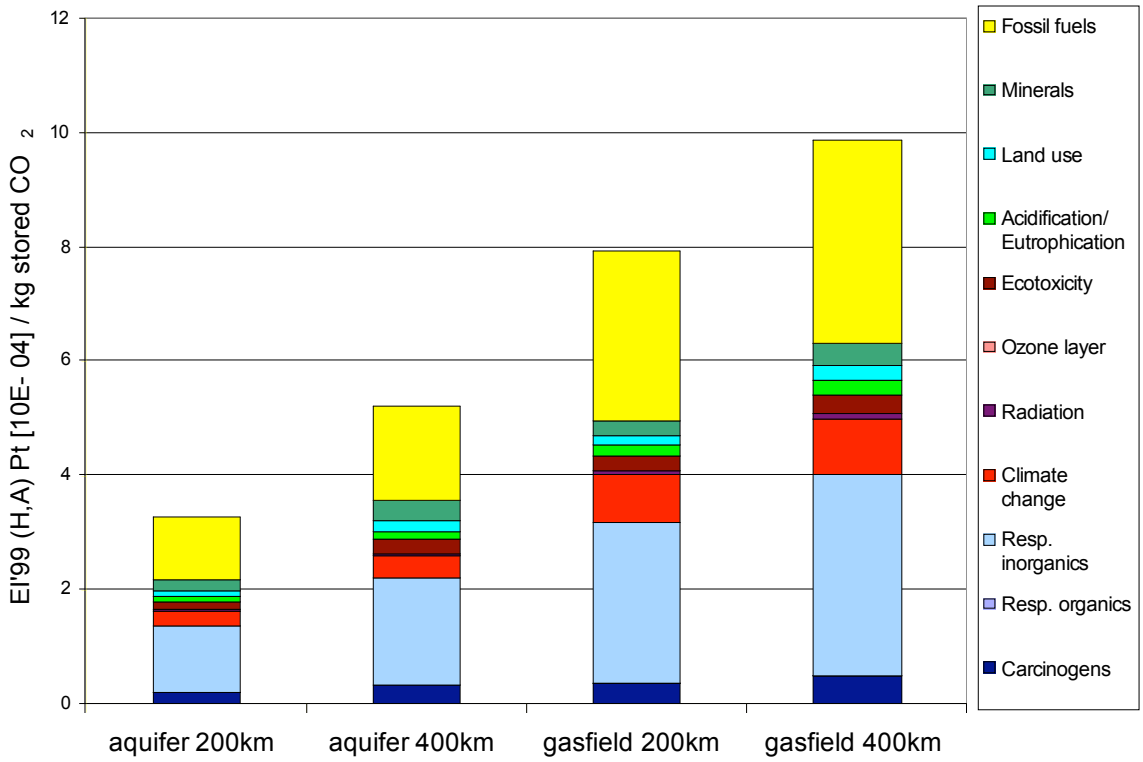

Figure 13 Comparison of the four possible combinations for the transport and the storage of CO_2 using Eco-indicator 99 perspevtive Hierachiest.

As expected, with increasing transport distance and increasing injection depth the total environmental impacts will increase. It has to be keept in mind that the used method EI'99 (H, A) gives a relatively high weight to the fossil resources. The impact categories "fossil fuels" resources, "respiratory inorganics" and "climate change" show the highest variation for the different cases. This fact comes primarily from the additional energy requirement with increasing transport distance and injection depth. The energy is assumed to be provided by the UCTE electricity mix. The year 2000 UCTE mix has a composition of 16% hydro power, 37% thermal nuclear and 47% conventional thermal power. This circumstance explains the higher impacts on the above mentioned categories due to the high share of the conventional thermal power in the electricity supply mix. By doubling the transport distance and introducing recompression the environemntal burdens increase accordingly. The lifetime of the pipeline has also a high influence on the construction effort required. The key factor of the storage process is the

required energy for injection which distinctly increases with depth. Keeping in mind the two key factors, the required injection pressure and the volume flow, the results for storage may change to lower total environmental impacts if an average higher density would have been considerde for the calculation of the pump head (in this study the density at the suction site was assumed, see section 4.3.3). The additional material used for the increased pipeline length of 400 km is only marginally contribution to total EI'99 (H, A) score. The distribution of the impact categories may change by using a different perspective. The Individualist for instance, does not valuated the fossil resources but only the mineral resources.

Figure 14 shows the results for global warming potential (GWP 100 years) measured in terms of CO_2 equivalent per kg CO_2 stored. The previously discussed conclusions are also reproduced in this illustration. The increase in distance and depth will induce higher GHG emissions, in particular higher CO_2 emissions. The case storage in a deep saline aquifer with 200 km transport represents the best option in terms of overall environmental burdens measured by EI'99 (H,A) as well as in terms of CO_2 emissions due to the smallest energy and material requirement.

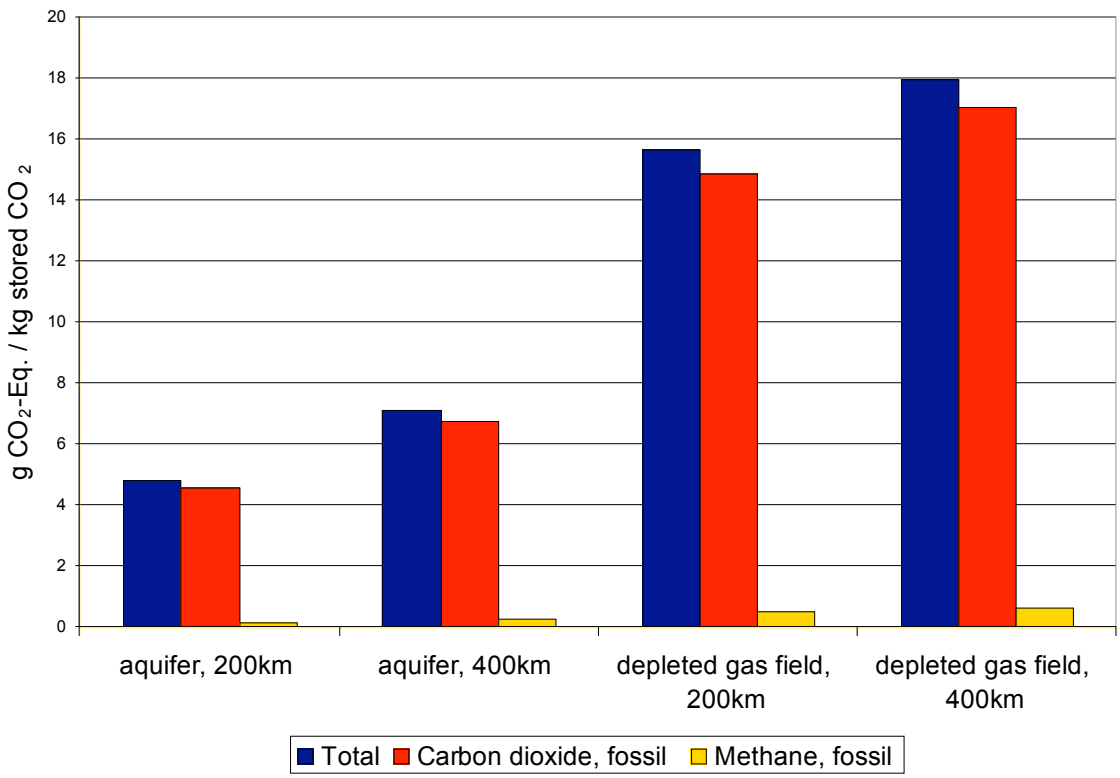

Figure 14 CO_2 equivalents in g per kg stored CO_2 for the four different cases.

In Figure 15 the contributions of the transport and the storage process to the total EI'99 (H,A) points are shown. The share of the transport for all cases except for the case aquifer 400 km is smaller than the share of the storage. This is due to the high injection energy which is required for storage compared to the recompression and construction energy for the transport. In the case aquifer 400 km the construction of the pipeline and the energy required for recompression prevails the energy needed for the injection into the aquifer. This comes from the rather shallower depth compared to the depleted gas

field storage option. Consequently, the material and in particular the construction effort for the pipeline has a higher weight in the transport and storage chain. It can be concluded that for shallower storage depth the transport process has a higher influence on the whole process of transport and storage than in the case of greater storage depth where the high energy requirement for injection will dominate.

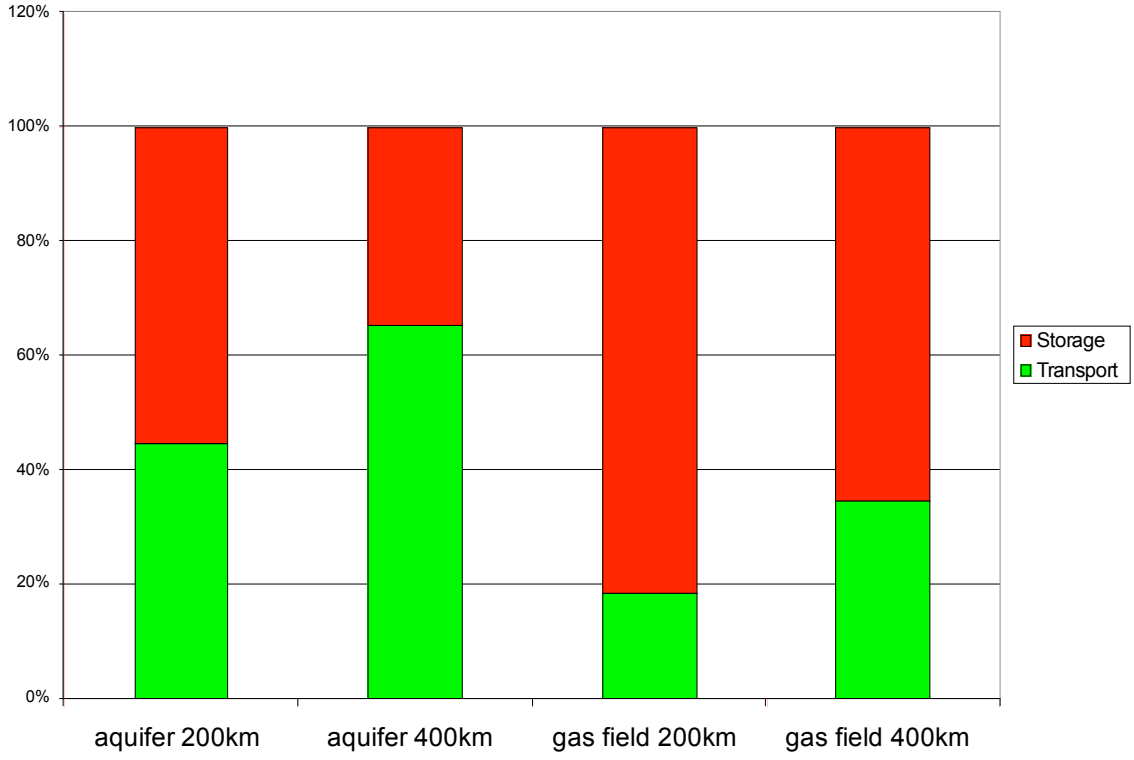

Figure 15 The shares of the process transport and the process storage on the total burdens for the four different cases, according to Eco-indicator '99, Hierarchist perspective.

5.2 Power Plant and CCS Technology

To compare the energy production of a pulverized hard coal power plant with CCS technology to a reference plant without CCS (Dones et al. 2007) the functional unit must be transformed from "kg stored CO_2" to "kWh". The transformation is made over the known retention of 854 g CO_2 per kWh, the carbon dioxide than it is then transported and stored. The reference hard coal power plant is shortly described in section 4.1.2.

Figure 16 shows the results of the comparison for overall environmental burdens using the Eco-indicator '99, Hierarchist perspective. In Figure 17 the comparison, using the global warming potential (GWP 100) measured in terms of CO_2 equivalents, is plotted.

The first bar in each graph represents the reference 600 MW hard coal power plant without CO_2 capture, the second bar the power plant with CO_2 capture, with reduced net power of 470 MW. The last two bars show the plant with capture and the additional transport and storage for the case "aquifer 200 km" and "gas field 400 km", respectively. These two options for transport and storage are represented here because they provide the best and worst case of the analyzed reference cases in terms of overall environmental burdens.

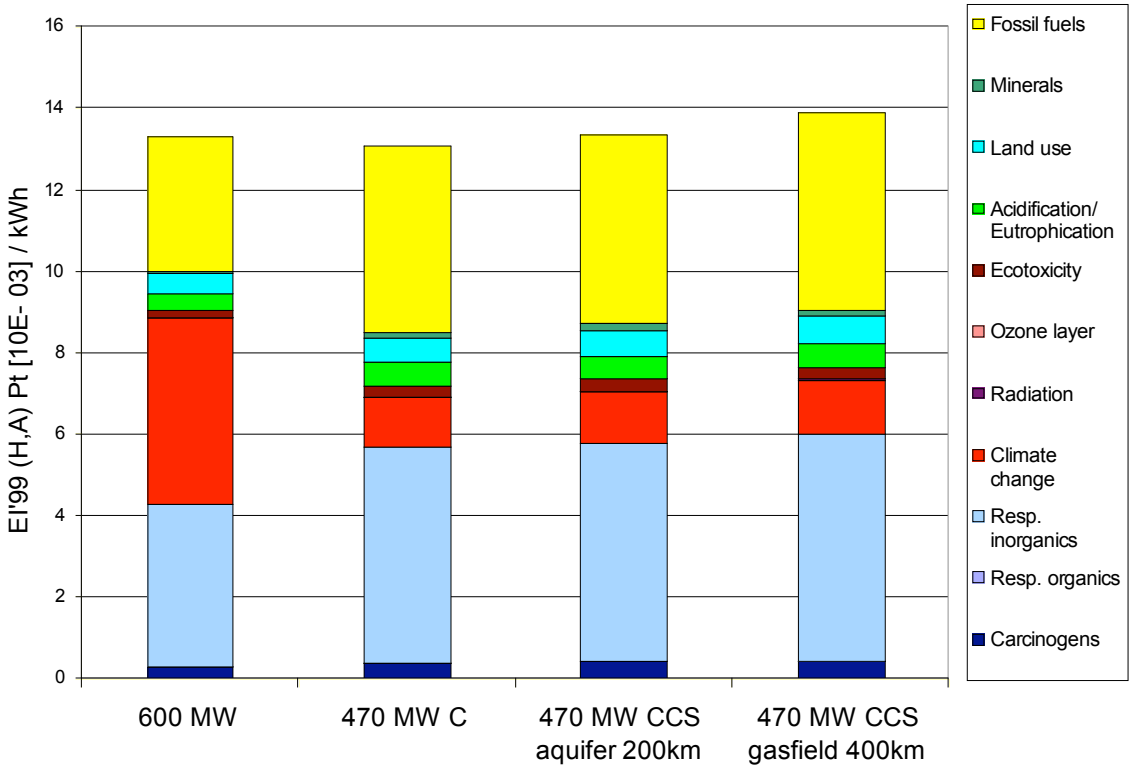

Figure 16 Eco-indicator points, Hierarchist perspective, per kWh for the following systems (from left to right): reference power plant 600 MW without CCS, the power plant 470 MW with CO_2 capture, the power plant 470 MW with 200 km transport to CCS aquifer and same plant with 400 km transport to depleted gas field.

Using the EI'99 perspective Hierarchist (see Figure 16), which give a relatively high weight to the consumption of fossil resources, the case "470 MW CCS gasfield 400km" has the highest ecopoints among the four compared cases. Without considering the impact category "fossil fuels", the three cases with CO_2 capture score slightly lower than the case reference power plant 600 MW. The ranking of the cases may change as well as the distribution of the impact categories by using a different perspective. The Individualist for instance, does not valuated the fossil resources but only the mineral resources.

Besides the category "fossil fuels", the categories "respiratory inorganics" and "climate change" are the main constituents of the total environmental impacts. As intended the impact category "climate change" decreases significantly by capturing the CO_2 emissions at the power plant. However, therewith the energy and material requirements per unit of kWh increase. This is mainly reflected in the categories "fossil fuels" and "respiratory inorganics". The increase in the category "fossil fuels" can be explained over the additional hard coal fired at the power plant and the higher energy requirement for transport and storage provided by the UCTE power mix. The power plant net efficiency decreases from 45 % (600 MW reference plant) to approximately 35 % (470 MW plant with CO_2 capture). The additional hard coal needed to provide the energy to separate the CO_2 amounts to nearly 1/3. This results in higher emission rate per unit of kWh which influence mainly the category "respiratory inorganics". The combustion of hard coal induces particulate, SO_2 and NO_x emissions besides CO_2 emissions (it has here

assumed that all emissions per unit of burned coal do not change with introduction of capture). In other words it needs more fossil resource for the same amount of electricity produced with a hard coal power plant using CCS technology. The available capacity of fossil fuels will then be consumed faster. But considering the capacity of coal, still available for a couple of centuries, this may not be a problem in near future.

Keeping in mind the assumption made for the calculation of the injection energy (see section 4.3.3) the results for the cases with transport and storage option may change to lower total environmental impacts. This because one key factor for the calculation, the volume flow only a function of the density, is assumed as an average value during the pumping process. By refining the definition of the density during the pumping, it would lead to a lower estimation. The ranking between the different power plant options will then be less distinct.

In Figure 17 the reduction of the CO_2 and CO_2 equivalent emissions by the capture and sequestration of CO_2 is shown. The first bar to the left represents the reference power plant without CO_2 capture, the following bars the power plant with capture of CO_2 and the different options for transport and storage as in Figure 16. The total CO_2 emissions from the full chain with CSS decrease by approximately 80%, depending on the selected CCS option, in comparison to the reference plant without CCS. The total GHG emissions will decrease by approximately 72% depending on the relative case. Along the whole CCS chain the transport and storage processes have only a marginal influence on the additional emission caused by the CCS technology.

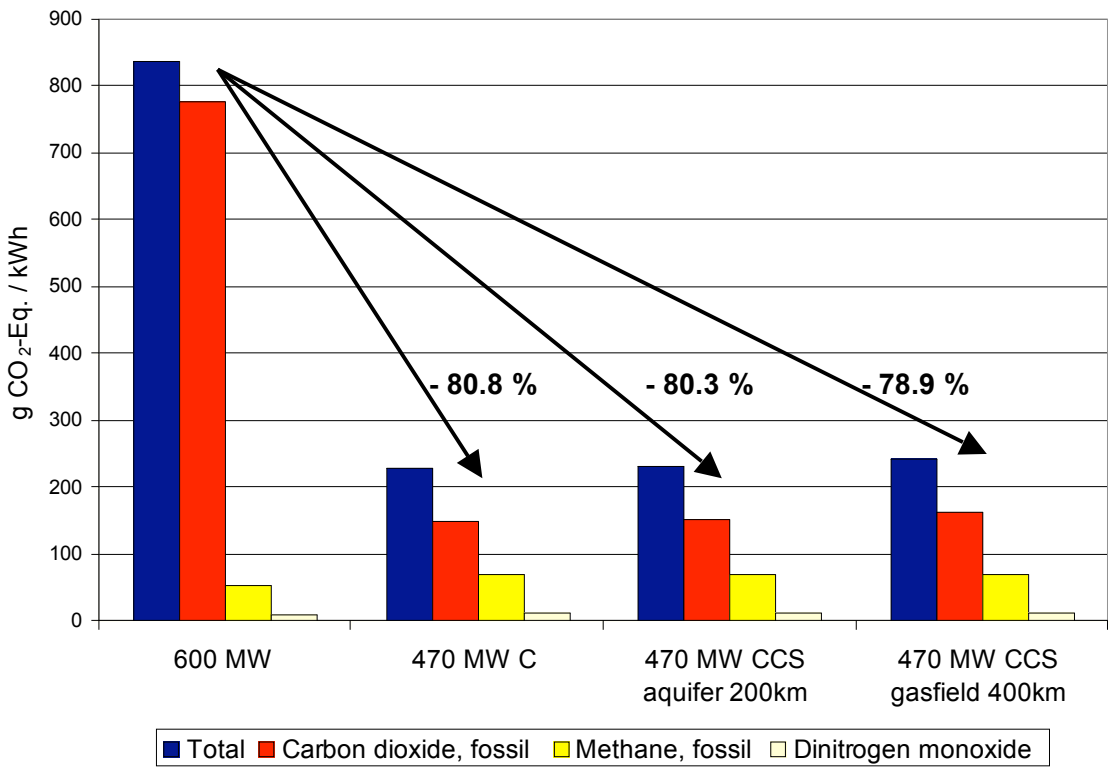

Figure 17 CO_2 equivalent emissions per kWh for the reference power plant 600 MW without CCS, the power plant 470 MW with CO_2 capture, and the power plant 470 MW with CCS aquifer 200km resp. gas field 400km. The arrows and relative percent values show reduction of CO_2 only (red bars).

The total CO_2 captured at the power plant has been assumed 90%. The capture, transport and storage processes will cause additional CO_2 emissions which decrease the total reduction of CO_2 emissions. The reduction amounts to 80.8%, 80.3% and 78.9%, respectively for the three different analyzed capture cases (see Figure 17). The intentions of “near-zero emission” CCS technology are not entirely successful even though a significant reduction of CO_2 emissions is reached. The technology will cause additional CO_2 emissions of about 10% depending on the selected transport and storage technology. This means that the total GHG emission is more than double the one expected considering the “near-zero emission” power plant operation only, at least for the analyzed power plant and capture technologies.

The contribution analysis to total environmental impacts of the different processes on the whole electricity production chain for the different power plant options is shown in Figure 18. The first bar represents the case power plant with CO_2 capture and the storage option aquifer 200 km transport by pipeline, the second the storage option depleted gas field 400 km transport by pipeline and the last bar the reference power plant without CO_2 capture.

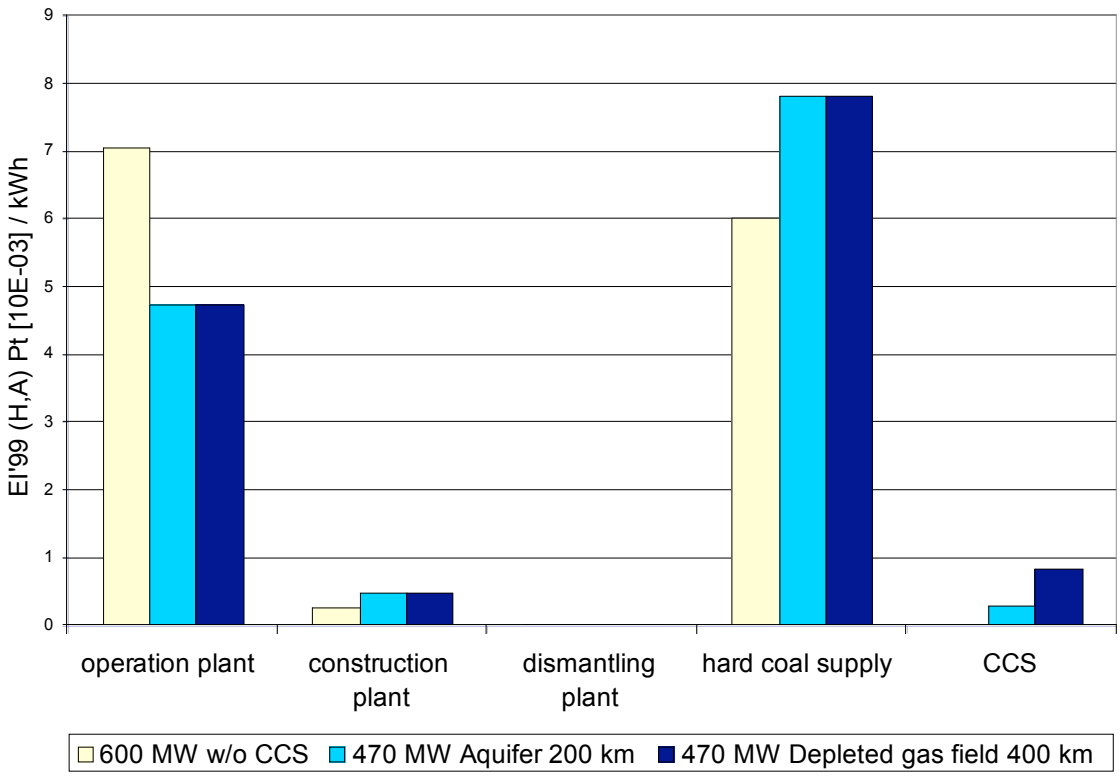

Figure 18 The distribution of environmental burdens on the different processes of the whole process chain for different power plant options.

For the process “operation plant” the options with CCS are significantly better due to the clear reduction of the CO_2 emissions induced in this process. The processes “construction plant” and “hard coal supply” cause higher environmental burdens than in the reference plant. In particular, “fossil resources” are here attributed to “hard coal supply”. The power plant options with capture have a net efficiency 1.3 times lower than the reference plant without capture. Consequently for the same amount of produced

electricity they need more hard coal and also more power plant infrastructure. The contribution of the process CCS is in about the same order as the “construction plant” and has a less important relevance along the whole chain of electricity production.

The share of the CCS technology to total GHG from the whole electricity production chain depends obviosuly on the selected transport and storage option. The share of the best case “aquifer 200” is about a factor four lower than the share of the worst case “gas field 400 km”. Compared to the share of the other processes the transport and storage process is less important. The small share of the CCS technology along the whole electricity production chain can be seen Figure 19.

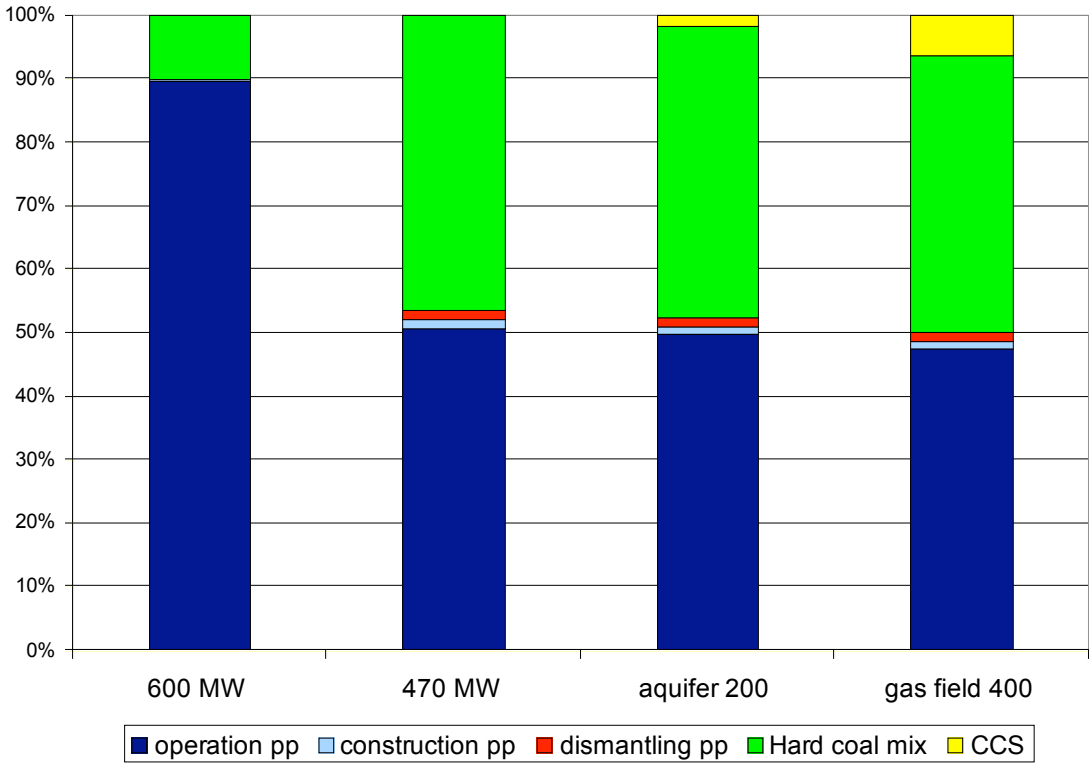

Figure 19 Share of selected processes to total emission of CO_2 equivalent for the different reference cases without and with CCS.

Other Transport and Storage Options

Based on the above presented cases, not substantial changes in the results are expected for total scores of EI’99 (H,A) and GHG by selecting different transport and storage options. The contribution of the CCS to the whole chain is relatively small.

The transport option by ship provides an attractive and flexible alternative for brining the CO_2 to far offshore injection sites. But additional materials and energy are required for the intermediate storage because transport can only occur in batches. The break-even distance is about 1000 km according to Figure 20. The costs are a rough indicator to estimate the material and energy requirement and also therewith to appreciate approximately the environmental burdens. It is expected that the ship as a possible transport option may even cause fewer impacts on the system for very long transport distances.

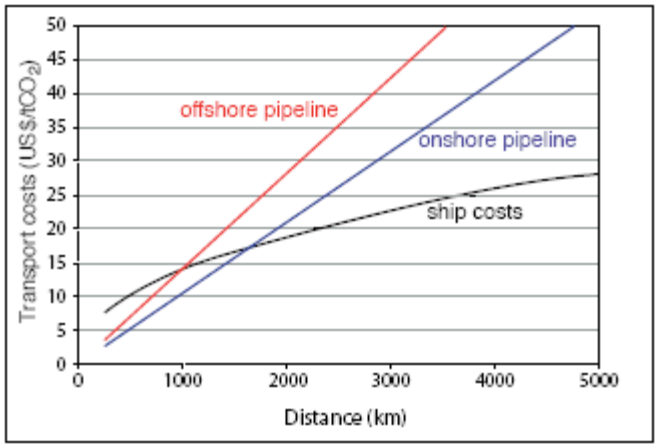

Figure 20 Costs plotted against distance for onshore pipelines, offshore pipelines and ship transport. Pipeline costs are given for a mass flow of 6 MT CO_2/yr. Ship costs include intermediate storage facilites, harbour fees, fuel costs, loading and unloading activities, and also additional costs for liquefaction compared to compression (Source: IPCC 2005)

Considering deep coal seams with enhanced coal bed methane recovery (ECBM) as a possible storage option the problem of the CO_2 net balance arises. The produced CH_4 will be burnt and hence causes additional CO_2 emissions. In this way the net balance of the CO_2 decreases. For one desorbed CH_4 molecule two CO_2 molecules can be adsorbed (UBA 2005). Consequently the net balance will be positive if CH_4 is completely burned. The system boundaries in the case of ECBM have to be set very clearly.

The goal of the CCS technology to reduce the CO_2 emission significantly is achieved. But the “near-zero emission” CCS technology goal is somewhat missed. In total the CO_2 emissions are reduced by approximately 80% depending on the selected CCS option, and the GHG even only about 72%. The captured share is 90% of the emissions of the reference case that means the CCS technology will cause additional CO_2 emissions of about 10%.

5.3 Sensitivity

5.3.1 Sensitivity Analysis: Variation of the Parameter Δp for Injection

Background

The estimation of the required pressure difference which has to be overcome in order to inject the CO_2 into the hosting formation is afflicted by several uncertainties. First the reservoir pressure can vary enormously depending on the specific storage site. In the model used in this study a hydrostatic pressure of 9.8 kPa/m has been assumed. Another major uncertain parameter is the overpressure required for the CO_2 to be injected at adequate rate. Therefore the sensitivity to the variation of this parameter on the environmental performance of the whole system is analyzed here.

Approach

For the modelling of the range of the required pressure difference Δp the following assumptions are made. In addition to the reference case two extreme cases are chosen to capture the likely interval of the required Δp:

- *Minimum case*: 80 bar (pressure at delivery to well head) is enough for injection, i.e. no extra pumping is required
- *Maximum case*: 60 bar overpressure considered additional to the hydrostatic pressure, i.e. doubling overpressure of 30 bar of the reference case is assumed.

The assumption of the minimum case is based on the Sleipner project (Statoil 2007, IEA 2006). There, a pressure of 66 bar at the well head is enough for the injection for 800 m depth.

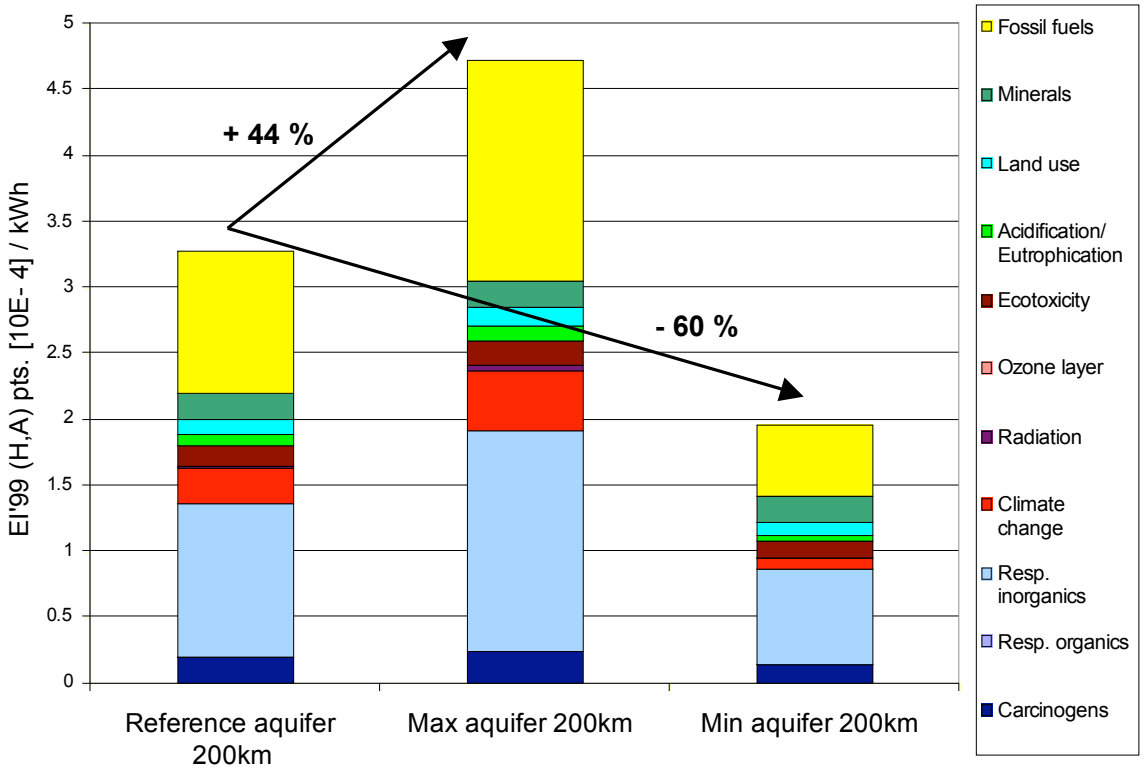

Figure 21 Comparison of the results of the sensitivity applying estimated minimum and maximum pressure difference, using the Eco-indicator 99 (H. A).

Results

The variation of the impacts measured in EI'99 points (H, A) is shown in Figure 21. The first bar represents the reference case and the following the two sensitivity cases. As expected the pressure difference to overcome for injection has a high influence on the system. For the assumption of the minimum pressure the "best" case (i.e. miniumum environmental impact) is reached. The maximum case induces an EI'99 (H,A) points increase of 44 % compared to the reference case, the minimum case a decrease of 60 %.

The variation in the pressure difference □p results in a different energy requirement. Due to the fact that the energy is provided by the UCTE electricity supply mix with a share of 47 % conventional thermal power the impact categories "fossil fuels", "respiratory inorganic" and "climate change" show the highest change. Also in Figure 22, showing GHG results, the same conclusion can be found.

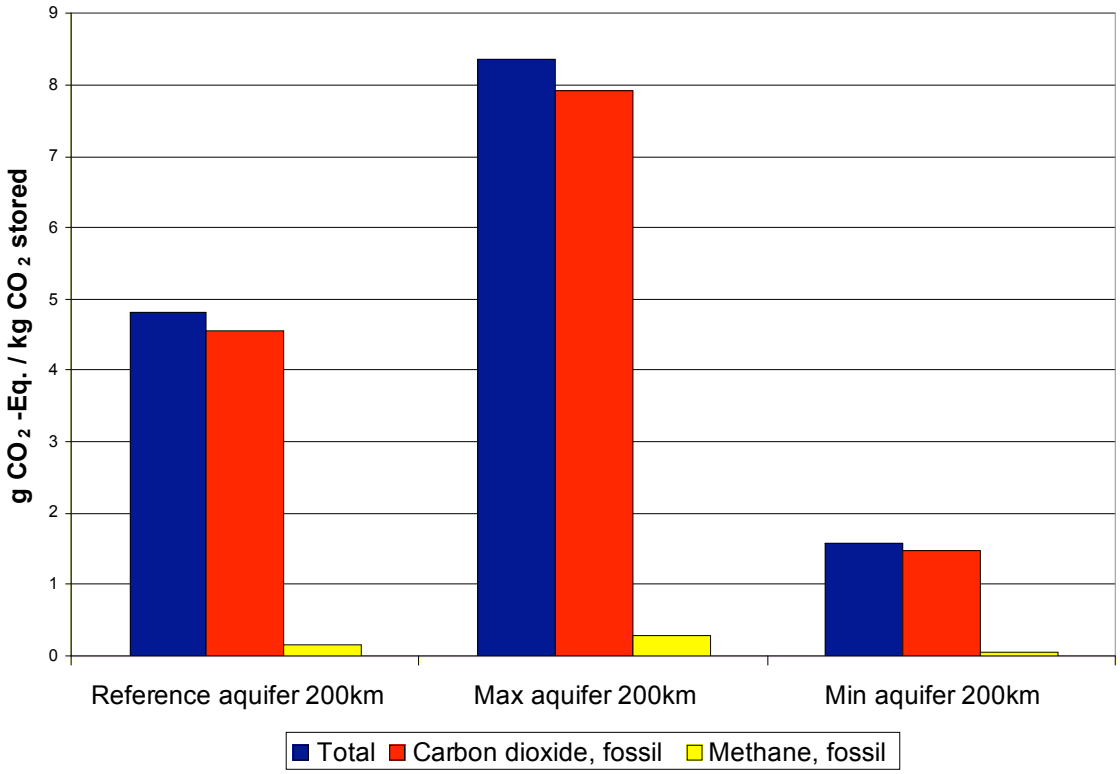

Figure 22 Comparison of the results of the sensitivity applying estimated minimum and maximum pressure difference, using the CO_2 equivalents (IPCC 2001 (100 year)) method.

Considering the influence on cumulative results, when modelling specific sites, the pressure difference Δp should be accurately specified if any variation during the injection phase would occur. This should be taken into account when defining an average value over the lifetime. However, for modelling a generic reservoir as conducted in this study an average value as proposed in section 4.3.3 is considered to be adequate.

5.3.2 Further Parameters to Analyse

One parameter of interest is the lifetime of the different facilities in particular the lifetime of the pipeline. Another parameter that may have a high influence on the system is the steel demand for the pipeline construction. A key value is also the density of the transported and injected CO_2. A small variation in pressure or temperature causes a high change of the CO_2 density for the temperature and pressure ranges considered. The accurate determination of the value is crucial for design and environmental assessment of the system.

6 Conclusion

6.1 Summary

A life cycle assessment (LCA) for selected transport and storage options of supercritical carbon dioxide with focus on European conditions has been carried out. The onshore pipelines – with and without recompression unit – as a feasible transport option and saline aquifers as well as depleted gas fields as possible storage options have been assessed.

The emphasis lies on the conduction of the life cycle inventory (LCI) for the selected options. Therefore a model has been built for the selected transport and storage processes. The state of the CO_2 and its corresponding properties depending on the temperature and the pressure are crucial for the system design. The CO_2 density applied in this model is an average value over the transport process as well as over the storage process. The dimension of the pipeline depends on the volume flow which is a function of the density. Also the calculation of the required energy for recompression and in particular for CO_2 injection depends highly on the volume flow respectively the CO_2 density. Other used properties of CO_2 have also been assumed as average values. Depending on the importance to the design parameters, they may have a high influence on the system requirements. Another critical value associated with the properties of CO_2 is the lifetime of the facilites which can play an essential role in the overall system. The corrosive character of CO_2 when it meets water require adequate material uses for the transport and storage facilites, which influences their lifetime. The storage process modelled in this study is affected by high uncertainties because accurate data to characterize the injection site is missing.

The comparison of the options is done at the life cycle impact assessment (LCIA) level using the Eco-indicator 99, Hierarchist perspective, and the CO_2 equivalents (IPCC 2001 (100 year)) method. The selection of the impact method may have a distinct influence on the results and the ranking of the options. The application of different other methods is recommended for future assessments. The EI‘99 gives relatively high weight to the fossil energy resources. The method “CO_2 equivalents” compares the global warming potential (GWP 100) of the different GHG emissions by weighing them with CO_2-equivalent factors. It is obvious that this method must be applied in the context of the CCS technology since its primary goal is to reduce GHG emissions.

As expected, with increasing transport distance and increasing injection depth the overall environmental burdens will increase. The results show that the chain of CO_2 transport and storage depends highly on the energy required for injection as well as on the pipeline material and construction effort. Different results could be achieved if the relation between the transport distance and the injection depth is changed. With increasing depth the storage process becomes more and more important, whereas increases of distance of the order of two no not have the same importance for the environmental burdens. It can be concluded that for shallower depth the transport process has a higher influence on the whole process chain than for greater depth, where the high energy requirement for injection will dominate.

The entire CCS chain is completed by application of data for the capture process available from ongoing PSI research. The calculation of the environmental burdens along the whole process chain “electricity production with CCS” shows that CCS technologies emit per kWh more than generally claimed by promoters of “near-zero emission” fossil power plant technologies. However, CCS provide a significant reduction of the CO_2 emissions within the electricity production systems of fossil origin. The results illustrate that the influence of the selected transport and storage option along the entire CCS technology chain is less important compared to the capture process. Nevertheless, it has to be emphasized that the chosen post-combustion capture technology is highly energy consuming, more than other possible technological pathways. The share of the transport and storage on the total impacts is only a few percent calculated along the whole CCS chain. The relation between the worst and best analyzed transport and storage options is a factor of about four. Based on this assessments not much change in the results is expected by selecting different transport and storage options.

It is important to bear in mind that the LCA, conducted in this study, carries substantial uncertainties. The main uncertainties are connected to the storage process, namely uncertainties about the reservoir characteristics and the design and operation of CO_2 injection. The density assumed as an average value over the whole process is also afflicted with high uncertainties due to the high variation in the area of supercritical state. Furthermore, a lot of cut-offs and assumptions have been made over the whole transport and storage chain. The uncertainties of the transport process are smaller due to the application of a proven technology.

6.2 Conclusion

This assessment shows that the results of the conducted LCA depend on several parameters currently not accurately known. The key factors that have been identified for the transport and storage system are the material and construction effort of the pipeline as well as the energy required for the CO_2 injection. Among other factors, the above expenditures highly depend on the volumetric flow rate, and in turn on the CO_2 density, which is assumed as an average value. An increase in depth has a higher influence on the environmental performance of the overall system than an increase in transport distance. Different LCIA methods can produce distinct qualitative differences depending on the concept. Therefore, the results have to be interpreted carefully.

The main conclusions to be drawn from this LCA study are the following:

- Irrespectively of which transport and storage option is selected, the share of environmental impacts of transport and storage is less important than the capture process and the power plant operation (under the assumption of no leak from the final reservoir);
- By the application of the CCS technology,the total CO_2 emission reduction achieved for the full coal energy chain for the generation of electricity is ~80%, and the total GHG reduction even ~72%, clearly less than generally assumed for “near-zero emission” fossil power technologies at around 90% as a minimum;
- As calculated in this study, ransport and storage technology may emit about the same CO_2 equivalent per kWh as the power plant;
- The electricy production at the hard coal power plant with CCS technology requires additional substantial fuel resources.

It is important to keep in mind the high uncertainty in the modelling. The results should be taken as indicative against the background of the given uncertainties and are a reflection of the used simplified calculations. However, the above conclusions appear to be defensible and believed to be meaningful for contributing to the climate energy policy debate.

6.3 Outlook

Considering the goal of determining the order of magnitude of average conditions for implementing CCS in Europe, this work provides a reasonable first LCA estimation. A more accurate determination of the key parameters (for individual cases as well as ranges) would certainly improve the study results and reduce the uncertainties. By improving the understanding of the storage process, a more accurate determination of the key parameters, especially the required injection pressure, would be possible. Nevertheless, a more precise determination of the parameters would require increasingly detailed data which may not yet be available in the literature in a directly usable form for an LCA. With this kind of exploratory assessment for such complex and not yet fully established processes, the decision whether or not to study more accurately a certain part of the involved technologies in LCA terms always depends on the expected change in results. Preliminary sensitivity analysis serves to identify such areas.

Besides providing intervals, the sensitivity analyses need to be continued to identify other potentially important parameters which may have a substantial influence on the system. A more accurate determination of these parameter may further improve the model results.

The application of additional life cycle impact assessment (LCIA) methods is recommended. The EI'99 (H,A) puts a relatively high weight on fossil fuels, whereas the use of other EI'99 perspectives as well as other LCIA methods altogether may lead to somewhat different ranking of the compared technologies. Nevertheless, the main results would probably remain within the ranges of the findings obtained in this study.

Although the environmental results are not fully satisfactorily, the relevance of the CCS technology as a bridge to fill the gap until renewable and other CO_2-free/neutral energy technologies are readily available remains. The model results of this study allow further comparison with other energy supply systems.

Assessment of the total costs of CCS technologies is certainly necessary for a full assessment of sustainability, besides the understanding of social acceptance. All these sustainability aspects may strongly influence the decision making for implementing such technologies for GHG curbing. A future more accurate life cycle analysis (LCA) perfomed on different capture technologies, additional to a thorough cost estimation should be pursued considering the potentiality of CCS for contributing to mitigate global climate change.

7 References

Aspelund et al. 2006: Aspelund a., Molvnik M. J., de Koeijer G.: Ship Transport of CO_2. Technical Solutions and Analysis of Costs, Energy Utilization, Exergy Efficiency and CO_2 Emissions. Chemical Engineering Research and Design Volume 84 Number A9 Special Issue Carbon Capture and Storage, pp. 847-856, 2006.

BMU 2007: Bundesministerium für Umelt, Naturschutz und Reaktorsicherheit (ed.): Fischedick M., Esken A., Pastowski A., Schüwer D., Supersberger N., Nitsch J., Viebahn, P., Bandi A., Zuberbühler U., Edenhofer O.: RECCS Strukturell-ökonomischer Vergleich regenerativer Energietechnologien (RE) mit Carbon Capture and Storage. Wuppertal Institut für Klima, Umwelt, Energie GmbH; DLR – Institut für Technische Thermodynamik; Zentrum für Sonnenenergie- und Wasserstoff-Forschung; Potsdam-Institut für Klimafolgenforschung. Wuppertal, Stuttgart, Potsdam. Online version: http://www.erneuerbare-energien.de/files/pdfs/allgemein/application/pdf/reccs_zusammenfassung.pdf

Bauer et al. 2007 C. Bauer, R. Dones, T. Heck, S. Hirschberg (2007) Comparative environmental assessment of current and future electricity supply technologies for Switzerland. In proceedings of 3rd International Conference on Life Cycle Management, August 27 to 29, 2007, Zurich, Switzerland.

Bock et al. 2001: Bock B. R., Rhudy R. G., Nichols D. E.: Economic Evaluation of CO_2 Sequestration Technologies. Semi-Annual Technology Progress Report.

CO_2NET 2004: Capturing and Storing Carbon Dioxide: Technical lessons learned, European Carbon Dioxide Network.

CO_2SINK 2007: Technical Information: Drilling & Injection. Access Date: 10.5.2007. Available from: http://www.co2sink.org/techinfo/modelling.htm

Dialer 2007: Dialer K.: Personal communication. Winterthur

Done et al. 2007: Dones R., Bauer C., Heck T., Mayer-Spohn O., Blesl M.: "Final technical paper on technical data, costs and life cycle inventories of advanced fossil fuels", Sixth Framework Programme of the European Commission, Project no: 502687, NEEDS - New Energy Externalities Developments for Sustainability. To be issued 2007.

efunda engineering fundamentals. Fluid Mechanics: Pipe Roughness. Access Date: 10.5.2007. Available from: http://www.efunda.com/formulae/fluids/roughness.cfm

EU 2004: European Commission: European CO_2 Capture and Storage projects, Sixth Framework Programme. Office for Official Publications of the European Communities, Luxembourg.

Faist Emmenegger et al. 2003: Faist Emmenegger M., Heck T., Jungbluth N.: Erdgas. In: Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz (Ed. Dones R.). Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH retrieved from: www.ecoinvent.ch

Felder et Dones 2007: Felder R., Dones R. Evaluation of ecological impacts of syntetic natural gas from wood used in current heating and car systems. Biomass and Bioenergy (2007), doi:10.1016/j.biombioe.2006.08.005

Frischknecht et al. 2004: Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Heck T., Hischier R., Nemecek T., Rebitzer G., Spielmann M., "Overview and Methodology". Final report ecoinvent 2000 No. 1. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland (2004). Retrieved from: http://www.ecoinvent.ch.

FZ Jülich 2006: Forschungszentrum Jülich: Linssen J., Markewitz P., Martinsen M., Walbeck M.: Zukünftige Energieversorgung unter den Randbedingungen einer grosstechnischen CO_2-Abscheidung und Speicherung. Abschlussbericht des Forschungsvorhabens FZK 0236889 im Auftrag des Bundesministeriums für Wirtschaft und Technologie.

Germanwatch 2004: Germanwatch (ed.): Duckat R., Treber M., Bals C., Kier G: CO_2-Abscheidung und -Lagerung als Beitrag zum Klimaschutz, Ergebnisse des „IPCC Workshop on Carbon Dioxide Capture and Storage" vom November 2002 und Bewertung durch Germanwatch, online version: http://www.germanwatch.org/rio/ccs04.htm

Goedkoop et al. 2000: Goedkoop M., Müller-Wenk R., Mettier Th., Hungerbühler K., Braunschweig A., Klaus Th.: Eco-indicator 99 – eine schadensorientierte Bewertungsmethode. Nachbearbeitung zum 12. Diskussionsforum Ökobilanzen vom 30. Juni 2000 an der ETH Zürich. Online version: http://www.lcainfo.ch/df/DF%201%20bis%2012/DF12.pdf

GreenPrices 2007: GreenPrices Green energy in Europe: Corrosion stops CCS project. GreenPrices Weekly, nr. 59 3 July 2007. Access date: 4.7.2007. Available at: http://www.greenprices.com/eu/newsletter/newsletterarchive/GPWK_59_070705ws.asp# restricted.

Heddle et al. 2003: Heddle G., Herzog H., Klett M.: The economics of CO_2 Storage. MIT LFEE 2003-003RP Massachusetts Institute of Technology; Massachusetts, USA.

Holloway et Lindeberg 2004: Holloway S., Lindeberg E.: How safely can we store CO_2? Access Date: 13.6.2007. Available from: www.regjeringen.no/upload/kilde/md/nyh/2004/0029/ddd/ppt/225627-holloway-presentation.ppt

IEA 2004: International Energy Agency (IEA): Prospects for CO_2 Capture and Storage. Paris Cedex, France: OECD/IEA, 2004.

IEA 2006: Gale J.: The Sleipner Project and Monitoring Experiences. IEA Greenhouse Gas R&D Programme. 2nd Nova Scotia Energy Research and Development Forum, 24th to 25th May 2006, Saint Francis Xavier University, Antigonish, Nova Scotia, Canada.

IPCC 2001: Climate Change 2001: The Scientific Basis. In: Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (ed. Houghton J. T., Ding Y., Griggs D. J., Noguer M., van der Linden P. J. and Xiaosu D.). IPCC, Intergovernmental Panel on Climate Change, Cambridge University Press, The Edinburgh Building Shaftesbury Road, Cambridge, UK. Online version: www.grida.no/climate/ipcc_tar/wg1/.

IPCC 2005: IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Johnson et al. 2006: Johnson N., Yang C., Odgen J.: Build-Out Scenarios for Implementing a Regional Hydrogen Infrastructure. Proceeding of the National Hydrogen Association (NHA) Annual Conference. Long Beach, California. Online version: http://hydrogen.its.ucdavis.edu/publications/pubpres/2006pub/johnsonnha/

Kaszuba et al. 2003: Kaszuba J. P., Janecky D. J., Snow M. G.: Carbon dioxide reaction processes in amodel brine aquifer at 200 °C and 200 bars: implications for geological sequestration of carbon. Applied geochemistry 18 (2003)1065-1080.

Le Thiez et al. 2007: Le Thiez P., Mosditchian G., Trop T., Feron P., Ritsema I., Zweigel P., Lindenberg E.: An innoovative European integrated project: CASTOR-CO_2 from capture to storage. Access Date: 9.5.2007. Available from: http://uregina.ca/ghgt7/PDF/papers/poster/114.pdf

Mazzotti et al. 2006: Mazzotti M., Cremer C., Radgen P.: Carbon dioxide capture and storage, lecture notes, ETH Zurich summer term 2006.

Mazzotti et al. 2007: Mazzotti M., Boulouchos K., Burg J-P., Dones R., Hirschber S., Jansohn P., Siegrist M.: Carbon dioxide management in Swiss power generation (CARMA). Presented at CCEM General Assembly, PSI on June 12, 2007.

McCollum et Odgen 2006: McCollum D. L., Odgen J. M.: Techno-Economic Models for Carbon Dioxide Compression, Transport, and Storage & Correlations for Estimating Carbon Dioxide Density and Viscosity, Institute of Transportation Studies, University of California, Davis. Online Version: http://hydrogen.its.ucdavis.edu/publications/pubpres/2006pub/mccollum06/

Nelson et al. 2005: Nelson C. R., Evans J. M., Steadman E. N., Harju J. A.: Factors Affecting the Potential for CO_2 Leakage from Geologic Sinks. Grand Forks, Energy and Environmental Research Center (EERC), University of North Dakota, USA.

NREL 2004: National Renewable Energy Laboratory (ed.): Spath P. L., Mann M. K.: Biomass Power and Conventional Fossil Systems with and without CO_2 Sequestration – Comparing the Energy Balance, Greenhouse Gas Emissions and Economics. NREL/TP-510-32575, Colorado, USA.

NETL 2006: Carbon Sequestration Technology Roadmap and Program Plan 2006. U.S. Department of Energy, Office of Fossil Energy (Ed.), NETL.

Ploetz 2003: Ploetz C.: Sequestrierung von CO_2: Technologien, Potenziale, Kosten und Umweltauswirkungen. Externe Expertise im Auftrag des WBGU 2003.

SINTEF 2003: SINTEF Petroleum Research (ed.): Zweigel P., Heill L. K.: Studies on the likelihood for cap rock fracturing in the Sleipner CO_2 injection case – A contribution to the Saline Aquifer CO_2 Storage (SACS) project. Trondheim, Norway.

Statoil 2007: personal communication.

TEMA 1999: Standards of the Tubular Exchanger Manufacturers Association, 8th Edition. Tarrytown, New York, 1999, p.184.

UBA 2006: Umweltbundesamt (ed.): Radgen P., Cremer C., Warkentin S., Gerling P., May Dr. F. , Knopf S.: Verfahren zur CO_2-Abscheidung und –Speicherung. Abschlussbericht. Fraunhofer-Institut für Systemtechnik und Innovationsforschung (ISI) in Zusammenarbeit mit Karlsruhe und Bundesanstalt für Geowissenschaften und Rohstoffe Hannover.

UCTE 2000: Net production of UCTE countries. Access date: 2.7.2007. Available from: http://www.ucte.org/statistics/production/e_default.asp

Vauck et Müller 2000: Vauck W. R. A., Müller H. A.: Grundoperationen chemischer Verfahrenstechnik. Stuttgart, deutscher Verlag für Grundstoffindustrie.

VDI 2002: VDI-Wärmeatlas. Berlin-Heidelberg, Springer Verlag: 9. Auflage.

ANNEX

A.I Properties of Carbon Dioxide

The relevant physical and chemical properties of carbon dioxide are described hereinafter. The ranges and values assumed for the different properties of carbon dioxide in the calculations were taken from (VDI 2002).

A.I.1 Carbon Dioxide

Carbon dioxide is a chemical compound consisting of two elements, carbon and oxygen, in the ratio 1:2. Its molecular formula is CO_2. It is present in the atmosphere in a low concentration of 370 ppm (IPCC 2005). Pre-industrial concentration was 280 ppm. Carbon dioxide is an odour-, taste- and colourless, not inflammable, and relatively inert compound. Under normal temperature and pressure conditions, CO_2 is a gas. Its density is higher than the density of air and only at relatively high concentrations (exposure threshold 40 000 ppm (BMU 2007)) CO_2 can be dangerous for human's health.

Carbon dioxide plays an essential role in the carbon cycle. Terrestrial and aquatic plants assimilate carbon dioxide and release oxygen that sustains animal life. This process is called photosynthesis. Moreover, CO_2 is one of the most important GHGs. Among natural sources like volcanic activity and decomposition of carbonates, anthropogenic activities cause emissions of CO_2, including combustion of fossil fuels and other carbon-containing materials, fermentation of organic compounds, and human's breathing (IPCC 2005). In the last centuries the concentration of carbon dioxide in the air has steadily been increasing.

A.I.2 Physical properties of CO_2

Carbon dioxide at normal temperature and pressure conditions is a gas. The physical state of CO_2 is a function of its temperature and pressure as shown in the phase diagram in Figure 23. At low temperatures CO_2 is solid. Frozen CO_2 is referred to as dry ice. Below pressures of 5.2 bar CO_2 will sublime directly into the vapour state by addition of heat. The liquid phase will only exist at intermediate temperatures between the triple point and the critical point by compressing to the corresponding pressure. The triple point is characterized by a stable coexisting of all three states, the liquid, the gaseous and the solid state.

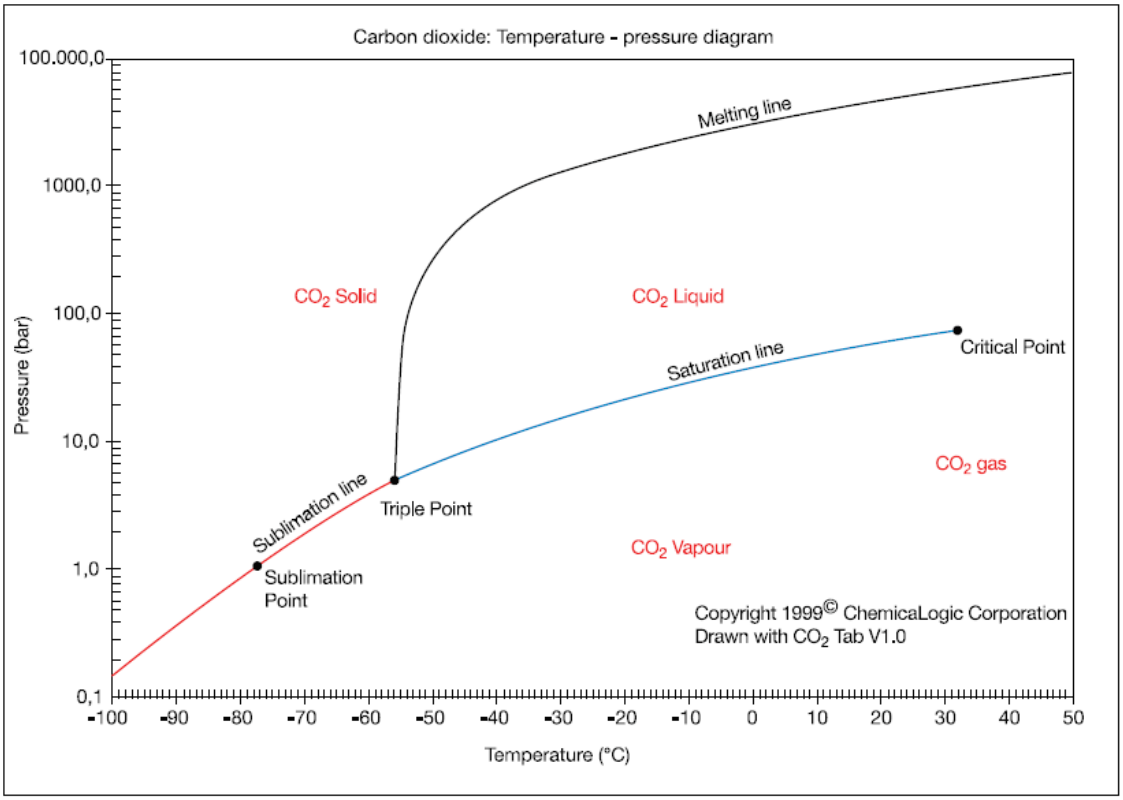

Figure 23 Phase diagram for CO_2 (Source: IPCC 2005).

Above the critical point with a temperature of 31.1°C and a pressure of 73.9 bar, CO_2 is in a supercritical state also referred to as the dense phase. “A distinct separation of the gas state and the liquid state is only possible below this critical point; above only a distinction between less dense or more dense is possible“ (Mazzotti 2006). Supercritical CO_2 has a density more liquid-like whereas its viscosity and diffusivity are more gas-like. These properties of CO_2 are essential for its transport and storage processes. Table 30 gives an overview of selected physical properties of CO_2.

Table 30 Properties of CO_2.

Property	Value
Molecular weight	44.01
Critical temperature	31.1 °C
Critical pressure	73.9 bar
Critical density	467 kg/m^3
Triple point temperature	-56.5 °C
Triple point pressure	5.18 bar
Boiling (sublimation) point (1.013 bar)	-78.5 °C
Gas Phase	
Gas density	2.814 kg/m^3
Gas density at STP	1.976 kg/m^3
Specific volume	0.506 m^3/kg
Heat capacity C_v (constant volume) at STP	0.0364 kJ (mol^{-1} K^{-1})
Heat capacity C_p (constant pressure) at STP	0.0278 kJ (mol^{-1} K^{-1})
Viscosity at STP	13.72 µN.s/m^2
Thermal conductivity at STP	14.65 mW (m K^{-1})
Solubility in water at STP	1.716 vol vol^{-1}
Enthalpy at STP	21.34 kJ mol^{-1}
Entropy at STP	117.2 J mol K^{-1}
Entropy of formation	213.8 J mol K^{-1}
Liquid Phase	
Vapour pressure at 20°C	58.5 bar
Liquid density at -20°C and 19.7 bar	1032 kg m^{-3}
Viscosity at STP	99 µN.s/m^2
Solid Phase	
Density of carbon dioxide snow at freezing point	1562 kg m^{-3}
Latent heat of vaporisation (1.013 bar at sublimation point)	571.1 kJ kg^{-1}

With STP for Standard Temperature and Pressure, which is 0°C and 1.013 bar

Source: modified from IPCC (2005)

The density of CO_2 is a function of its temperature and pressure as shown in Figure 24. Figure 25 shows the viscosity of CO_2, which varies with the temperature and the pressure.

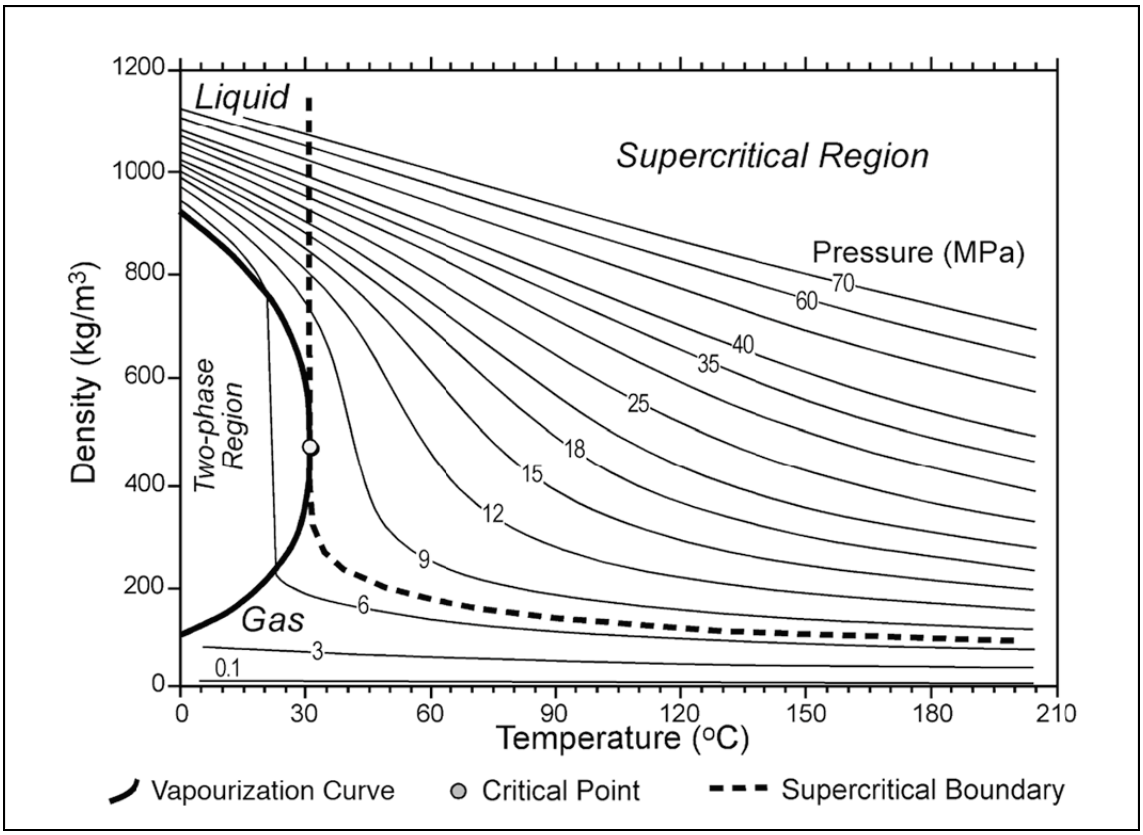

Figure 24 Variation of CO_2 density as a function of temperature and pressure (Source: IPCC 2005).

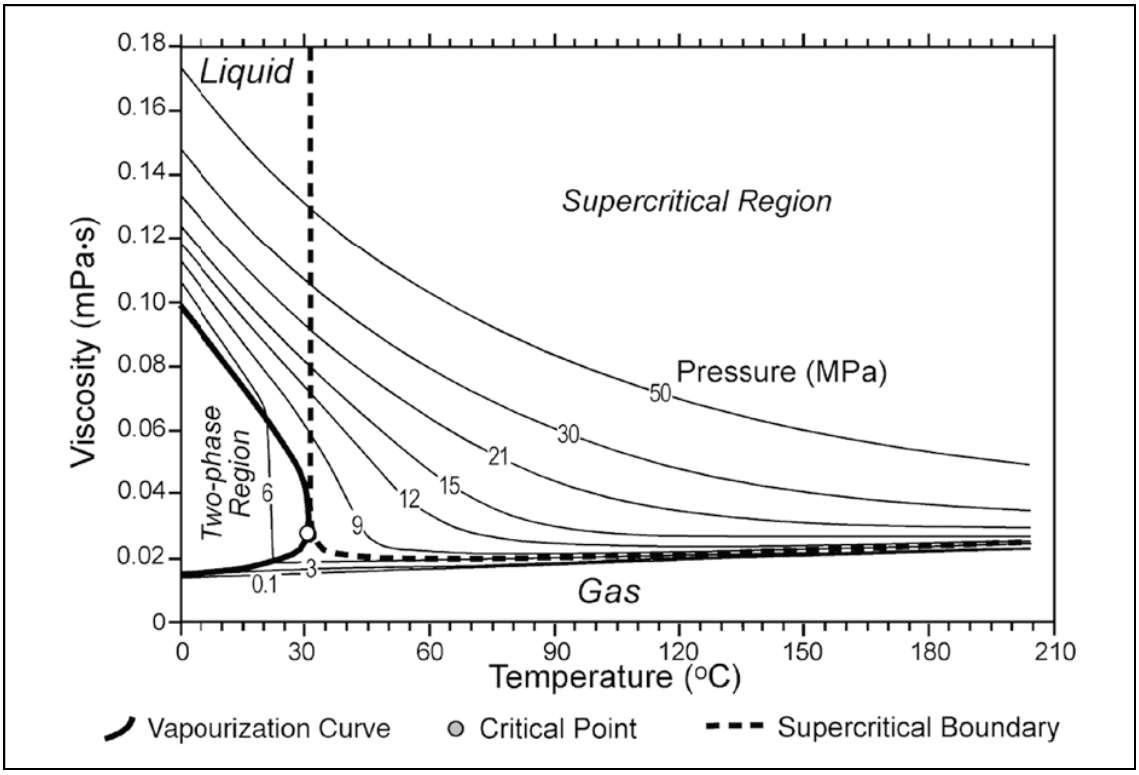

Figure 25 Variation of CO_2 viscosity as a function of temperature and pressure (Source: IPCC 2005).

A.I.2 Chemical Properties of CO_2

When it dissolves in aqueous solution, carbon dioxide forms carbonic acid which is too unstable to be easily isolated. The solubility of CO_2 in an aqueous solution decreases as the temperature increases and as the pressure increases. Increasing water salinity will also decrease the solubility of CO_2 in water. Figure 26 shows the solubility of CO_2 in water as a function of temperature and pressure.

The dissolution of CO_2 in water will form carbonic acid which lowers the pH of the solution. The pore water in reservoirs naturally containing CO_2 is very acid. This induces outer corrosion of the steel casing. Low-pH conditions will also lead to leaching and mobilization of toxic heavy metals such as lead (Pb) and arsenic (As). In terms of carbon sequestration, the acid solution causes leaching of minerals and weakening the underground formations used for geologic sequestration. (Nelson et al. 2005)

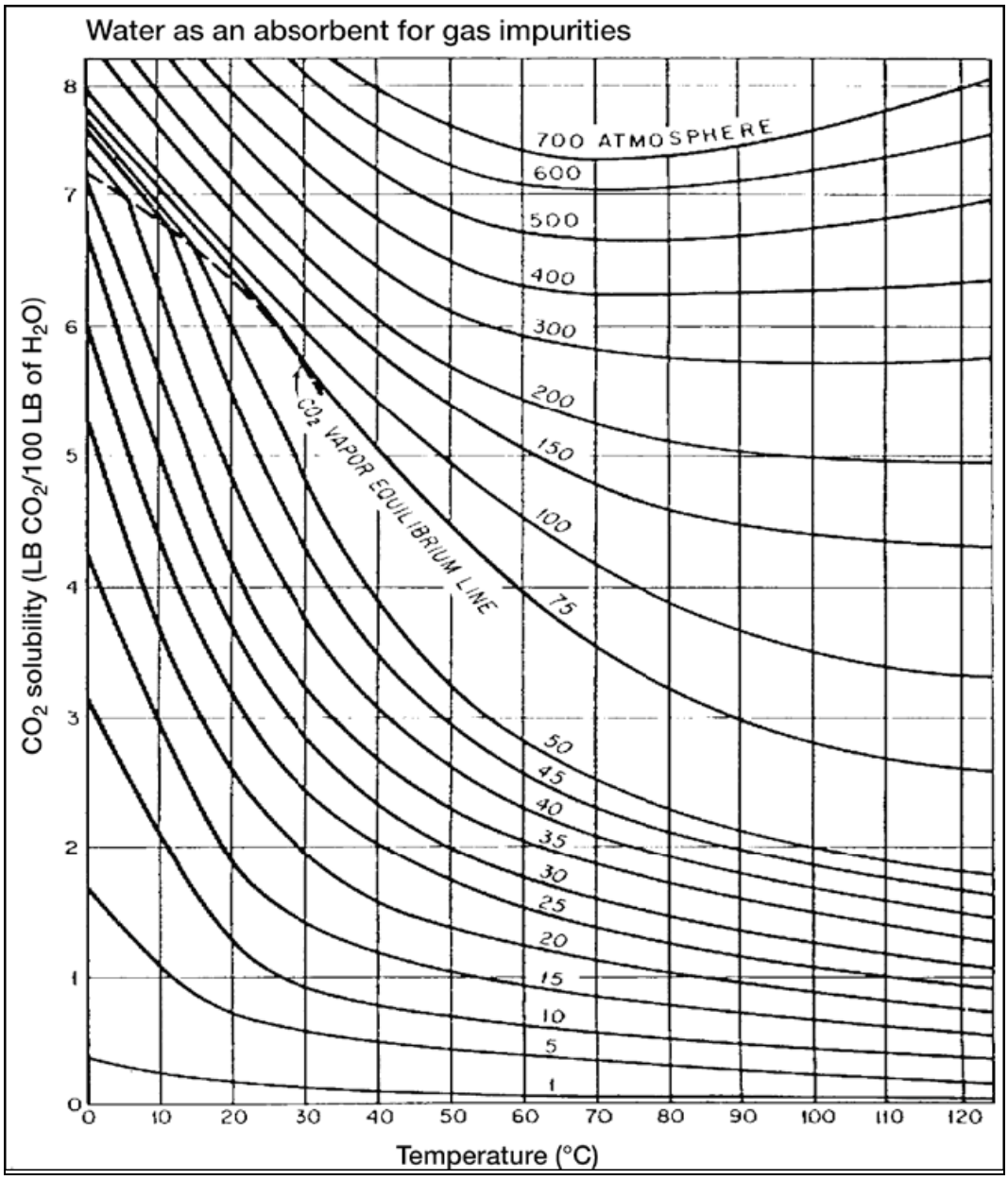

Figure 26 Solubility of CO_2 in water (Source: IPCC 2005).

A.II Calculations

A.II.1 Pressure Drop in Pipelines

For smooth pipes the roughness is only a function of the Reynolds number. The resulting pressure drop for the investigated system with the assumption of a smooth pipe is tabled in Table 32 as a comparative value.

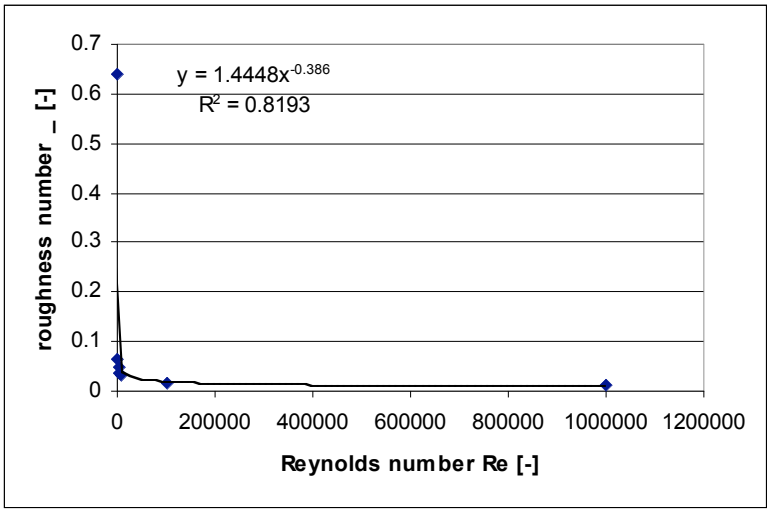

Figure 27 Roughness number λ as a function of the Reynolds number Re.

In the turbulent area with high Reynolds numbers the dimensionless roughness number λ is a function of the absolute roughness k of the pipe. This is valid for rough pipes.

In (Vauck et Müller 2000) the dimensionless roughness numbers λ are tabled as function of the reciprocal of the relative roughness n of the pipe. The relative roughness is given by the ratio of the absolute roughness k and the pipe diameter D (see Equation 5).

Equation 5 Relative roughness n

$$n = \frac{k}{D}$$

In order to approximate this relation between and n Equation 6 is conducted by the graph in Figure 28.

Equation 6 Relation between the roughness number and the reciprocal of the relative roughness n of the pipe.

$$y = 0.1677 \cdot x^{-0.3141}$$

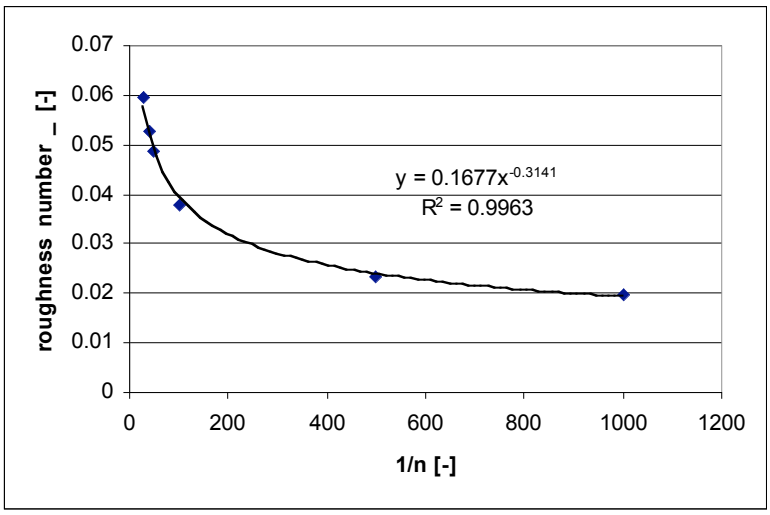

Figure 28 Roughness number as a function of the reciprocal of the relative roughness n of the pipe.

The calculated roughness numbers is shown in Table 31 as well as the tabled values found in (Vauck et Müller 2000) and the relative difference of them which is acceptable as an approximation.

Table 31 Tabled and calculated roughness numbers .

		y = 0.1677x^-0.3141	
1/n = 1/(k/d)	tabled	calculated with equation 6	tab- pot [%]
30	0.0596	0.0576	3%
40	0.0529	0.0526	0%
50	0.0485	0.0491	-1%
100	0.038	0.0395	-4%
500	0.0234	0.0238	-2%
1000	0.0197	0.0192	3%

With the absolute roughness k of the pipe the roughness number λ can be calculated. The resulting pressure drop for the pipe over a defined distance L is given by Equation7. In Table 32 the pressure drop as function of the roughness number is tabled for rough pipes of different absolute roughness and for smooth pipes for comparison.

Equation 7 Pressure drop in a pipe

$$\Delta p = \lambda \frac{L}{D_i} \cdot \rho \cdot \frac{v^2}{2}$$

Table 32 Pressure drop for different pipe materials.

Material	Absolute roughness k [mm]	Roughness number λ [-]	Pressure drop Δp [bar]	Source
rough pipes				
new steel	0.02	0.0067	25	Vauck et Müller 2000
welded, used, cleaned steel	0.15	0.0126	46	VDI 2002
no information	0.046	0.0087	32	Bock et al. 2001
commercial steel	0.000045	0.0010	4	efunda engineering fundamentals
smooth pipes	-	0.0024	9	Vauck et Müller 2000

A.II.2 Heat Loss from Pipelines

Here only a rough estimation of the heat loss in a pipe with turbulent flow is conducted to appraise the required thickness of the insulation. The problem is assumed to be static and linear. In reality there is an exponential decrease of temperature over distance and the differental equations have to be integrated. Moreover, the thickness of the steel pipe wall is neglected.

In a first step the allowed temperature drop per unit length of 10 °C per 200 km is determined over the assumed inlet temperature of 50 °C and the outlet temperature of 40 °C. The outlet temperature is set to 40 °C in order to have a security range for CO_2 to stay in supercritical state over the critical temperature of 31.1 °C. As insulation material rock wool with a thermal conductivity of 0.035 W/(m·K) is assumed. The selected parameter values are listed in Table 33. The values of the CO_2 properties are interpolated between the values tabled in (VDI 2002). The isobaric heat capacity c_p has a high variation with temperature and pressure at the area of interests. Especially the value for the isobaric heat capacity c_p is very sensitive to the whole calculation. Already a small variation of the value from 7 kJ/ (K*kg) to 5 kJ/ (K*kg) will result in an increase of 34% of the insulation thickness.

The system of equations for heat transfer by conduction and convection with the two uncertain parameters q and T_{wall} is listed below (see Equation 8).

Equation 8 Heat transfer by conduction (I) and convection (II)

$$\dot{q} = \frac{k_f}{\Delta x} \cdot \left(T_{wall} - T_{soil}\right) \quad (I)$$
$$\dot{q} = h \cdot (T_{fluid} - T_{wall}) \quad (II)$$

The term 1/h in Equation 9 is negligible compared to the term $\Delta x/_{kf.}$ Then it is simple to solved after the heat loss q. The heat transfer coefficient is calculated with the Nusselt Number (see Equation 10). The exponent n is an experience value and set to 0.33 (Dialer 2007) for this calculation.

Equation 9 Heat loss

$$q = \frac{1}{\frac{\Delta x}{k_f} + \cancel{\frac{1}{h}}} \cdot \left(T_{fluid} - T_{soil}\right)$$

Equation 10 Nusselt Number. Equation (II) is called the Dittus-Boelter equation.

$$Nu = \frac{h \cdot L}{k_f} \quad (I)$$
$$Nu = 0.023\,\mathrm{Re}^{4/5}\,\mathrm{Pr}^{n} \quad (II)$$

The parameter of interest is the thickness of the required insulation Δx for not exceeding the allowed temperature drop of 10 °C per 200 km. Therefore the heat loss by heat transfer q is set equal to the loss of heat content of the CO_2 mass flow after a length of 200 km (see Equation 11) and following solved after Δx.

Equation 11 Heat flux of CO_2 heat transfer (1) and heat content (2) equated and solved after Δx.

$$\dot{Q}_1 = A_{pipe} \cdot \dot{q} = A \cdot \frac{k_f}{\Delta x} \cdot \left(T_{fluid} - T_{soil}\right) \qquad (1)$$

$$\dot{Q}_2 = Q_{in} - Q_{out} = \dot{M}_{CO_2} \cdot c_p \cdot \left(T_1 - T_2\right) \qquad (2)$$

$$\dot{Q}_1 = \dot{Q}_2$$

$$\Delta x = \frac{A \cdot k_f \cdot (T_{fluid} - T_{soil})}{\dot{M} \cdot c_p \cdot (T_{in} - T_{out})}$$

Figure 29 shows the schematic of the problem for illustration. The calculated □x results in 0.03 m (seeTable 33).

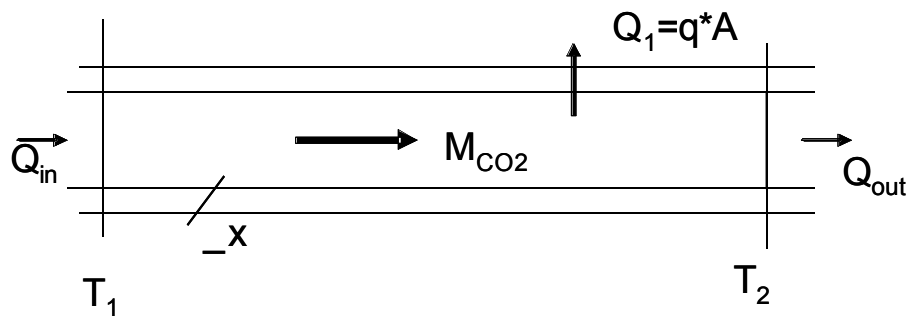

Figure 29 Schematic of the heat loss problem ($T_1 > T_2$).

Table 33 Parameters for heat loss calculation and resulting insulation thickness. The values for the CO_2 properties are an interpolation of the values found in (VDI 2002).

CO_2 properties at 95 bar and 45°C			
density		kg/m^3	446
Kinematic viscosity		m^2/s	7.57E-08
dynamic viscosity		Pa/s	3.35E-05
specific heat capacity	c_p	kJ/ (K*kg)	7.01
heat transfer coefficient	k_f	W/(mK)	0.058
calculated heat transfer coefficient	h	$W/(m^2K)$	1973
Parameter Pipe			
inner diameter	D_i	m	0.573
outer diameter	D_{out}	m	0.609
Perimeter	U	m	1.80
length pipe	L	m	200000
other parameters			
mass flux CO_2	M	kg/s	250
thermal conductivity rock wool	k_f	W/(mK)	0.035
T_{soil} 1m below surface	T_{soil}	°C	10
mean temperature of the CO_2	T_{fluid}	°C	45
temperature inlet	T_1	°C	50
temperature outlet	T_2	°C	40
Velocity	v	m/s	2.17
dimensionless numbers			
Prandtl number (tabled)		-	3.8
Nusselt number		-	2.1E+04
Reynolds number		-	1.6E+07
calculated insulation thickness	Δx	m	0.03

A.II.3 Calculations for Pipeline Transport

A.II.3.1 Steel Requirement

The amount of steel is calculated with Equation 12. The pipe dimensions are defined in section 4.2.2. An addition of 3 % of the resulting requirement is made for considering the valves, flanges etc. This estimation is rather high. The steel usually used for CO_2 pipes is low alloyed carbon steel. Table 34 shows the applied parameters for the calculation. The resulting steel demand amounts to 2.7E+05 kg per km pipeline.

Equation 12 Mass m per unit length

$$m = \frac{\pi \cdot (D_{out} - D_{in})^2}{4} \cdot \rho_{steel}$$

Table 34 Parameters for the calculation of the steel demand.

Parameter	Unit	Value
Density steel	kg/m^3	7850
D_{out}	m	0.609
Wall thickness	m	0.018
Demand steel	kg/m	262.3
Plus factor 3 % for valves ect.	kg/m=t/km	270.2
Total demand steel	kg/km	2.7E+05

A.II.3.2 Rock Wool Requirement

The required rock wool amount is calculated the same way like the steel demand with Equation 12. The thickness of the insulation is calculated to 30 mm in A.II.2. The parameters used and the resulting rock wool demand are shown in Table 34.

Table 35 Used parameters for the calculation of the rock wool demand and the resulting amount of rock wool.

Parameter	Unit	Value
Density rock wool	kg/m^3	85
D_{out}	m	0.669
Wall thickness	m	0.030
Demand rock wool	kg/km	5119

A.II.3.3 Sand Requirement

The required sand for filling the trench is calculated with the volume difference between the trench and the volume occupied by the pipeline including the insulation layer of 30 mm. The trench dimensions are assumed by the requirement of minimum buried depth of 0.9 m (IPCC 2005). Figure 30 shows the schematic of the trench dimensions. The parameters applied for the calculation are listed in Table 36 The sand demand for filling the trench results to 4.40E+06 kg sand per km pipeline.

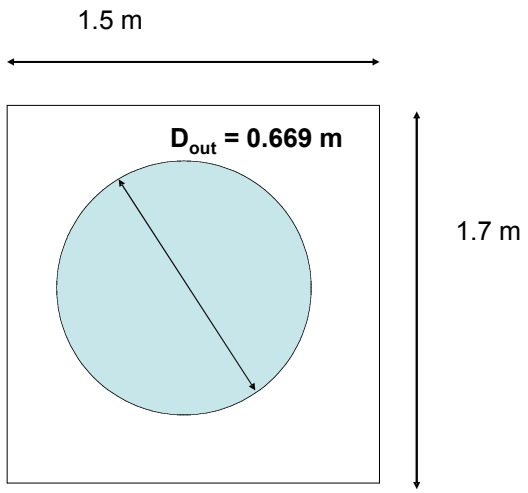

Figure 30 Schematic of trench with pipeline.

Table 36 Parameters for the calculation of the sand demand.

Parameter	Unit	Value
V trench	m^2	2.55
V pipe	m^2	0.35
D_{out} Diameter pipe+insulation	m	0.669
Δ V	m^2	2.20
Density sand	kg/m^3	2000
Demand sand	kg/km	4.40E+06

A.II.4 Sensitvity of Parameter Δp

The variation of the parameter Δp for injection, will change the required energy due to the direct proportionality. In Table 37 and Table 38 the pressures for the different sensitvity cases are shown for saline aquifers respectively depleted gas fields. Table 39 gives the parameters applied for the energy calculation and the resulting energy requirement.

Table 37 Reference case, maximum and minimum case for the sensitivity analysis of the required Δp for saline aquifers.

		Saline aquifer		
Case		reference	maximum	minimum
		30 bar	2x30bar	80 bar enough
Depth	m	800	800	800
hydrostatic pressure	bar	78.4	78.4	78.4
pressure required at bottom hole	bar	108	138	80
Δp required	bar	28.4	58.4	0

Table 38 Reference case, maximum and minimum case for the sensitivity analysis of the required Δp for depleted gas fields.

		Depleted gas field		
Case		reference	maximum	minimum
		30 bar	2x30bar	reservoir p enough
Depth	m	2500	2500	2500
hydrostatic pressure	bar	172	172	172
pressure required at bottom hole	bar	202	232	172
Δp required	bar	202	232	172

Table 39 Used parameters for the calculation of the power demand for injection for the different sensitivity cases for saline aquifers and depleted gas fields.

		Saline aquifer			Depleted gas field		
		reference	max	min	reference	max	min
required Δp	bar	28.4	58.4	0	121.5	151.5	91.5
efficiency η	-	0.85	0.85	0.85	0.85	0.85	0.85
Power per well	MW	1.5	3.1	0	6.4	8.0	4.8
per 2 wells	MW	3.0	6.2	0	12.9	16.0	9.7
Power per 2 wells	kWh/kg CO_2	0.007	0.014	0	0.029	0.036	0.022

A.III Reservoir Overpressure

The range of values of interest of the overpressure found in (Bock et al. 2001) is shown in Table 40. The overpressure is calculated with the difference of the tabled downhole injection pressure and the tabled reservoir pressure. The value reported for the reservoir pressure of depleted gas fields is remarkable. However, as noticed in section reservoir pressure (cf. 4.3.1) reservoir pressures can deviate clearly from the hydrostatic pressure gradient.

Table 40 Context of overpressure value found in (Bock et al. 2001).

Parameter	Units	Gas reservoir	Oil reservoir	Aquifer*	Remark
CO_2 mass flow rate	t/d	7389	7389	7389	
Downhole injection pressure	MPa	15.2	15.2	15.2	
Reservoir pressure	MPa	3.45	13.78	8.62	gas: unexpected value
Overpressure	MPa	12	1.4	7	calculated
Thickness	m	30.5	42.7	36.6	
Depth	m	1524	1554	1539	
Permeability	md	15	15	15	

*midpoint between gas and oil reservoir properties