UNIVERSITÄT POTSDAM

Wirtschafts- und Sozialwissenschaftliche Fakultät

Magisterarbeit

Social Conditions of Technological Change

The Case of Carbon Capture and Storage

Potsdam, 10.01.2005

Eingereicht bei Prof. Dr. Carlo C. Jaeger (1. Gutachter)
und Dr. Ottmar Edenhofer (2. Gutachter)
von Christian Flachsland
Matr.-Nr.: 704890
Email: Ch.Flachsland@web.de

PAGE INTENTIONALLY LEFT BLANK

ZUSAMMENFASSUNG

Ziel dieser Arbeit ist eine umfassende Untersuchung der sozialen Aspekte von Technologien zur Abscheidung und geologischen Lagerung von Kohlendioxid (englisch: CO_2 capture and geological storage CCGS). CCGS wird zunehmend als zusätzliche Option in einem Portfolio von Energietechnologien zur Vermeidung des anthropogenen Klimawandels erachtet. Allerdings konzentriert sich die entsprechende Forschung fast ausschließlich auf die ingenieurstechnischen und geologischen Aspekte. Diese Arbeit verfolgt einen interdisziplinären Ansatz, der auf Forschungen aus Ingenieurswissenschaften, Geologie, Ökonomie, politischer Philosophie und Soziologie zurückgreift, um die sozialen Aspekte von CCGS systematisch zu analysieren. Zentrale technische Aspekte und Risiken von CCGS werden identifiziert und diskutiert. Relevante Interessengruppen (stakeholder) werden beschrieben und ihre jeweiligen Positionen analysiert. Da die technische Machbarkeit von CCGS notwendige, die soziale Unterstützung jedoch die hinreichende Bedingung für die großskalige Einführung von CCGS sein wird, werden vier zentrale Determinanten für die Diffusionsfähigkeit dieser Technologie ausgemacht: (a) Grenzkosten der Technologie, (b) Opportunitätskosten der Technologieinvestitionen, (c) durch den ordnungspolitischen Rahmen verursachte Kosten, und (d) Transaktionskosten, die durch soziale Prozesse der Kommunikation, Kooperation und Konflikte entstehen. Aufgrund dessen wird für die Einführung von CCGS ein ordnungspolitischer Rahmen benötigt. Es werden ausgewählte ordnungspolitische Fragen näher behandelt, die in künftigen gesellschaftlichen Diskussionen über die Einführung von CCGS von zentraler Bedeutung sein könnten. Diejenigen Aspekte, die in jedem künftigen ordnungspolitischen Rahmen unbedingt behandelt werden sollten, werden identifiziert. Darauf aufbauend werden mit Carbon Sequestration Bonds und einem auf Emissionshandel basierenden ordnungspolitischen Rahmenvorschlag zwei Instrumente für die gesellschaftliche Einbettung von CCGS auf ihre Tragfähigkeit vor dem Hintergrund dieser ordnungspolitischen Aufgaben überprüft. Abschließend werden auf der Basis der gewonnen Erkenntnisse relevante zukünftige Forschungsfragen formuliert. Ein Anhang enthält eine Zusammenfassung von Literatur, in der die bestehenden ordnungspolitischen Bedingungen für CCGS untersucht werden.

PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

This thesis aims at comprehensively exploring the social aspects of CO_2 capture and geological storage technologies (CCGS). CCGS is increasingly regarded as an additional option in a climate change mitigation technology portfolio. However, related research focuses almost exclusively on the engineering and geological aspects. This thesis adopts an interdisciplinary approach drawing together available research from engineering, geology, economics, political philosophy and sociology in order to systematically analyze the various socially relevant aspects of CCGS. Crucial technical aspects and risks that are associated with CCGS are identified and comprehensively discussed. Relevant stakeholders are identified and their respective positions analyzed. As technical feasibility will be necessary but not commensurate condition for the large-scale implementation of CCGS, four decisive social determinants of the viability of CCGS are identified, including (a) marginal costs of technology, (b) opportunity costs of investment, (c) economic costs induced by regulatory framework, and (d) transaction costs resulting from social processes of communication, cooperation and conflict. Regulation will be required that adresses these issues. Selected regulatory issues that could be central in future debates about CCGS are discussed. Also, regulatory aspects that will have to be addressed by any future regulatory framework for CCGS are identified. Finally, with Carbon Sequestration Bonds and a certificate trade based regulatory scheme two regulatory approaches for CCGS are discussed with respect to their ability to meet such requirements. In the conclusion, relevant future research tasks are formulated based on the findings of the thesis. In an appendix a review of analyses of existing regulatory conditions for CCGS is provided.

PAGE INTENTIONALLY LEFT BLANK

Overview of Contents

Table of Contents

List of Figures

List of Tables

List of Acronyms

AAU	Assigned Amount Unit
AoR	Area of Review
CCS	carbon dioxide capture and storage
CCGS	carbon dioxide capture and geological storage
CDM	Clean Development Mechanism
CER	Certified Emissions Reduction
CH_4	Methane
CO_2	Carbon Dioxide. Note that: 1t Carbon C = 3.67t Carbon Dioxide CO_2
COP	Conference of Parties
CWA	Clean Water Act
DOE	United States Department of Energy
ECBM	enhanced coal bed methane recovery
GS	geological storage of carbon dioxide
Gt	Gigaton
GHG	greenhouse gas
GIS	Geographic Information System
IEA	International Energy Agency
IEA GHG	International Energy Agency Greenhouse Gas Programme
EIA	environmental impact assessment
ENGO	environmental non-governmental organization
EOR	enhanced oil recovery
EPA	United States Environmental Protection Agency
FEMA	Federal Emergency Management Act
FERC	Federal Energy Regulatory Commission
FLPMA	Federal Land Policy and Management Act
FWQA	United States Federal Water Quality Administration
JI	Joint Implementation
Mt	Megaton
NETL	National Energy Technology Laboratory
NO_x	nitrogen oxides
OSHA	Occupational Safety and Health Administration
ppm	parts per million
PWS	public water system
RD&D	Research, Development and Demonstration
RMU	Removal Unit
ROW	Right of Way
SO_x	sulfur oxides
SWDA	Safe Water Drinking Act
UIC	Underground Injection Control program
USDW	underground source of drinking water

1. Introduction

This thesis aims at comprehensively exploring the social aspects of CO_2 capture and geological storage technologies (CCGS). CCGS is increasingly regarded as an additional option in a climate change mitigation technology portfolio. However, related research focuses almost exclusively on the engineering and geological aspects. In this thesis an interdisciplinary approach is applied drawing on available research from engineering, geology, economics, politics and sociology in order to analyze the various socially relevant aspects of CCGS.

This is reflected in the structure of the thesis which is divided in chapters, subchapters, sections and subsections. In subchapter 1.1, CCGS is situated in the context of climate change and energy policy. Chapter 2 explores the critical technical aspects of CCGS in depth and thereby establishes the basis for the following analyses. A short description of CO_2 capture and transport technologies (2.1) is followed by a description of geological exploration, injection and monitoring technologies, including discussion of analogical underground injection processes (2.2). In 2.3 economic costs of CCGS are addressed briefly. The subchapters 2.4 and 2.5 systematically and comprehensively discuss local and global safety, ecological, and economic risks of CCGS including the global potential (opportunity) of CCGS for contributing to climate change mitigation. Also, analyses of the social distribution of these risks (and benefits) are conducted. Subchapter 2.6 summarizes the findings on the technical aspects of CCGS and draws conclusions concerning their social implications, with special emphasis on risks.

Chapter 3 investigates social aspects of CCGS. In 3.1 relevant theoretical considerations from the social sciences are introduced. These include the concept of modernization risks given by Ulrich Beck (3.1.1), a conceptual framework for for dealing with modernization risks as public problems as proposed by John Dewey (3.1.2), a brief summary of conflict theory as a tool to analyze social processes of conflict and cooperation (3.1.3), and (3.1.4) some sociological and economical concepts for understanding the dynamics of technological change. Subchapter 3.2 is the central part of the thesis and develops a sociological analysis of CCGS by identifying and discussing the position of relevant stakeholders (3.2.1), public perceptions of CCGS (3.2.2), some geopolitical considerations (3.2.3), and finally provides an analysis of the crucial social determinants of the viability of climate change mitigation technologies in general and CCGS in particular (3.2.4). It is argued that there are four determinants for the implementation of CCGS: (a) marginal costs of technology, (b) opportunity costs of investment, (c) economic costs implied by regulatory framework, and (d) transaction costs resulting from social processes of communication, cooperation and conflict.

The chapters 4 and 5 do then investigate a future regulatory framework for CCGS. Chapter 4 identifies and discusses some selected regulatory issues that have to be addressed by any future regulatory scheme. These include legal status of CO_2-stream for geological storage and underground injection processes (4.2.1), site selection, acquisition and permission (4.2.2), social definition of an acceptable leakage rate (4.2.3), monitoring, leakage and verification/accounting (4.2.4), short- and long-term liability (4.2.5), the relations between

CCGS, renewables and incentives for climate change mitigation technologies (4.2.6), and the adoption of CCGS in developing countries and countries in transition (4.2.7).

These analyses enable to systematically outline and conceptualize regulatory requirements of CCGS in 5.1. Subchapter 5.2 situates regulation of CCGS in the context of the UNFCCC process and analyzes its current treatment therein, with a focus on the Kyoto Protocol (5.2.1) and the European Union Greenhouse Gas Emission Trading Scheme (ETS) (5.2.2). Finally, in 5.3 a proposal for regulating CCGS is discussed. A brief discussion of the rationale of regulation for CCGS (5.3.1) is followed by an outline and systematic discussion of the concept of Carbon Sequestration Bonds (CSB) and an alternative but related emission certificate trading based scheme developed by Edenhofer et al. [2004a]. Also, Green Energy Certificates are discussed which in concert with Carbon Sequestration Bonds may provide the basic structure of a future regulatory framework that could enable the transition of the current energy system towards a more sustainable future.

In the Conclusion findings are summarized and further research needs identified. With appendix A a review of literature analysing the current state of regulation concerning CO_2 capture and storage is provided.

1.1 Background

If anthropogenic emissions of CO_2 resulting from the combustion of fossil fuels (coal, oil, gas) will continue to rise or remain at the level of today, changes in the global climate system can be expected due to increases in global mean surface temperature resulting from the greenhouse effect. [IPCC 2001]

In order to mitigate climate change, anthropogenic CO_2 emissions have to be reduced towards zero within the next 100 years. Today, annual anthropogenic CO_2 emissions are ~30Gt per anno. Business-as-usual (BAU) calculations expect annual emissions to rise to levels as high as ~80Gt CO_2 per year. [Edenhofer et al. 2005b]

Reducing CO_2 emissions at this order of magnitude while enabling economic growth especially in developing countries imposes a considerable challenge for humankind: the entire global energy system has to be restructured in a way that reduces the pressure on the global climate resulting from the emission of carbon dioxide. At the same time, the IEA projects almost a doubling in global electricity demand until 2030. [IEA 2004a, 416]

Three approaches are commonly put forward that aim at mitigating climate change while allowing for an increase in global energy consumption, with a fourth only recently receiving more attention. These approaches are usually regarded as elements of a complementary portfolio of options for mitigating climate change and include:

1) improvements in efficiency of energy use,

2) extended use of nuclear power,

3) large-scale implementation of renewable energy technologies, and

4) capture and storage of CO_2 stemming from large point sources (CCS).

While there is a wide and positive consensus on the option of improving efficiency of energy use, its potential to achieve deep reductions in CO_2 emissions in the long run is inherently limited. [see e.g. Edenhofer 2005a]

Extending the use of nuclear power implies a number of problems. First, nuclear power plants involve catastrophic risks both during operation and in the final storage of radioactive wastes (e.g., Harrisburg, Tschernobyl, see Perrow [1992]). Related to this are, second, considerable problems with public support of nuclear power in many countries. Third, light-water reactors require considerable amounts of Uranium, a scarce resource. If the share of nuclear electricity production is only to remain constant until 2030, ~500 light-water reactors of current type would have to be constructed. If the share of nuclear energy in electricity production were to increase to 35%, 1000 new plants of this kind would be required. Fourth, only fuel reprocession plants or fast breeder reactors could reduce the dependence on Uranium. However, these technologies enable the construction of nuclear weapons; therefore, this option is not viable for large parts of the world due to security reasons. Finally, it is questionable whether nuclear power is competitive in a liberalized electricity market. The energy enquete commission of the German Bundestag assessed investment costs for nuclear power plants at € 1700-2000 per kW, while investment costs for a conventional coal-fired power plant were assessed at € 1175-1300 per kW only. [Enquete Kommission 2002, 455-459; Edenhofer et al. 2005b]

Renewable energies comprise wind, solar, biofuel, geothermal, tidal and related approaches. If CO_2 emissions are to be reduced on a significant scale in the next century, there is a broad consensus that a large-scale adoption of renewables will be required. However, renewables are currently not cost competitive at the large-scale and are faced with restrictions of their own (e.g., availability of land). [see e.g. WBGU 2003] It is expected that their performance will increase within the next decades, but if cost reductions come slow and renewables fail to meet drastically increasing global energy demands, then either considerable welfare losses will result or fossil fuels will have to remain in use, thereby putting the global climate in jeopardy.

Therefore, the technology of capturing CO_2 from the exhaust stream or fossil energy input of large point sources, liquefying and transporting it to suited storage media (other than the atmosphere) and injecting it therein has received increased attention in recent years. CCS could allow for the continued use of fossil fuels without harming the global climate, thereby giving the renewables more time to improve their performance. Also, carbon dioxide capture and storage (CCS) allows the fossil fuel related industries to accept climate change as a pressing global problem because it abolishes the exclusive trade-off between renewables or fossil fuels when it comes to climate change mitigation. With CCS at hand, tackling the problem of climate change is not synonymous with the immediate abolishment of the entire fossil fuel sector. However, CCS is facing a variety of difficulties, most notably the leakage of CO_2 from storage reservoirs to the atmosphere, adverse ecological impacts, risks for humans, and economic risks that arise if significant investments are allocated to CCS instead of renewables that are going to be required in the long run. Also, storage capacity for CO_2 in media other than the atmosphere is ultimately limited. Therefore, CCS is usually regarded to be a bridging technology that allows to buy time for the necessary transformation of the energy system in the 21st century. [see e.g., Bauer 2005] All of these aspects are going to be investigated at more detail in the following chapters.

2. Technical aspects of CO_2 capture and geological storage

This chapter aims at providing an overview of CO_2 capture, transport and geological storage technologies.[1] The known associated risks are discussed.

From a methodological point of view it is attempted to generate a "thick description" [Geertz 1973] of CCGS technologies as proposed by Perrow [1992, 383]. Perrow develops this concept by contrasting with descriptions commonly put forward by those experts and risk assessment companies that tend to render the features and risks of technologies negligible by presenting them in the form of anonymous statistical data.

> "The latter [risk assessments, C.F.] (...) [are, C.F.] quantitative, exact, logically coherent, economical and detached. (...)[They, C.F.] praise the advantages of technology and the natural sciences (...). A thick description pays respect to subjective dimensions and cultural values, and is in our case skeptical towards systems and institution that have been created by human beings. It emphasizes social ties and the preliminary character and ambiguity of experience." Perrow [1992, 383; own translation]

The approach adapted here will make use of the state-of-the art literature on the technical, geological and economical aspects of CCGS and puts an emphasis on difficulties and risks involved, without neglecting the treatment of available experience from analogical processes. This does not imply or rest on a preliminary decision about the feasibility and desirability of CCGS operations. It is rather regarded as a necessary precondition for society to make an informed judgement about the selection and application of CCGS as a climate change mitigation approach.

Marchetti [1977] is commonly considered to have been the first to propose carbon dioxide capture from large point sources and subsequent storage in media other than the atmosphere. Marchetti proposed to collect CO_2 from significant point sources (power stations, industrial blast furnaces, refineries) and to dispose of it into the thermohaline undercurrent of the oceans, e.g. the Mediterranean current entering the Atlantic at Gibralter. The aim was to mitigate climate change resulting from the greenhouse effect by storing anthropogenic CO_2 in another media than the atmosphere. Marchetti argued that ocean injection would basically enhance the natural CO_2-uptake of the oceans.

While Marchetti's ocean storage approach was pursued in several projects in the late 1990s, today's carbon dioxide capture and storage efforts focus on the geological storage of captured CO_2, both on- and off-shore (under the seabed). This is because direct injection of CO_2 into the ocean faces both severe environmental and legal uncertainties, the latter relating

[1] CCGS involves a wide range of technologies, related research communities, and industries. Subsumption of these divergent technical and social fields under the single term CCGS is a relatively new phenomenon. [Wilson et al. 2003, 3482]

to the 1972 London Conventionthat prohibits the dumping of wastes and other matter into the marine environment.[2] [see e.g., Lenstra and van Engelenburg 2002; Johnston et al. 1999]

This thesis focuses on the on-shore geological injection of CO_2 only. Other storage concepts apart from geologic and oceanic disposal are the utilization and mineralization of CO_2. However, the current market potential and availability of large-scale utililization options for CO_2 is generally considered low.[3] Mineralization processes of CO_2 occur over geological timespans, but it unclear how they could be enhanced in order to become an option for safe CO_2 emission abatement.

The following subchapters will discuss the technologies of CO_2 capture, transport, and geological storage and the related local and global risks. In addition, economic aspects (costs) will be treated in 2.3 on the microeconomic level and in 2.5 on the macroeconomic scale.

2.1 CO_2 capture and transport

Before CO_2 capture and transport schemes are discussed, a brief overview of potential sources and the orders of magnitudes involved in CCGS operations is given.

2.1.1 Carbon dioxide sources

Immobile facilities emitting large amounts of CO_2 resulting from the extraction, treatment or combustion of fossil fuels will be the main sources of CO_2 for CCGS operations. These include fossil fuel power plants (mainly coal and gas), iron and steel factories, cement factories, ammonia producing facilities, oil and natural gas production installations, and refining facilities. Collection of CO_2 from mobile and/or smaller, spatially distributed sources (e.g. vehicles, home furnaces, small electrical generators) is considered to be too costly due to the extensive CO_2 collection network (e.g., pipelines) required.

The overall global carbon dioxide emissions from such large point sources have been ~14Gt in 2002. [IEA 2004a, 75] A single 500 MW coal-fired power plant produces approximately 4Mt CO_2 per year. Assuming a lifetime of 30 years, this amounts to cumulated emissions of 120Mt CO_2 for a single medium sized coal-fired power plant. [Holloway et al. 1996, 118]

---

[2] It can also be assumed that there is public opposition to ocean injection to CO_2. De Figueiredo et al. [2002] and de Figueiredo [2003] present a case study of an ocean sequestration pilot project off the coast of Hawaii that was to take place in 2001 but failed to be conducted due to opposition by members of the local public. While the case study provides interesting insights into mechanisms regarding public perceptions of CCS, it appears that crucial factors in determining public opposition in the Hawaii case (e.g., social meaning of the ocean) are not analogical to onshore geological storage exercises.

[3] Commercial uses of CO_2 include enhanced oil recovery (EOR), which will be discussed below. Other utilization opportunities include bottling, horticulture, chemical manufacturing, and fertilization of micro cultures that yield economic benefits. However, in case of large-scale implementation of CCS, CO_2 supply would clearly exceed commercial demands, as the US industry, for example, uses only ~36Mt/y CO_2 today, 80% of which are injected in EOR operations. Put into the perspective of 14Gt/y anthropogenic CO_2 emissions from large point sources, only small fractions of the captured CO_2 could be utilized in industrial processes. [see Anderson and Newell, 2003; Herzog et al. 1997; Stevens et al. 2001]

In the following sections only capture technologies for fossil power plants are presented. This is because these are the main point sources of CO_2 (~25% of overall global annual emissions in 2002 stemmed from fossil fuel power plants; see IEA [2004, 75]) and are most frequently discussed in literature. However, some of the approaches presented can be applied to other CO_2 producing facilities as well, for example post-combustion approaches.[4]

2.1.2 CO_2 capture options

It would be impractical to dispose of the whole flue gas stream of fossil fuel power plants. First, vast quantities of underground storage space would be required, and second, the energy needed to compress all of the flue gas would be about 65% of the total energy output of a coal-fired plant. The flue gas of fossil power plants contains only a maximum of 16% CO_2. Therefore, only capture concepts that involve a separation of a pure CO_2 stream are being discussed. [Holloway 1996]

In general, three CO_2 capture approaches at power plants can be distinguished. In the oxyfuel scheme, a fossil fuel would be combusted in an O_2 atmosphere instead of ambient air. The resulting flue gas would contain up to 100% CO_2 that could directly be compressed, cooled (for transportation) and injected without significant treatment. However, if the resulting CO_2 stream were delivered for injection without further treatment, it would likely contain SO_x, which could lead to increased material corrosion as well as hazards and regulatory problems in the storage process. As combustion in oxygen results in very high temperatures that can deteriorate the combustion chamber, it is planned to recycle some of the flue gas and mix it with O_2 in order to decrease combustion temperatures (and increase the CO_2 content of the resulting flue gas). The main drawback of the oxyfuel approach is the energy requirement of the oxygen production process, which depending on the method can consume 25-30% of the electricity output of a power plant. In addition, the viability of the oxyfuel approach has yet to be demonstrated in a large-scale application. [Bauer 2005, Ch.5]

In pre-combustion schemes a syngas is produced from a fossil fuel feedstock (e.g., coal). Depending on demand, this syngas can either be combusted (e.g., IGCC power plants), or transformed into separate H_2 and CO_2 streams through water shift processes. The H_2 can either be combusted in order to generate electricity or it may fuel a hydrogen economy (e.g., fuel cells, transportation). However, this approach has not been demonstrated on a significant commercial scale yet. [Bauer 2005, Ch.5]

Finally, post-combustion approaches would leave current power plant design basically unchanged. They are therefore also referred to as end-of-the-pipe technologies and can be compared to SO_x removal processes, which are simply added at the end of the plant operation process in order to avoid the environmental impacts of the emission of sulphurs. The most common and best developed technology for removal of CO_2 from a flue gas stream is chemical absorption. An amine (e.g., Monoethanolamine MEA) is contacted with the flue gas and reacts with the CO_2 molecules. It is then pumped into a stripper unit where it is heated, thereby releasing the CO_2 molecules which are removed from the stripper. The CO_2 is then cooled and compressed for transport. The stripped MEA is returned to the flue gas

[4] For an overview of CO_2 capture schemes and costs at other facilities than power plants, see Anderson and Newell [2003].

and the process starts over again. Depending on the source, flue gas will contain SO_x, NO_x, H_2S, N_2 and inorganic oxide particles, which – if captured along with the CO_2 and not removed – could lead to problems "downstream" during transport or storage, analogical to the problems of the oxyfuel approach. [Bauer 2005, Ch.5; Celia and Bachu 2003; Wilson et al. 2004b]

Efforts to develop other chemicals that are more efficient than MEA are currently under way. One major drawback of MEA stripping is that it requires considerable amounts of energy (reducing plant efficiency by ~7-13%). Also, large amounts of the solvent degrade or are vented along with the flue gas, which makes substitution of the chemical necessary.[5] Therefore, other schemes to remove CO_2 from the flue gas are also being discussed and developed, but none of them seems to be commercially viable today. These include physical adsorption, which involves preferential diffusion of CO_2 through a semipermeable membrane; pressure swing adsorption (PSA), where CO_2 is preferentially adsorbed by a physical matrix at low pressures and released and removed at higher temperatures. Analogically, temperature swing adsorption (TSA) involves physical adsorption at low temperatures and release of CO_2 at higher temperatures. The energy requirements of the two latter processes are considerable. [Bauer 2005, Ch.5; Holloway 1996]

In all of the three approaches, carbon dioxide emissions from fossil power plants would be reduced by 91-100%.

It is worth noting that due to energy requirements of the CO_2 separation process plant efficiency losses of 7-35% would be incurred. This would result in higher fuel input per unit of delivered energy. This is commonly referred to as the "energy penalty" of capture processes. The additional energy input raises the costs of electricity production, for example. Also, the energy penalty implies that application of CO_2 capture increases the overall CO_2 production, as more fossil fuel is combusted relative to a base case.[6] [Bauer 2005, Ch.5]

2.1.3 CO_2 compression and transport

Before transport, the CO_2 will be cooled and compressed in order to attain supercritical state, which will allow for higher CO_2 pipeline throughput rates and more effective use of scarce storage capacities, thus rendering CCGS economically more efficient. Also, H_2O will be removed in order to avoid corrosion of the pipeline. At ambient ground-surface temperature (25°C) and pressure (0.1Mpa), CO_2 is a gas with a density of 1.8 kg/m^3 (The density of air under these conditions is 1.2 kg/m^3). Compressed supercritical CO_2 has a density of 260-800 kg/m^3, depending on pressure and temperature, and behaves like a fluid in many respects. This enables higher pipeline flow rates. As vaporization of CO_2 in the pipeline does inhibit flow, recompression is required in some pipeline schemes. The 320km pipeline delivering CO_2 from a North Dakota Gasification Plant to an enhanced oil recovery operation at

[5] It is estimateed that about 2000-2500t of MEA would be lost annually in 250-500MW power plants. The costs of MEA are US$ 970 per ton. [Bauer 2005, Ch.5]

[6] It is therefore argued that in case of insufficient short- to mid-term storage integrity of geological CO_2 reservoirs, more CO_2 would be emitted to the atmosphere in a CCGS regime than in the BAU case, that is, climate change would actually be enhanced by CCGS measures. [Union of Concerned Scientists 2002, 3]

Weyburn Field, Canada, does not require recompression. [Holloway et al. 1996, 120; Gale and Davison 2002; Bauer 2005, Ch.5; Moberg et al. 2003]

Today, there are ~3,100km of existing CO_2 pipelines worldwide with a capacity of 44.7Mt/y, most of them in the USA (2,800km). About 2,400km of these are larger pipelines with at least 1Mt/y throughput. To put these numbers into perspective, in the USA in 2000 there were some 514,000km of natural gas transmission pipelines, and ~248,000km of hazardous liquid pipelines. [Gale and Davison 2002]

2.1.4 CO_2 emissions from CCGS operations prior to underground injection

Additional atmospheric CO_2 emissions from CCGS operations would not only result from the energy penalty induced by the capture process, but also from the energy required for compressing, cleaning, transporting (e.g., recompression) and finally injecting the captured CO_2. In addition, in all these phases CO_2 may leak out of the system (fugitive emissions). Fugitive emissions could be quantified by comparing separated CO_2 at the power plant with the amounts of CO_2 ultimately injected underground through an injection wellhead. Both process energy requirements and fugitive emissions should be taken into in addition to the energy penalty for an overall estimate of the CO_2 reductions achieved by CCGS, which refers to the issue of accounting and verification[7] and the overall efficiency of CCGS as a climate change mitigation option. [IEA 2004b, 15]

[7] A definition of verification and accounting is provided in 5.2.1.

2.2 Geological storage of CO_2

By discussing processes that are analogical to geological storage of CO_2, it will be shown that subsurface injection of anthropogenic substances and containment of CO_2 within geological formations is already taking place. After that, the injection phase, geophysical and geochemical trapping mechanisms, and available monitoring technologies are described. The subchapter is concluded by an overview of the most important existing CCGS operations.

2.2.1 Analogues for geological storage of CO_2

The following subsections provide an overview of some processes that are analogical to the geological storage of CO_2 and can thus provide some experience for CCGS operations. These processes include recovery of naturally occurring CO_2, acid gas injection, industrial waste disposal, and natural gas storage. Although experience for geological storage of CO_2 will be available from these processes, it should be kept in mind that significant differences to CCGS processes do exist (e.g., volumes would be much larger for CCGS (upscaling), and CO_2 has chemical and physical features quite different from some of the injected substances).

The problems that are associated with some of the analogical processes discussed in this section will be systematically discussed in subchapter 2.4. Therefore, the following sections will only describe the nature and scope of analogical operations.

Recovery of naturally occurring CO_2

Carbon dioxide occurs naturally as a result of geological and geochemical processes (e.g., thermal decomposition of limestone, volcanic activity, hydrocarbon reservoirs) in large, often high-purity (>90%) deposits in many sedimentary basins. In the USA (~28Mt/y), Hungary or Turkey, for example, CO_2 fields are being exploited to provide injectant for enhanced oil recovery operations. The integrity of natural CO_2 reservoirs varies from formations that are thought to have contained CO_2 for geological timescales, and reservoirs that are constantly leaking. [Stevens et al. 2001]

Due to the coupling of natural CO_2 extraction with EOR operations, carbon dioxide market prices vary with oil prices. In 1998 the average price for pure, high-pressure CO_2 delivered in the Permian basin of Texas and New Mexico was US$ ~11 per ton. Gross annual revenues from commercial sales of CO_2 exceeded US$ 350 million. [Stevens et al. 2001]

Acid gas injection

Acid gas injection is conducted in order to avoid the adverse impacts of H_2S emissions on human health and the environment. It involves the separation and subsequent geological injection of H_2S and CO_2 that is produced along with the extraction of oil or gas. The CO_2 is re-injected as a by-product because its separation from H_2S would be more costly than the disposal along with the sulfur (acid gas contains 15-98% CO_2). Depleted oil and gas reservoirs and saline aquifers are the acid gas injection formations of choice. In order to avoid corrosion of materials, H_2O is removed from the acid gas stream.

Acid gas injection is mainly applied in Western Canada today. This is due to a change in local sulfur emissions regulation in 1990, which increased the requirements to H_2S recovery and incineration, until then the standard operation to dispose of H_2S produced along with oil or gas. The altered regulatory environment induced the implementation of up to 42 acid gas injection operations until 2000 (39 were active 2003). In 2004, a cumulated total of ~2.5Mt CO_2 and ~2Mt H_2S had been injected into geological formations in Western Canada. Other acid gas injection projects exist in the USA and Abu Dhabi, for example. [Bachu and Gunter 2004; IEA GHG 2003; Heinrich et al. 2003, 14-16]

Canadian regulation does neither require monitoring of the in-situ behavior of the injected acid gas, nor is monitoring of adjacent formations (e.g., drinking water reservoirs) mandated. After abandonement of an injection well, no monitoring regime controlling the behavior of the injected fluids is required.[8] Subsurface monitoring of injection site pressure, temperature, flow rate and gas composition is conducted via the wellhead, only.[9] It is worth noting that regulation in Europe requires monitoring of vertical leakage of injected acid gas in order to verify that leakage remains minimal and acceptable. No remedial procedures have been developed in Western Canada (e.g., in case of leakage), except closure of problematic wells, and possible removal of the injected gas. [Bachu and Gunter 2004; IEA GHG 2003; Heinrich et al. 2003, 14-16]

One well blow-out occurred as an operator exceeded the permitted injection pressure (leading to closure of the injection site by the regulatory authority). In one case, acid gas has leaked into an adjacent oil reservoir. Two other projects have been suspended by the regulatory authority due to overpressurization.[10] [Bachu and Gunter 2004; IEA GHG 2003; Heinrich et al. 2003, 14-16]

Liquid waste injection

Injection of liquid industrial or municipal[11] wastes is a standard application in the USA today. Instead of cleaning or disposing of liquid wastes into rivers or shallow formations, they are being injected into deep (>800m) geological formations.

In the USA, underground injection is principally regulated in a federal-state regulation scheme which discriminates 5 classes of injection wells, each relating to different

[8] This leads Bachu and Gunter, authors of the IEA GHG [2003] study, to conclude: "However, at present it might be difficult to demonstrate credible evidence for acid gas containment within a geological reservoir without a detailed monitoring programme being undertaken at an acid gas injection site." [IEA GHG 2003, vi]

[9] Report of these variables to the regulatory authority is mandatory.

[10] Heinrich et al. [2003, 13-16] state that human errors are not uncommon in handling of the H_2S and CO_2 (e.g., valves are not completely closed). This has led to complaints from communities adjacent to acid gas injection operations, as H_2S has a rotten egg smell and can easily be detected. This would not be the case with untreated CO_2, which is an odorless and transparent gas. It is worth noting that the sources cited by Heinrich et al. [2003] concerning the incidents that led to complaints by local communities are publicly not available (e.g., unpublished conference presentations, personal communications). This pattern can often be observed in literature on CCGS: it is claimed that no or few incidents of an (analogous) operations have been reported in literature; then some personal communications are cited that cannot be reviewed by the reader. A critical, independent and comprehensive review of risks and case studies on problematic incidents at processes that are analogical to CCGS would be a valuable resource in order to better understand and be able to the assess the risks of CCGS. While a first study is available [Benson et al. 2002], further research would be very desirable.

[11] Subsurface injection of lightly treated municipal wastes is only conducted in Florida. See section 2.4.3 for this and the leakage problems that have occurred at these operations.

underground injection activities.[12] Class I injection wells are most relevant and analogical to CCGS as they comprise wells that inject hazardous and non-hazardous industrial or municipal wastes beneath the lowermost formations containing an underground source of drinking water (USDW). In the US there are currently 485 Class I wells injecting about 35 billion liters of industrial wastes per year. Benson et al. [2002] report that in 1987 the cost of liquid hazardous waste disposal ranged from US$ 49 to US$ 207 per ton. The permission process for a hazardous class I injection well can cost in excess of US$ 2 million due to the required geological testing and modeling. Class I wells must not contaminate potential USDWs, that is, a strict no-migration policy is mandated with respect to drinking water. [Benson et al. 2002, 6]

The most notorious difference between industrial waste injection and CCGS may be that industrial wastes tend to migrate away from the injection well with little buoyant force driving them up and down, while CO_2 has a strong upwards buoyancy. Interestingly, lightly treated municipal wastes do have an upwards buoyancy as well.

Natural gas storage

Natural gas (essentially methane CH_4) is stored underground in order to help meet cyclic changes in seasonal and/or daily demand. In the US, underground natural gas storage has been operated for 90 years. Today, 450 US projects store approximately 119Mt[13] of natural gas in 30 states. While these are significant quantities, they constitute less than 10% of the USA anthropogenic greenhouse gases in 2002. Most US natural gas storage projects make use of depleted oil and gas reservoirs. 51 reservoirs are brine-filled aquifers, and 40 salt caverns. Depleted oil and gas reservoirs are easier and cheaper to develop because the geologic structure and trapping mechanism are usually well characterized from existing wells of prior extraction operations. Aquifer storage projects require extensive site characterization and well testing in order to evaluate the permeability and continuity of the cap rock.

Developing a natural gas field generally takes between two and four years, as water that has intruded the formation (depleted oil and gas reservoirs) or is naturally existent (aquifers) has to be displaced slowly in order to avoid overpressurization. In case of salt caverns, these have to be mined first.

Monitoring requirements vary between the different states, but they do in general almost exclusively focus on assuring that no leakage occurs through the wellbore. Geophysical monitoring of the operations is not required. Risk of leakage mainly derives from overpressurization of the reservoir, which increases the storing capacity. Well problems and the presence of fractures or faults are the main direct reasons for leakage. Like CO_2, natural gas is less dense than water and has an upwards buoyancy. Remediation measures in case of problematic incidents include producing or venting the gas accumulating in shallower layers and/or reducing reservoir pressure. After closure of a natural gas storage site, no long-term monitoring is required because as much natural gas as possible is previously recovered. Only

[12] An overview of US regulation of underground injection activities is provided in Appendix A.
[13] Assuming natural gas is pure methane.

few projects apply systematic monitoring of gas leakage into shallower geological strata. [Benson et al. 2002, 7-8; 105-122; Lippmann and Benson 2002]

In world-wide comparison, the USA have the largest natural gas storage volumes (2/3 of total world capacity), followed by Russia, Ukraine, and Germany. [Sedlacek 2003]

The most important differences between natural gas and CCGS operations are that CO_2 is denser and more viscous (thus less mobile and more prone to potentially harmful accumulation) and reactive (especially when dissolved in water) than CH_4. Also, it is not explosive or flammable. The timescales for geological CO_2 storage operations should clearly exceed those for natural gas storage, and much larger volumes would be involved. [Damen et al. 2003, 14]

2.2.2 Injection

A CO_2 injection site will comprise an incoming CO_2 transmission pipeline, a CO_2 delivery and (if required) recompression station, a pipeline distribution network, and a monitoring system. The quality and quantity of the incoming CO_2 will be controlled. Additional treatment, e.g. filtering of particles, introduction of inhibitors or re-compression may be necessary. The CO_2 will then be delivered to the individual injection wells through the pipeline distribution network. The monitoring system will control pressure and carbon dioxide flows during the injection process. A packer at the bottom, a back flow preventer in the middle and an emergency shutdown valve at the top of the injection well should principally make sure that no CO_2 can escape through the well. [Holloway et al. 1996, 120]

Prior to injection the operator of a storage project will construct a simulation model of the geological formation. Using experience from prior CCGS- and analogical projects, the injection process and possible CO_2 migration trajectories within the formation are simulated. Hazards due to existing and abandoned wells, faults, fractures, ground moving, potential seismicity and other mechanisms are identified. [for an overview of required pre-injection evaluations, see Holloway et al. 1996, 135-138]

In general, only reservoirs below 800m are considered for CO_2 storage because at this depth CO_2 reaches supercritical state, at which the higher density of CO_2 ensures optimal use of the storage capacity. At 800m depth, water with 15% total dissolved solids by mass has a density of ~1100 kg/m^3. CO_2 has a density of 260-800 kg/m^3. This density difference generates buoyancy forces that drive injected CO_2 upward. [Damen et al. 2003, 5]

Holloway et al. [1996, 265] recommend to use several injection wells with low injection rates rather than one well with a high flow rate in order to increase the CO_2 sweep efficiency of a reservoir, that is, to maximize CO_2 uptake per unit of volume. This is due to dissolution features of CO_2 in water [Holloway et al. 1996, Ch.4].

After the injection period the injection well will be sealed. Current modeling calculations suggest that after the CO_2 reservoir has been sealed, it will remain overpressured for several decades. [Zhou et al. 2004]

2.2.3 Trapping mechanisms and reservoir types

Containment of injected CO_2 within a geological reservoir depends on several mechanisms. This section will discuss the geophysical and geochemical trapping mechanisms that will work towards a containment of carbon dioxide within the target formation, whereas in the later section 2.4.6 possible leakage mechanisms will be discussed. Also, the role of formation porosity and permeability for the diffusion of injected CO_2 is discussed. The following subsections then shortly characterize the formations that are considered for CO_2 storage and are concluded by an overview of the quantitative availability of these reservoirs for CCGS.

Geological formations that are considered for long-term storage of CO_2 are:

- depleted oil and gas fields,
- active oil fields with enhanced oil recovery operations,
- deep unminable coal seams, and
- saline aquifers.

Salt domes or oil shales are of less interest due to the inherent difficulties of developing them for large-scale CO_2 storage.

Trapping mechanisms

Geological or structural trapping due to an impermeable geological strata (cap rock seal) is considered to be the most important trapping mechanism in GS. The main risk of this mechanism involves cap rock failure due to fractures, disintegration, permeability and other mechanisms which are discussed below. Depending on the cap rock material, geochemical interaction with CO_2 might enhance or decrease the sealing properties of the cap rock. This has to be investigated on a site-by-site basis. [Holloway et al. 1996, 267; Damen et al. 2003, 5-7]

Solubility trapping is based on the fact that CO_2 is highly soluble in water and also dissolves in oil. It can therefore be an important trapping mechanism in deep saline aquifers and depleted oil and gas fields, which are filled with water or/and fluid hydrocarbons. When the CO_2 is completely dissolved in a fluid, leakage is considered to be less likely (since there is no free floating supercritical CO_2 plume). Still, CO_2 might be released as a consequence of pressure and temperature changes in the reservoir or due to surface release of the CO_2-containing fluid. CO_2 solubility decreases with increasing fluid temperature and salinity, and increases with increasing pressure. The timescale of the dissolution process of CO_2 in aquifers is unclear. It depends on several factors, including the surface area of CO_2 that is in contact with the formation fluid. Model simulations of dissolution processes suggest a range of 5,000 to 100,000 years (varying site-specifically) until complete dissolution, but solubility of CO_2 under field conditions remains an uncertainty. In general, the solubility of CO_2 in formation waters with 15% total dissolved solids by mass is ~35 kg/m^3. [Bruant et al. 2002; Damen et al. 2003, 5; Gale 2003]

Hydrodynamic trapping refers to a process in which CO_2 is dissolved into the formation water by solubility trapping, and its mobility is further reduced by low aquifer flow velocities, often in the order of 1-10 cm/yr, which inhibit further lateral movement of the dissolved CO_2. [Bachu et al. 1994] The effectiveness of this trapping mechanism depends both on successful CO_2 dissolution and slow formation fluid speeds. If the dissolution rate is low and fluids flow rates high, then hydrodynamic trapping will not be an effective trapping mechanism. [Bauer 2005, Ch.5]

Mineral trapping involves the reaction of CO_2 with minerals and organic matter present in geologic formations. In these reactions the CO_2 becomes part of the solid matrix of these structures. For example, reactions with silicate minerals can form calcium, magnesium, and iron carbonate precipitates. Mineral trapping is considered to be the safest trapping mechanism as it results in a stable and non-gaseous compound which is relatively irreversible. However, the amount of injected CO_2 that will react with minerals or organic matter is considered to be small. Estimates are subject to considerable uncertainties and range from 1% to a maximum 20% of injected CO_2 becoming mineralized, most of it early in the lifetime of a project (5-25 years). [Bruant et al. 2002; Damen et al. 2003, 5; Gale 2003; SACS 2003]

Finally, if CO_2 is to be injected into coal seams, the coal surface preferentially physically adsorbs CO_2 molecules and releases previously adsorbed methane. Adsorption in coal beds is therefore considered the most stable large-scale trapping mechanism for CO_2.

The in-situ porosity and permeability of a reservoir determines the rate at which injected CO_2 can diffuse through the formation space and depend on the formation type. Reservoir porosity and permeability could be altered by geochemical interactions between CO_2, formation waters and reservoir rocks. In carbonate formations, carbonate minerals will dissolve in the vicinity of the injection wells, with subsequent enhancement of reservoir porosity, permeability and injectivity. However, these minerals could precipitate farther away in the reservoir if the formation waters that are saturated with them reaches zones of lower pressure or higher temperature. Monitoring of temperature and pressure at the disposal site is therefore crucial in the injection phase in order to attain optimal injection pressures and to avoid overpressurization. In sandstone formations, geochemical reactions are more difficult to predict because of significant differences between individual formations. Mineral trapping might occur in these formations, and the rock structure should be enhanced in the injection zone in order to increase the porosity and permeability of the injection zone. [Holloway et al. 1996, 266]

Depleted oil and gas fields

Depleted hydrocarbon reservoirs have generally been well researched and are principally considered to be relatively safe, since they have held oil or gas, and in fact quite often remarkable amounts of CO_2, for millions of years. More specifically, the cap rock sealing of depleted oil and gas fields is known and generally believed to be effective. [Holloway et al. 1996, 126; Damen et al. 2003, 5; Stenhouse et al. 2004, 5] However, there are concerns that human activity (i.e. large-scale production of hydrocarbons) could have lead to changes in the integrity of these reservoirs in general and the cap rock seal in particular. Abandoned wells could impose significant leakage risks. [Jimenez and Chalaturnyk 2003]

Enhanced oil recovery (EOR)

Enhanced oil recovery (EOR) is a standard practice in the oil producing industry since the 1970 energy crises because states concerned about energy security (e.g., USA and Canada) introduced subsidies for EOR operations.[14] [DTI 2002, 77-79] CO_2 is injected into oil reservoirs in order to improve the viscosity of oil. Combined with injection of water which increases reservoir pressure and forms a water front 'pushing' the oil towards production wells, this enables production of oil with low viscosity that could otherwise not be extracted. The CO_2 (along with produced CH_4 and H_2S) is removed from the emerging oil and then re-injected. Therefore, CO_2 storage is not the primary aim in EOR, and operators usually aim at using as little CO_2 as possible as it is a market commodity which is usually purchased from natural CO_2 producing companies. The volumes of CO_2 effectively stored are therefore usually low. [Holloway et al. 1996, 116; Heinrich et al. 2003, 18-19] Enquete-Kommission [2002, 476] assessed that only 50% of injected CO_2 remain within the reservoir. Data summarized by Heinrich et al. [2003] suggests that higher retention rates are possible if EOR operations explicitly aim at CO_2 storage, e.g. at the Weyburn EOR operations (see section 2.2.5).

This operation, situated in southeastern Saskatchewan, Canada, is the only existing EOR operation that explicitly aims at storing anthropogenic CO_2, which is removed at the Dakota Gasification Facility in North Dakota. At Weyburn, monitoring schemes are installed that allow for the observation of the injected CO_2, which is also unusual. It is intended to inject ~18 Mt of CO_2 and thereby produce ~130 million barrels of enhanced (additional) oil. Including the CO_2 that is produced due to the electricity requirements of the EOR operation, 14 Mt CO_2 that otherwise would be emitted to the atmosphere are expected to be stored underground. [Heinrich et al. 2003, 17-18]

The cap rock sealing of oil fields is known and has usually proved to be able to contain high pressure fluids over geological timescales. Unlike carbon dioxide injection in depleted oil and gas fields aquifers, EOR results in an average reservoir pressure reduction since generally more fluids will be produced than injected. Reservoir stability can therefore be expected to be a less problematic issue. [Holloway et al. 1996, 116]

Beginning in 1972 in Texas, in 2000 there were 84 commercial or research-level EOR projects worldwide. 72 of these projects are sited in the USA. Global EOR operations produced ~200,000 barrel of oil per day in 1998, which corresponded to 0.3% of the average daily worldwide oil production that year. In the United States this amounted to 6% of total domestic crude oil being produced in EOR operations. [Heinrich et al. 2003, 17; Abelson 2000]

No environmental impact statements are required for current EOR operations. Around 5% of the total amount of CO_2 injected into a reservoir is 'lost', but the exact mechanisms are not understood. [Heinrich et al. 2003, 20, citing a personal communication by a Kinder Morgan CO2 company official]

While the major drawback of EOR as a CO_2 storage option is that only limited amounts of CO_2 are effectively stored, benefits arise from the increased oil production, rendering this

[14] Federal subsidies to EOR in the USA, for example, were estimated at US$ 160 million in fiscal year 1999. [DTI 2002, 77]

option particularly attractive for commercial operations and, in case of implementation of an emission constraining regulatory framework comprising CCGS, putting EOR application among the most attractive geological storage alternatives.

Coals seams

CO_2 storage in coal seams is unique in the sense that it involves adsorption to the coal matrix, production of methane and specific physical hydrodynamic trapping processes. Injected CO_2 would ideally displace CH_4 molecules from the coal matrix at a ratio of ~2:1 due to preferential adorption of CO_2 molecules. That is, two CO_2 molecules would replace one CH_4 molecule.

As some coal seams have held methane for millions of years,[15] it is argued that CO_2 storage in unminable coal seams involves a low risk of leakage. If operated at overpressure, however, the risk of leakage may be higher. [Damen et al. 2003, 5; 8]

Enhanced coal bed methane (ECBM) operations would involve injection of CO_2 into unminable coal seams and recovery of displaced CH_4 via production wells, thereby providing a financial benefit of CO_2 storage operations. Only one commercial ECBM operation does exist in the San Juan Basin in New Mexico. The Recopol project in Poland is the most important ECBM research effort in Europe. [Anderson and Newell 2003]

However, storing CO_2 in coal seams is the least developed geological storage option. Several chemical and physical aspects remain to be clarified. For example, adsorption of CO_2 molecules has lead to swelling of the coal matrix in the San Juan Basin pilot operation, which could reduce reservoir permeability and/or induce stresses in over- or underlying strata. [Wildenborg and van der Meer 2002, 63-64; Damen et al. 2003, 8]

Deep saline aquifers

Deep (>800m) saline or brine aquifers contain salty, undrinkable water that sometimes also contains traits of toxic substances (e.g., heavy metals, trace minerals). They have little foreseeable economic or societal benefit as a drinking or agricultural water supply because of their depth and high concentrations of dissolved solids. Aquifers cover large areas and are often sited close to stationary CO_2 emission sites. [Bruant et al. 2002]

A major difference with gas and oil reservoirs is that the cap rocks of aquifers do not have proven to be impermeable in the past. In fact, most aquifers do not have an impermeable cap rock at all. As they are not of economical interest, deep saline aqifers are usually not as well researched as hydrocarbon reservoirs. They would therefore require more extensive pre-injection characterization and testing than hydrocarbon structures, which could increase the relative costs of CCGS at aquifers. [Holloway et al. 1996, 126; Damen et al. 2003, 7]

Two trapping mechanisms apply for CO_2 storage in saline aquifers apart from a structural trap: solubility and hydrodynamic trapping. When injecting CO_2 in an aquifer it will at first displace formation water as a supercritical fluid forming a CO_2 plume, before dissolving in

[15] For each coal bed storage project it would have to be clarified whether methane has degassed in the past in order to assess the reservoir integrity. [Damen et al. 2003, 8]

the formation water (solubility trapping); then, the dissolved CO_2 will migrate along with the formation flows (hydrodynamic trapping).

The Sleipner project at Utsira formation in the North Sea is the first commercial deep saline aquifer CO_2 storage project in the world. Since 1996, 1Mt/y carbon dioxide that is produced along with natural gas is removed and injected into the Utsira sandstone formation which has an impermeable cap rock. The development of the CO_2 is monitored, and no leakage has occurred since begin of the operations (see 2.2.5). [Torp and Gale 2003]

Availability

The following Table 2.1 shows ranges of estimates of global CO_2 storage capacities for the different geological storage options. There are several problems associated with such assessments, e.g. no site-specific security standards are taken into account, and in the case of depleted oil and gas fields often intrusion of water after extraction of the hydrocarbon resource lowers the reservoir capacity but is usually not taken into account in such calculations. A proper CO_2 estimate of geological CO_2 storage potential would have to carry out site-specific analyses concerning reservoir size and integrity.[16]

Except depleted oil and gas fields, only the storage potentials of on-shore formations are displayed in Table 2.1.

Table 2.1: Estimates of global capacities for on-shore geological storage of CO_2. Source: Compilation by Bauer [2005, Ch.5].

Reservoir type	Estimates of global storage capacity (Gt CO_2)
Enhanced Oil Recovery (EOR)	110
Depleted oil and gas fields (incl. off-shore)	500 – 2,000
Unminable coal seams	600 – 2,600
Saline Aquifers with trap	150
Saline Aquifers without trap	5,500 – 36,000

Enhanced oil recovery operations have the least potential for CO_2 storage. However, they will likely be preferred first options (as well as ECBM) due to the economic benefits that arise from selling enhanced oil. [Kallbekken and Torvanger 2004, 9-11; Wilson et al. 2003, 3476; IEA GHG 2002, iii] Aquifers with structural traps do also show less potential when compared to the other options. Depleted oil and gas fields and unmineable coal seams have significant storage potentials, and the potential of untrapped aquifers is virtually abundant if compared to anthropogenic CO_2 emissions: in one fossil fuel intensive SRES-BAU case (A1C) cumulated emissions of 7.200Gt CO_2 are projected until 2100, for example. [WBGU 2003, 111] While these figures are all subject to considerable uncertainties, they suggest that the availability of geological storage potential may not impose a significant barrier for CCGS operations at least in a short- to mid-term perspective.

[16] For a detailed discussion of the approaches and assumptions of reservoir assessment studies, see Bauer [2005, Ch.5].

While geographical distribution of storage sites, that is, the matching of sinks and sources, could in principle be a restrictive factor, it is generally assumed that due to the broad global distribution of relevant geological formations and the availability of pipeline transportation this issue should not constitute a major threshold for an implementation of CCGS.

It can be assumed that good (that is, large reservoir space and low leakage potential) formations will be used first for CCGS operations, and that with increasing cumulative underground injection of CO_2 reservoirs with decreasing quality might be used.

2.2.4 Monitoring

The monitoring requirements of geological CO_2 storage operations can be roughly divided into three classes: 1) operational monitoring; 2) verification monitoring; and 3) environmental monitoring. [Chalaturnyk and Gunter 2004] A second approach for classifying monitoring activities might be to introduce and discuss the distinct monitoring technologies. In reality, however, most monitoring activities will serve several purposes (e.g., monitoring the development of the CO_2 plume), while some will be performed in order to meet a very specific requirement (e.g., monitoring of potable groundwater formations). The following summary of monitoring tasks is structured with respect to the requirements of a regulatory framework and is based on work by Benson and Myer [2002]. Each point combines several monitoring activities and purposes.

1) Control of injection rates, wellhead and formation pressures in order to be able to control the injection process and to avoid exceeding crucial formation pressurization rates (operational monitoring), and verification of injected CO_2 volumes (verification monitoring).
2) Observation of the development of the CO_2 plume (operational monitoring) and assessment of the integrity of reservoir, cap rock (detection of faults and fractures), injection well and abandoned wells (operational and environmental monitoring). Closely related to this issue is accounting for (i) successful CO_2 containment or (ii) leakage; in the latter case, quantification of a leakage rate/ leakage volumes is necessary from a regulation point of view (verification monitoring).
3) Evaluation and optimization of effectiveness of using a storage reservoir, including assessment of solubility of CO_2 in formation fluids and detection of geochemical interactions (e.g., mineralization processes). Also, models developed to predict the containment rates of CO_2 in the reservoir should be modified and fined-tuned according to monitoring data (operational and verification monitoring).
4) Depending on regulation, monitoring of groundwater and soil quality, ecosystem impacts and safety hazards including (micro-)seismicity caused by CO_2 injection (environmental monitoring).

It is apparent that operational and verification monitoring are closely related. However, from the point of view of environmental monitoring the points 1-3 are also relevant and could be labeled environmental monitoring as they involve observing the mechanisms that may eventually lead to environmental hazards.

Monitoring will likely be a part of of the permitting process for CO_2 injection activities, as it includes reservoir characterization (quantitative storage potential, reservoir integrity).

The following discussion of the available and relevant monitoring technologies is not strictly structured according to the categories developed above. Instead, an intuitive approach is chosen that makes a distinction between injection well monitoring, deep underground (subsurface) monitoring and surface (including soil) monitoring schemes. Each level comprises several of the monitoring tasks outlined above and is, to some degree, linked to the other levels.

Well monitoring

Well monitoring is a label for two distinct issues. The first concerns the control of the active CO_2 injection well. The second relates to the identification, characterization and performance control of (often unknown) abandoned wells at the storage site.

One aim of injection well monitoring is to verify the injected quantities of CO_2 that can be accounted for within a regulative framework. Another aim is to ensure that appropriate flow rates are not exceeded or under-run, and that critical pressures in the injection zones remain within safe limits. Injection monitoring requires devices that measure CO_2 flow rate, injection and formation pressures. Such technology is readily available from analogical injection activities and is considered to meet the requirements of CO_2 injection processes. [Damen at al. 2003, 17; Benson and Myer 2002, 140]

Detecting and characterising abandoned wells at the storage site can be a very difficult task. Allison [2001] describes the difficulty in identifying abandoned wells. In some regions in the USA, for example, there are abandoned wells which can be more than 100 years old. Often there are no records available on the whereabouts and characteristics of such wells. [Celia and Bachu 2003]

Deep subsurface monitoring

One aim of deep subsurface monitoring is to trace and optimize the development of the CO_2 plume (desired migration path with respect to leakage, high CO_2 solubility, high mineralization rates; injection pressure and flow rate optimization with regard to these factors). Another aim is to detect possible leakage pathways (cap rock, faults and fractures etc.) and actually occuring leakages (e.g. into potable groundwater aquifers), including quantification of leakage rates (if possible). Also, induced seismicity or ground heaving should be monitored and, if possible, controlled.

Several methods are available for conducting deep subsurface monitoring. The most important are geophysical approaches (seismic, gravity, electric conductivity, magnetic). Formation pressure measurement, geochemical monitoring, and tilt meters for detecting (micro-)seismic events are other deep-subsurface monitoring devices.

Seismic methods are routinely used for exploration in the hydrocarbon industry (esp. oil) and are considered to be the most highly developed monitoring technologies available. Seismic reflection methods involve artificial sound waves being shot across the storage site, and their reflections being recorded. Because gas (CO_2) and water have different densities and sonic velocities, differing reflections allow for location of a CO_2 plume in water. A seismic approach can cover a large area with a high resolution. Typical line spacing for constructing a 2-D seismic data grid for characterizing a geological setting is 1.5 to 3km. Such density is sufficient to define the presence and approximate size of closures in a basin, but more data would be required to establish the exact size of a trap and to define specific spill points, fractures and faults. In order to enable a 3-D interpretation of the subsurface structure, several 2-dimensional sections through the earth (typically to depths of 5km or more) with a line spacing of 12-25m can be combined. Carrying out such analyses over several periods allows for the construction of a 4-D seismic time-lapse analyses of the reservoir. This technology is applied at the Sleipner project, where it was found that supercritical CO_2 accumulations with a thickness as low as about one meter can be detected by causing detectable changes in the seismic signal. However, experience also showed that dissolved CO_2 is more difficult to detect and to quantify. It was found that 3D-data allows for the detection of smaller fractures and faults, but it is argued that very small fractures and joints are beneath the limit of seismic resolution. [SACS 2003] Others contend that detection of such small potential leakage pathways is possible, but if CO_2 were to migrate through these ruptures it could not be observed and quantified. [Benson and Myer 2002, 143] In general, the necessary resolution for seismic mapping of a reservoir largely depends on the respective formation properties; e.g., a relatively flat cap rock allowing for considerable horizontal CO_2 migration would require more extensive 3D-surveying than a curved dome which would serve as a stable (with respect to horizontal movement) trap of the buoyant CO_2. [SACS 2003; Holloway et al. 1996, 126-127; Damen et al. 2003, 18; Torp and Gale 2002]

While seismic reflection surveys are considered to be the best available method relative to other deep subsurface approaches, they also are the most expensive. For costs of this approach see subchapter 2.3 below.

An alternative to the surface-based seismic reflection method is available with cross-well seismic monitoring. This involves sending and receiving a seismic signal from two adjacent wells. However, this approach is considered to be relatively expensive due to the required drilling of an additional wellbore. [Hoversten et al. 2003; Heinrich et al. 2003, 19]

Time-lapse imaging is becoming a more common method but is considered to be a much less mature technology than exploration geophysics. [Benson and Myer 2002, 142]

Other geophysical techniques include gravity, magnetic and electrical conductivity surveying. Their advantages are low costs and simple data acquisition, but they provide data that are less detailed than those of seismic surveys. Their role is therefore seen to provide complementary data to seismic surveys in order to overcome their shortcomings.

Gravity approaches allow for identification of porous sedimentary rocks (displayed as gravity lows), faults, structural highs and major basic or granitic intrusions. Also, larger volumes of CO_2 can be detected. This feature and its relative cost-effectiveness (on-shore) render this method an inexpensive possible 'catastrophic early warning system' that might allow for the early detection of large leakages in brine or oil bearing formations. [SACS 2003, Benson and Myer 2002, 142]

Magnetic data are usually collected by airborne surveys, e.g. with helicopters flying ~50m above ground level. These analyses are based on differential rock magnetics due to specific mineral contents of these rocks (e.g., magnetite). Volcanic rock structures and faults can be detected using this method.

Electrical conductivity applications generally work by moving electrodes across the surface, usually along a straight line. This method allows for the analysis of resistivity and unit thickness of a layered sequence, and 3-D models can be developed if sufficient data are collected. Conductivity methods are widely applied to locate aquifers in groundwater studies and are considered to be useful at CO_2-storage operations in aquifers. However, their resolution is inferior to that of seismic data, and data interpretation is considered to be more difficult. [Benson and Myer 2002, 142; Holloway et al. 1996, 127-128]

Formation pressure measurements can be conducted via monitoring wells drilled into the storage formation. However, at the Sleipner operation costs of € 45 million were calculated for drilling and setting up a permanent formation pressure monitoring well. The high cost are due to rig rates and the time needed to drill the well. [Torp and Gale 2003]

For the monitoring of seismicity and ground movement, tilt meters, a combined surface/ downhole geophone network recording the sound induced by the expanding CO_2 front, and a water-levelling network in combination with satellite radar observations can be applied. [Damen et al. 2003, 18; Holloway et al. 1996, 139]

Geochemical monitoring is useful for both directly monitoring the movement of CO_2 in the subsurface and for understanding the reactions taking place between CO_2 and the reservoir fluids and rocks. For the first purpose, introducing tracers (noble gases, SF_6 and perfluorcarbons) into the CO_2 gas stream and collecting samples at adjacent wells could be a very effective method.[17] Concerning the latter applications at the Weyburn EOR site, for example, well samples are taken of produced fluids before and after injection. Chemical composition and isotope data analyses allow for the examination of mineralization processes of injected CO_2. However, these geochemical reactions are not completely understood. [Benson and Myer, 141; Damen et al. 2003, 18] Also, in order to assess cap rock properties and geochemical interactions between cap rock and injected CO_2, rock samples can be taken which are then investigated in laboratories. This enables analysing the development of the integrity of the cap rock, for example. [SACS 2003, 12]

In addition, groundwater quality changes can be measured by taking water samples from wells drilled into these formations. Tracers in the CO_2 stream might facilitate detection of CO_2 migrating into groundwater. [Benson and Myer 2002, 146]

Direct monitoring of subsurface CO_2 migration and concentrations is possible in the presence of mine galleries adjacent to or above the storage reservoir. This is the case at the RECOPOL project which is a research project for CO_2 storage in coal seams. Simple ambient air IR-sensors, which will be described in the next subsection, can be used to measure CO_2 concentrations within such galleries. [Damen et al. 2003, 18]

To sum up, seismic methods are considered to be suited best for CO_2 detection and tracking in deep brine or oil bearing formations. Other approaches do not achieve the same degree of resolution. However, at shallower depth CO_2 is a gas and therefore geophysical techniques are less suited for detecting it. [Benson and Myer 2002, 142]

[17] If several CO_2-injection projects would be performed at the same reservoir, this method could be useful for answering the question 'Whose is it?', especially in case of leakage. [Benson and Myer 2002, 141]

The major drawback of all these deep-subsurface monitoring technologies is that quantifying the amount of CO_2 that is present in a reservoir and defining an exact leakage rate is difficult. Therefore, several techniques will have to be combined with reservoir simulation models in order to improve the ability to determine these crucial variables. However, model simulations are facing their own limitations. There is, for example, a trade-off between computational capacities and reservoir resolution. Desirable high resolutions (e.g., down to a few meters) do require vast computing capacities that are usually not available.This is one of the reasons why exact quantification of underground CO_2 migration and leakage is difficult [Benson and Myer 2002, 143], if not impossible.

Surface monitoring

Surface monitoring is required for two reasons. The first is to detect hazards for humans (operation personnel, local communities) and ecosystems. The second is to quantify leakage rates (if possible) with regard to a regulatory framework for CO_2 emissions.

Three kinds of surface monitoring schemes are relevant for this: the first concerns the detection of elevated CO_2 concentrations in ambient air, the second aims at detecting and quantifying soil gas fluxes, and the third relates to the detection of seismic events.

Concerning the detection of elevated and potentially hazardous concentrations of CO_2 in ambient air, monitoring of CO_2 concentrations in closed buildings is a routine operation in industrial processing of CO_2. Real-time monitors (small infrared (IR) detectors) and air sampling (using gas bags) are used to make sure that critical indoor values are not being exceeded, and they are considered to be well established. IR detectors depend upon light attenuation by CO_2 at a specific wavelength, usually 4.26 µm. [Benson et al. 2002, 38]

Detection of elevated CO_2 concentrations in the outside is more difficult. In principle, IR-detectors can also be used and should be sufficient in order to detect CO_2 concentrations that could affect human health. However, detecting slow and diffuse leakage will be a more difficult, if not impossible task, as there is no exact monitoring approach available for this purpose.

For example, biogeochemists use IR-detectors to conduct large-footprint ecosystem-scale eddy-flux measurements that aim at investigating the carbon cycle. For this purpose they use 2-5m tall towers in concert with wind and temperature data to reconstruct average CO_2 flux over large areas, assuming thorough atmospheric mixing (which is empirically hardly ever the case). However, for long-term monitoring in the field gas chromatographs with thermal conductivity detectors (GC-TCD) are considered to be more suitable than IR detectors because they are more rugged. Mass spectrometry is the most accurate method for measuring CO_2 concentrations, but is also the least portable. Electrochemical solid-state CO_2 detectors exist, but they are not cost effective at this time. Remote sensing of CO_2 by satellites is principally possible but not practicable for detecting local leakage due to the long path length through the atmosphere and the inherent variability of atmospheric CO_2. In case of pipeline failures, thermal imaging using an airplane is a standard practice to detect leakages. [Benson et al. 2002, 38; Barrie et al. 2004]

It can be concluded that while detecting catastrophic releases and concentrations of CO_2 is not a problem with proven and widely available technology, a reliable field surface monitoring technology required for detection of slow and diffuse surface leakage of CO_2 from geological storage is currently not available. Benson et al. [2002,3] conclude:

> "We anticipate that remote sensing of all but very large CO_2 leaks from geologic formations will be difficult because CO_2 is a significant component of the atmosphere and varies naturally in space and time."

Therefore, it will be difficult if impossible to derive exact leakage rates by implementing a surface monitoring regime:

> "It should however be pointed out that with today's technology, while it is possible to detect the presence of CO_2, we have only a limited ability to make quantitative estimates of many of these parameters. Limited resolution may make it difficult to quantify the amount of leakage, should it occur." [Benson and Myer 2002, 145]

However, this is not considered to constitute a significant problem by Gale and Read [2004]. They argue that surface monitoring is essentially unnecessary and state:

> "(...) surface monitoring will provide additional evidence of the lack of leakage from the reservoir. (...) this may be more of a public relations exercise, rather than a vital monitoring component." [Gale and Read 2004]

For monitoring (induced) seismicity, readily available surface tilt sensors can be installed. However, such a low-cost scheme would not allow for detecting the exact location of seismic events. It can therefore be combined with a subsurface approach which would allow for localization and detection of seismic events and micro-seismicity. Such a combined scheme might help identifying possible CO_2 leakage pathways resulting from (micro-)seismicity, but would also more than double the cost of seismic monitoring relative to a simple surface monitoring scheme. Land deformation resulting from seismic events can be monitored by using radar imaging and airborne interferometic synthetic aperture radar analysis. [Benson and Myer 2002, 144; Holloway et al. 1996, 138-139]

2.2.5 Current CO_2 capture and storage projects

At Statoil's Sleipner West natural gas production field in the North Sea, CO_2 is removed from the extracted natural gas in order to reduce its CO_2 content from 4-9.5% to 2.5% in order to meet market requirements. The CO_2 is removed by using an amine scrubbing unit. While it had traditionally been vented to the atmosphere,[18] a norwegian emission tax of US$ ~50 per ton CO_2 motivated Statoil to implement the first large scale CCGS operation in the world. CO_2 is injected into the Utsira formation 1000m below sea bottom, a saline sandstone aquifer with a cap rock situated above the Sleipner gas field. Injection started in October 1996, and ~1Mt CO_2 per year has been injected since without report of significant problems. Since 1998, the injection operations have been accompanied by a 4D-seismic monitoring scheme conducted by The Saline Aquifer Storage Project (SACS), which after its scheduled termination in 2003 has been followed by CO2STORE. The project monitoring showed that – as predicted by simulation studies – the supercritical CO_2 accumulates under the overlying aquifer cap rock due to buoyancy effects. CO_2 has migrated laterally within the formation for

[18] In the case of the Sleipner natural gas and CO_2 production, this would have increased norwegian CO_2 emissions by 3%.

several hundred meters. No leakage to adjacent formations has been reported. Laboratory tests suggest that only 3% of the injected CO_2 are mineralized within the formation. A key delivery of the SACS project has been a Best Practice Manual. [Torp and Gale 2003; SACS 2003; Arts et al. 2004]

The Weyburn enhanced oil recovery project has already been mentioned above. One distinct feature of the Weyburn EOR project is that it does not use naturally occurring CO_2 but carbon dioxide that stems from a synthetic fuel plant in Beulah, North Dakota, that is run by Dakota Gasification Company. Per day, 5000 tons of 95% pure CO_2 are transported through a 320km pipeline (without recompression) and are injected into the Weyburn oil field in order to increase production lifetime by some 25 years, allowing for production of 130 million additional barrels of oil (since 1954, 328 million barrels have been produced; a waterflood scheme had been in place in order to increase reservoir pressure after the primary production had ceased in 1964). Another important aspect of the Weyburn project is that the injection operations are complemented by an international research project, led by the International Energy Agency's (IEA) Greenhouse Gas Program, which aims at gathering information on CCGS in EOR operations, in particular by monitoring the development of the injected CO_2. [Moberg et al. 2003]

Another major project is BP's In Salah natural gas project in Southern Algeria. Natural gas containing 10% CO_2 is produced, while market sale requirements ask for a CO_2 content of 0.3% only. Therefore, ~0.9 Mt CO_2 will be injected annually over the project's lifetime. [Riddiford et al. 2003]

At the Natuna off-shore gas field in the South China Sea, one of the largest gas fields in the world, a consortium including Exxon and the Indonesian State Oil Company plans to separate CO_2 that is contained at ~70% in the gas produced and to re-inject it into a sub-seabed aquifer. If the project goes ahead, up to 100Mt CO_2 will be injected annually. [Johnston and Santillo 2002, 104] Project commencement is terminated for 2010. [IEA 2003, 6]

Another off-shore CCGS project is planned by Statoil. At the Snøhvit natural gas production site in the North Sea, a project similar to the Sleipner operations is scheduled to commence regular operation in 2006. It is planned to inject a cumulative 23Mt CO_2 stemming from natural gas recovery into a sub-seabed formation over a timespan of 30 years. [Maldal and Tappel 2003].

2.3 Costs

From a systematic point of view, the following three issues make up the microeconomic costs of CCGS technology [Bauer 2005, Ch.5]:

- the extra capital effort,
- the extra energy effort, and
- the extra operation and maintenance (O&M).

If not denoted otherwise the following cost figures are all taken from Bauer [2005], who provides a detailed discussion of the uncertainties and problems that are associated with assessments of the costs of CCGS. Most notably it must be kept in mind that there is no CCGS operation existing today which is not embedded into a previously existing commercial operation, making reliable and generalizable cost calculations derived from empirical experience difficult. Therefore, CCGS costs are commonly computed applying different methods and taking into account different cost factors, which leads to great variations and general uncertainties in cost estimates. In addition, actual costs are expected to vary considerably depending on capture concept and site, transport requirements, geological formation specifications, and regulatory requirements.

Here, only a summary be presented in order to get an overview on the orders of magnitude of costs of CCGS. These will be expressed in emission mitigation (i.e. how much CO_2 emission is avoided relative to some baseline) costs US$/t$CO_2$. None of the studies does take into account the impact of regulatory regimes on the costs of CCGS. The figures do therefore represent estimates of the microeconomic costs of CCGS.

It is generally believed that CCGS has the potential for developing economies of scale that will render the technology economically more attractive in the future than at present, but it is unclear how and if cost reductions might evolve.

Capture

The main capital effort in the capture step arises from the capture facilities, and varies depending on the capture approach applied, size of the facility, etc. The extra energy effort varies correspondingly. Concerning O&M it is worth noting that it is estimated that MEA aborption processes at power plants of the orders of magnitude of 250-500MW will require ~2000-2500t MEA per year due to degradation of the solvent. The costs of MEA are US$ ~970 per ton. [Bauer 2005, Ch.5]

Calculated costs of CO_2 capture from power plants range from US$ 8 to 77 per ton avoided CO_2, depending on the type of capture process, plant type, and most importantly, the method for calculating costs. It can be shown that the lower cost calculations rest on questionable assumptions and should therefore be treated with great care. [Bauer 2005, Ch.5] Technological progress might reduce the costs to US$ 34-39 ton of CO_2 avoided. [Bauer 2005, Ch.5]

Another approach to measure the costs of capture that is often applied for power stations is to quantify the increase in electricity production costs. The estimates, assuming varying power plant types and capture methods, range from increases of 23% to 118% in electricity costs, depending on assumptions and methods. [for a more detailed account of capture costs and related literature, see Bauer 2005, Ch.5]

Compression and Transport.

Setting up compressor facilities and, most importantly, a pipeline network, constitutes the capital expense of the compression and transport step. The extra energy effort arises from the compression and pumping energy needs. O&M costs include safety measures for leakage detection.

Data assembled by Bauer [2005] suggest that overall onshore pipeline transport costs range from ~8-20 US$/t CO_2, depending on pipeline length, diameter, and annual flow rates.

Storage

Geologic exploration, setting up surface facilities, injection well drilling and casing and where necessary, drilling of monitoring wells, will be the major capital expenses of geological storage. Energy will be required for re-compression and injection, and Operation and Maintenance will include monitoring schemes and analyses.

The available estimates of site exploration costs vary between US$ 0.3 and 2 million, depending on available knowledge about the respective formations. Overall injection costs are calculated in the range of ~1.5-7 US$/t injected CO_2. [Bauer 2005]

Concerning the costs of monitoring, seismic reflection monitoring is the most expensive approach but also the best, which is due to the relatively high resolution rates. In 1996, Holloway et al. [1996, 126-127] stated that the cost of onshore 2-D data in the UK per line kilometer varied between ECU 6,500 and ECU 50,000 (more likely to be at the lower end of the cost range), depending on the area of the survey, permit problems, mobilization costs for crew and equipment, etc. 3-D seismic data are more expensive: in 1991, the average costs ranged from ECU 9,000 to 30,000 per km^2. [Holloway et al. 1996, 127] Myer et al. [2003] calculated 3D-seismic monitoring costs for a 1,000MW coal-fired plant CCGS project. It was estimated that per day 30,000t CO_2 would be injected into a 100m thick layer with a porosity of 12%, yielding an effective storage volume of 3.6%. This would create a CO_2 plume of 1125km^2. Assuming six surveys at a five year interval, a total monitoring expenditure of US$ 9 million was calculated, corresponding to US$ 0.03 per ton CO_2.

Cases: Sleipner & Weyburn

Torp and Brown [2004] report costs for the Sleipner and Weyburn operations, respectively. As both projects are part of larger commercial operations that were already in existence before the CCGS efforts, the authors state that isolating the costs of the genuine CCGS effort is difficult. However, the following data are provided by Torp and Brown: the costs of preparatory investigations at the Sleipner off-shore operation were estimated to be US$ 1.9 million (see Table 2.2). Four compressors are required to compress 1 Mt/y CO_2, resulting in compressor facility investment costs of about US$ 79 million. Drilling the injection well did cost US$ ~15 million. Operational costs (fuel costs for compressors and CO_2 tax incurred by exhaust of compressors) are given at US$ 7 million per year. While Torp and Brown [2004] do not mention this expense and it would have had to be installed even in the absence of an underground disposal scheme, SACS [2003, 2] reports the investment cost for the Sleipner MEA absorption unit at US$ ~250 million.

Table 2.2: Break-down of Sleipner Project Preparatory Costs. Source: Torp and Brown [2004].

Task	Cost (in million US$)
Seismic 3D survey (based on later survey costs)	0.4
Coring formation sand, well logs	0.9
Coring cap rock shales	0.5
Reservoir simulations (est. 6 person months)	0.1
Total preparatory costs	1.9

The Weyburn operation incurred US$ 100 million investment costs for the Dakota plant facilities (removal, compression) and the 320km pipeline. Injection facilities were already available from the oil production process. Maintenance and injection costs of the CO_2 injection operations are US$ 0.27 million per year. At a capital interest rate of 12,5%, overall operation costs of ~20 US$/t of CO_2 captured, transported and injected were calculated. [Torp and Brown 2004] It must be kept in mind that in EOR operations not 100% of CO_2 will remain in the storage formation long-term.

Summary

The following Figure 2.1 shows the overall costs of the CCGS process chain broken down into process steps for several assumptions about cost studies. Column A denotes the costs if the minimal calculated figures are taken from each step. Column B adds up the mean values of the respective cost estimate ranges, and column C shows the maximal calculated costs for each phase. As discussed above, these numbers must be treated with great care and can only provide an impression of the orders of magnitudes of costs involved in CCGS.

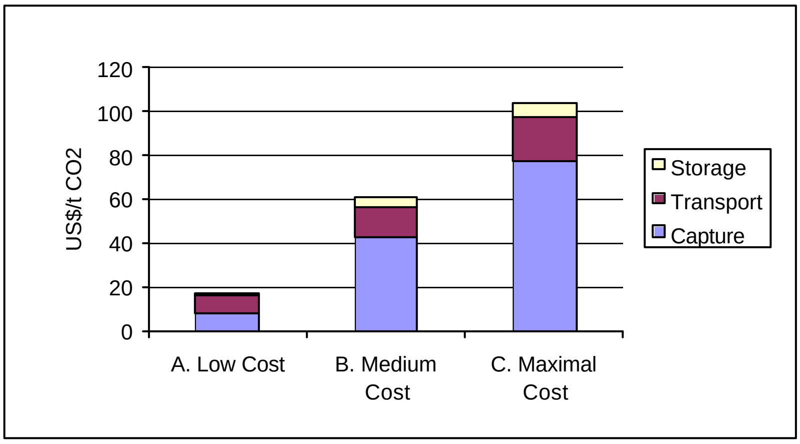

Figure 2.1 : Estimated overall costs of CCGS broken down by process steps for three assumptions about cost estimates. Column A represents the sum of the lowest cost estimates for each process step. Column B shows the costs if the mean value of the range of cost estimates for each process step is taken. Column C adds up the maximum cost estimates. Source: own based on compilation by Bauer [2005, Ch.5].

2.4 Local risks of CO_2 capture, transport and geological storage

This subchapter aims at providing a comprehensive overview and understanding of the local risks that can result from the implementation of CO_2 capture, transportation and geological storage operations. Before this, a general categorization of the risks of CCGS is introduced and substantiated.

2.4.1 Categorizing the risks of CCGS

Wilson et al. [2003, 3477] suggest to distinguish two classes of risks associated with CCGS: *local* health, safety and environmental risks, and *global* risks arising from leakage of CO_2 from an underground reservoir to the atmosphere. In addition, they specify three processes that constitute the local risks:

1) Release of CO_2 to the atmosphere or shallow subsurface (suffocation of humans or animals above the ground, impacts on plants above the ground, biological impact below the ground on roots, insects and burrowing animals).
2) Dissolution of CO_2 in subsurface fluids and mobilization of metals or other contaminants, contamination of potable water, and interference with deep-subsurface ecosystem.
3) Displacement of CO_2 and/or other fluids through ground heave, induced seismicity, contamination of groundwater by displaced brines, and damage to hydrocarbon and mineral resources.

For the following sections, the basic distinction of local and global risks will be adapted. It has the advantage of distinguishing both the scale of processes involved (e.g., local leakage vs. global climate change) and the social settings in which they are approached (e.g., national/regional regulation of injection operations vs. global climate change mitigation efforts). It must be taken into account, however, that for global risks only the *consequences* are truly global, while the physical leakage mechanisms involved do always unfold on a local and site-specific scale.

Wilson et al.'s categorization of three classes of local risks will not be adapted. The reason is that it fails to distinguish between geological and geochemical mechanisms which can but do not have to constitute risks, and the actual risks arising from the possible interplay of several processes involved in underground storage of CO_2. For example, mobilization of trace metals does not *per se* impose a risk to ecology and/or human beings, but only if combined with migration into potable groundwater aquifers or the soil, for example. Human induced ground heave *itself* does not necessarily constitute a risk, but if it e.g. leads to surface leakage of CO_2, or the destruction of housing and facilities, it certainly does.

The following approach is chosen here. First, the main focus will be put on local migration mechanisms and risks, as these are always involved in global risks (while the reverse does not apply). Second, the basic sequence of discussing the risks will follow the CCGS process chain (from capture to transport to storage). Third, within the sections on the risks of geological storage of CO_2, first subsurface migration and leakage mechanisms are discussed, without treating specific risks which may arise from these mechanisms (or their interplay); then, specific risks are characterised, usually arising from a complex interplay of several factors (i.e. migration and/or leakage mechanisms, geochemical and -physical reactions, relevance for ecosphere and humans, etc.). In fact, not all possible interactions leading to risks will be analyzed, as the number of possible combinations is abundant. Knowing the basic mechanisms and actual risks, however, should suffice to gain an impression of the risks involved in CCGS and allows to combine a large number of possible processes and interactions that may lead to specific risks. Then, building on this knowledge, the global risks of CCGS will be discussed. A brief analysis of the social distribution of risks of CCGS will be added.

The next section discusses the impacts of CO_2 can generally have on human health and ecosystems. After that, the risks which have been observed in some analogical processes (natural CO_2 occurrence, liquid waste disposal, natural gas storage, and nuclear waste storage) will be discussed. The rest of the subchapter is dedicated to analyses of the risks of CO_2 capture and storage and will follow the basic outline developed in the previous paragraphs.

2.4.2 Impacts of CO_2 on human health, animals and plants

At normal concentrations, CO_2 is generally regarded non-toxic for humans, animals and plants. It is odorless and colorless and therefore not detectable without technical devices, unless substances are added that render it perceptible. For example, mercaptans can be added analogically to natural gas handling, where this allows for detecting the highly inflammable gas by its smell. Experience at the Weyburn project suggests that adding mercaptans to CO_2 has a positive impact on leak detection. [Gale and Davison 2003]

In general, CO_2 is part of the biological processes of all living things. Different forms of life respond to hazardous CO_2 concentrations mainly due to physiological respiratory processes and pH level changes. Normal ambient atmospheric concentrations of CO_2 today are about 370 ppm. Humans can tolerate concentrations up to 10,000 ppm (1%) CO_2 with no physiological effect. Physiological adaptation without adverse consequences is possible until 3% (30,000 ppm). Significant effects on respiration and feeling of discomfort arise at concentration levels between 3-5%. Physical and mental ability is impaired and loss of consciousness can occur at concentrations above 5%. At more than 10% concentration, prolonged exposure leads to severe symptoms including rapid loss of consciousness, coma, or death. Several breaths of concentrations above 25 and 30% lead to immediate loss of consciousness and death. Depending on age and physical constitution there are variations in the response to elevated CO_2 concentrations. [Benson et al. 2002, 1-2; 19-22]

US federal occupational safety and health regulations set three limits to CO_2 exposure: 0,5% for an average 8-hour day or 40-hour week, 3% for a 15-minute exposure limit, and 4% as the maximum instantaneous exposure limit above which immediate danger to life and health is assumed. [Benson et al. 2002, 3]

Animals and plants show varying tolerance to CO_2 exposure, to some extent depending on their evolutionary adaptation to their ecological niche. Plants, insects and soil-dwelling organisms have a relatively higher tolerance to CO_2. However, all air-breathing animals have similar respiratory physiology, and prolonged exposure to CO_2-levels above 20-30% will kill most forms of life except some microbes, invertebrates, fungi, and insects. The identity and physiology of microorganisms in the deep subsurface is unknown, and therefore the effects of CO_2 exposure on these are uncertain. [Benson et al. 2002, 2, 22-30]

The local impacts of slower rises in CO_2-concentration levels are currently being investigated (in the context of global climate change research), but so far no clear insights have been derived. The impact of higher CO_2 concentrations (20-30%) on vegetation have been subject to research at Mammoth Mountain, California, where natural CO_2 outgassing has lead to tree killing, but the precise mechanisms involved are poorly understood. [Benson et al. 2002, 2; 29]

As CO_2 is denser and heavier than air, it is especially dangerous when it can accumulate in low lying, confined or poorly ventilated spaces. While the handling of compressed CO_2 is standard industrial procedure, fatalities stemming from fire-system malfunctions and confined-space accidents in industry show that there are significant related hazards. [Benson et al. 2002, 2; Holloway et al. 1996, 118]

2.4.3 Analogues

Natural analogues

Carbon dioxide is contained in CO_2-, natural gas, and oil reservoirs all over the world. One in ten oil and/or gas fields contains 1-5% CO_2, and one in a hundred contains 50% CO_2. [Damen et al. 2003, 11] High concentrations (>10%) of CO_2 at such locations usually stem from magmatic sources, while lower concentrations are attributed to the decomposition of organic matter and carbonate rocks. Effective trapping of CO_2 occurs in the same type of formations that contain hydrocarbons, that is, sedimentary rocks overlain by low permeability strata. A literature review conducted by Benson et al. [2002] found no event of naturally occuring catastrophic release from conventional hydrocarbon or gas reservoirs. Over geological timescales, however, all hydrocarbon reservoirs (whether oil or gas) are principally thought to leak. [Benson et al. 2002, 4]

Recovery of CO_2 for commercial purposes (mainly EOR operations) is conducted at several sites in the USA, Hungary and Turkey. At the world's largest supply formation in the USA, the McElmo Dome, commercial recovery of CO_2 has been conducted since 1984. As of January 1st, 2001, the field produces ~14.6 million tons of CO_2 per year from 41 wells. An alarm system is installed to alert the local community if a CO_2 leakage occurs. No leakage affecting local communities has been reported. At another major CO_2 recovery operation at Sheep Mountain Field in Southern Colorado, a well blow out occurred in 1982 (no report on consequences is given by Stevens et al. [2001]), and CO_2 was found to be blowing out of surface fractures on the west slope of Little Sheep Mountain, directly above a drill site. [Stevens et al. 2001]

Events of carbon dioxide release from other natural sources than CO_2 removal operations or hydrocarbon reservoirs can be divided into two categories. The first category includes diffuse off-gassing processes stemming from earth degassing (e.g., soda springs), biological respiration, and organic matter decomposition. These processes do hardly ever lead to reported fatal or catastrophical consequences. The second category comprises CO_2 leaks that usually result from volcanic or tectonic activity and the often associated geological fractures.

Such events can lead to locally elevated CO_2 concentrations, in the worst case catastrophies. [Holloway 1997b; Benson et al. 2002, 4]

The most often cited example for diffuse outgassing of CO_2 is Mammoth Mountain in California, where tree killing is incurred by daily fluxes of >1,200t CO_2 per day through ~30 hectares of soil. The flux of CO_2 became apparent when a US Forest Ranger reported symptoms of asphyxia when entering a small snow-covered cabin in the region. A survey of confined spaces in the area found CO_2 levels of >1% in campsite lavatories and small tents, 25% in a small cabin, and 89% in a utility vault with 0.6m diameter and 1m depth. [Holloway 1997b, 243] Tourists that were on holiday for skiing and staying overnight in a cabin at Mammoth Mountain died of suffocation due to increased concentrations of CO_2. [Greenpeace 2004a] The local campsite has been closed. [Farrar et al. 1995] The impacts of the Mammoth Mountain outgassing on the local ecology will be discussed in section 2.4.7.

Naturally carbonated springs constitute another example for diffuse off-gassing. They can be hazardous when found in caves, for example. In the 1948 eruption of Hekla (Iceland), eight sheep and a fox were asphyxated when entering invisible ponds of CO_2 that had formed at night in depressions of the ground surface. The ponds contained a 2m thick layer of air containing 40% CO_2. [Holloway 1997b, 242]

Next, a catastrophic release of CO_2 will be discussed. Lake Nyos in Cameroon is a deep tropical crater lake that routinely becomes supersaturated with CO_2 that probably stems from magmatic sources at its bottom. As tropical lakes do not turn over and the water layers are stratified, that is, they do not mix, the CO_2 accumulates at depth, thus increasing the density of the water, which contributes to further stratification of the water structure. This situation is unremarkable until there is a significant disturbance such as an earthquake or landslide, or the bottom waters reach supersaturation and CO_2 spontaneously begins to bubble up. Such an event is called limnic eruption. It is unknown exactly which of these mechanisms triggered the catastrophe at Lake Nyos in 1986, but in an explosion causing waves of 20-80m height (Zhang 1996 calculates lake-surface exit speeds of ~89m/s), about 0.25 Mt of CO_2 were suddenly released from the lake and spilled down a valley through the drainage system of the lake. On its way and within 4 ½ hours, the carbon dioxide caused damage to the vegetation, killed insects, birds, and animals (over 3,000 cattle), before reaching a village. 1,746 people died, and 846 were injured. Many of the victims exhibited large blisters and skin loss that remain unexplained. Fatalities occurred up to 14km away from the lake. The last victims were killed 24h after the incident when walking into low lying or confined areas, where CO_2 had accumulated. The carbon dioxide dispersed as soon as it reached an open valley. [Clarke 2001; Zhang 1996; Benson et al. 2002, 55-57; 17; Holloway 1997b, 243-244; for more details on the Lake Nyos event, see LeGuern and Sigvaldson 1989]

37 people were killed in a similar incident at Lake Monoun, Cameroon on August 15-16, 1984. The origin of this gas burst was assigned to a landslide on a land margin, causing the lake water to overturn and emit dissolved CO_2. [Holloway 1997b, 244]

Another CO_2-related catastrophe occurred at the Dieng volcano (Central Java, Indonesia), where in February 1979, during an eruption of the volcano, a large outflow of pure CO_2 from an existing volcanic vent killed 142 people fleeing from the eruption. There are persistent CO_2 emissions on the Dieng Plateau, destroying surrounding vegetation, and local people are aware of ‘Death Valleys’. Four workers were killed by CO_2 at a geothermal well near the volcano in February, 1988. [Holloway 1997b, 243]

Benson et al. [2002, 4] remark that the amounts of CO_2 involved at Lake Nyos and other natural disasters were small in comparison to the amounts that might be injected in CCGS operations. On the other hand, the amounts of CO_2 released in volcanic eruptures are considerable (e.g., a single eruption of Mt. Pinatubo in 1991 ejected about 42 Mt CO_2) but pose no direct hazard for humans or other forms of life due to dispersion high in the atmosphere. Therefore, Benson et al. [2002, 5] conclude that the catastrophic potential of CO_2 release is mainly determined by the nature of the release and subsequent levels of concentration and dispersion rather than the total amounts of CO_2 out-gassing. For example, low lying and confined spaces that restrict dispersion of leaking CO_2 represent the most dangerous settings in case of considerable leakage, due to their potential for accumulation of CO_2.

It can be concluded that leaking CO_2 can constitute a serious threat if ambient conditions allow for its accumulation (e.g. confined spaces, valleys). Subsurface storage of CO_2 might therefore pose a risk in populated areas, and surface conditions should allow for sufficient dispersion of leaking CO_2 in order to prevent hazardous concentrations from accumulating. [Holloway 1997b, 243; Benson et al. 2002, 5]

Liquid waste injection

Industrial waste was reportedly injected underground for the first time in 1939 by Dow Chemical. Early performance of these wells was mixed: many well failures and drinking water contaminations occurred. According to Benson et al. [2002, 6], failures were mainly attributed to (i) poor characterization of the confining units, (ii) improper well completion technology, (iii) use of well construction materials that corroded when exposed to the waste stream, (iv) inconsistent or inadequate monitoring, and (v) leakage through abandoned wells. Leaks related to injection activity and abandoned wells were identified to be the most frequent short-term failure mechanims. Regulations were updated in 1988 in order to meet these shortcomings, and according to Benson et al. [2002, 6] no incidents of drinking water contamination have been reported since.

In Florida[19] 0.5 Gt lightly treated municipal wastewater are injected annually into porous sediments at 104 injection wells. The injection operations are regulated as non-hazardous class I well activities under US EPA regulations.[20] Underground injection of wastewater is analogous to that of CO_2 with two respects: first because of the large quantities involved, and second because the sewage, like CO_2, is less dense than the surrounding fluids and has an upwards buoyancy.[21] Soon after commencement of the injection operations wastewater was found to have migrated into shallow drinking water aquifers at three monitoring sites. The reasons were mainly considered to be malpractice in site characterization (e.g., insufficient confinement[22]) and well drilling (some wells were finished *above* the USDW, which constitutes a clear violation of EPA regulation, as wastewater was now being injected

[19] Florida is the only US state to inject municipal sewage into geological formations.
[20] For an overview of current US underground injection regulation, see appendix A.
[21] CO_2 has a higher upwards buoyancy than sewage. [Wilson et al. 2003, 3480-3481]
[22] The confining cap rock is a thin impermeable dolomite horizon, approximately 4.6m thick.

directly into the USDW; furthermore, the confinement unit was punctured by failed drilling attempts). The contaminations of the USDW are in conflict with US drinking water regulation which mandates a strict zero-contamination policy. However, proponents of wastewater injection argue that impacts of these leakages are only small, and EPA has therefore proposed to allow for some leakage, as long as it is not considered to constitute a 'significant' pollution of USDWs. This has been challenged by environmental groups. The outcome of this issue is currently uncertain. Benson et al. [2002, 101] remark that these problems could have been avoided if the more restrictive and costly regulation scheme for Class I hazardous wells had been applied in the first place. [Benson et al. 2002, 96-102; Wilson et al., 2003, 3480-3481; Smith 2004, 37-38]

Natural gas storage

Benson et al. [2002, 7-8] summarize their investigation of natural gas storage analogues for CCGS with the notion that "underground natural gas storage projects have been operated successfully in the US for almost 90 years", and "modern procedures have made underground natural gas storage a safe and efficient operation". They state that hardly any published information on accidents or problems related to natural gas storage does exist and conclude that the operations can be regarded to be safe. [Benson et al. 2002, 118]

However, their analyses of six accidents at natural gas storage facilities indicate that lack of compiled information does not necessarily imply a lack of problematic incidents. At Hutchinson (Kansas), for example, on January 17th 2001 natural gas probably stemming from the Yaggi natural gas storage facility located 7 miles away from the city centre built up under and erupted at many sites in and around the city centre, often through abandoned wells that had long been forgotten. Explosions killed two people and destroyed downtown businesses; hundreds of people had to be evacuated. Businesses experienced losses of several million dollars. [Heinrich et al. 2003, 23] Half a year after the incident, the reasons for the incident were still unclear, but most likely a damaged injection well led to leakage and lateral migration of natural gas, and old abandoned (e.g., water-) wells (which had not been marked in maps) provided pathways for the eruptions. Benson et al. [2002, 118-119] received the information concerning this incident from newspaper articles.[23]

The technological standard of german natural gas storage facilities is considered to be internationally leading. [Sedlacek 2003, 402] However, in Berlin, Germany, an explosion occurred on March 23rd 2004 at a natural gas storage site operated by Gasag due to leakage resulting from maintenance operations using a novel chemical cleaning agent. A 30m high explosive flame wreaked life threatening burnings on three workers. [Berliner Zeitung 2004a, 2004b, 2004c]

In general, overpressurization is considered to be the main cause of leakage from natural gas reservoirs. More specifically, well failure (breaks in the casings, joints, defective cementing of casings), fractures, faults, and solution cavities that permit upwards gas movement through the seal are the most common leakage mechanisms. [Lippmann and Benson 2002]

---

[23] Allison [2001] provides a thorough account of the Hutchinson events. However, the geological explanations for the event remain hypothetical. The processes that caused the incident are not understood until today. A webpage on the incident and related activities is maintained by Kansas Geological survey and available at http://www.kgs.ukans.edu/Hydro/Hutch/

Nuclear waste storage

Nuclear waste disposal constitutes an interesting analogy to geological injection of CO_2 as it also involves the issue of long-term storage of unwanted and potentially harmful substances. However, considerable differences exist in the specific mechanisms of toxicity of the two applications. [Damen et al. 2003, 13] Although it may be worthwhile from a sociological point of view, I will not engage in a thorough discussion of the analogies between CCGS and nuclear waste storage, as this would exceed the scope of this thesis. Instead, the focus is on two issues. First, the determination of an 'acceptable leakage rate', and second the timescale for monitoring.

The issue of an 'acceptable leakage rate' from the storage site has given rise to considerable controversy in the discussion about final storage of nuclear wastes. As storage integrity in the long-term (>10,000 years) of both nuclear wastes and CO_2 can not be guaranteed (actually, some leakage is expected and readily accepted by site operators in both cases, see e.g. Benson et al. [2002, 9]), the affected social communities should participate in the definition of an acceptable leakage rate. This is an evaluative process that cannot be decided by "objective" scientific investigation. Some groups or societies may find that the acceptable level of risk of leakage of a waste should be 0%; in this case, a community may decide not to implement the respective process at all. Other communities may find risks larger than 0% for certain leakage rates acceptable, thus possibly allowing for the employment of the technology producing these risks.

The second issue relates to the timescale of monitoring nuclear waste storage projects. At the US WIPP[24] project for example, monitoring is expected to last 100 years after site closure, depending on compliance of monitoring data with data projected by modeling exercises.[25] These modeling exercises, however, are subject to considerable uncertainties. Similar problems arise in long-term monitoring and modeling of CO_2 behavior in geological formations. [Benson et al. 2002, 9-10; 123-135]

2.4.4 Risks of CO_2 capture and transport

Having discussed some risk analogies to CCGS, this and the following sections will focus on analyzing the specific risks and mechanisms of CO_2 capture, tranport and storage.

Capture

If MEA absorption is to become a standard approach for capturing CO_2, it has to be taken into account that considerable quantities of degraded MEA will have to be disposed of in an environmentally sound way. In addition, substantial amounts of the absorbent will be emitted along with the flue gas. Bauer [2005, Ch.5] reviewed several studies of absorption processes and found that MEA losses of 1.6-2kg (at a price of US$ 0.97 per kg MEA) per ton CO_2 captured are reported. Desideri and Paolucci [1999] find that a 237MW coal power plant would need 2740t MEA per year, some of which would be emitted to the atmosphere. Audus

[24] Wate Isolation Pilot Plant, one of two world-wide permitted long-term storage sites for radioactive wastes.

[25] Nearby ecological systems will be monitored for an unspecified "number of years" [Benson et al. 2002, 133] after site closure.

[2000] states that the quantities involved are speculative but he suggests that the losses at a 500MW gas-fired power station could be ~2000t/y sludge formed by decomposed amines,[26] and about 10t/y of carry-over in the flue gas. The environmental and health implications of both phenomena are not understood.

Another drawback of the MEA absorption approach is that high concentrations of MEA involve considerable danger of material corrosion which can imply plant downtimes, production losses, need of maintenance of equipment and even injury and death of working personnel. [Veawab et al. 2001]

Another noteworthy aspect of the capture step is that toxic substances may be captured and processed along with the CO_2. This could be problematic in later process steps and will therefore be treated at more detail below.

Transport

The risk resulting from transportation of CO_2 by pipelines is constituted by the chance of leakage and the adverse impacts of elevated concentrations of CO_2 on humans, animals and the ecosphere. Several model estimates on the local impacts of leakage as well as historical performance records of natural gas pipelines are presented and discussed in this subsection.

Holloway et al. [1996, 120-121] calculated possible scenarios in case of damage of a 250mm CO_2 pipeline. The total amount of liquid CO_2 contained between two adjacent isolation valves in such a pipeline would be about 3,000 t (~1,500,000 Nm^3). Three definitions of pipe defects are given:

- pinhole or crack: defects with a diameter up to 20mm.
- hole: defects with a diameter from 20mm to pipe radius (125mm).
- rupture: defects with a diameter larger than the pipe radius (125mm).

In case of a pinhole or crack, CO_2 would escape at a rate of up to ~6 kg/s and it would take about 150 hours to discharge all CO_2 contained in the concerned section of the pipe. At this rate, the carbon dioxide would probably disperse into the surrounding air without accumulation.

Failures of the hole category would lead to release rates of ~6 kg/s to ~240 kg/s. The CO_2 would be released within a period ranging from 150 to 3.5 hours.

A pipeline rupture would involve hole diameters between 125mm and 250mm. CO_2 would be released at a rate of up to 10 t/s and the CO_2 of one pipe section might be discharged in with 10 minutes. Such a process is properly termed an explosion, which in case of a buried pipeline would cause the overlying soil being abruptly pushed through the air, possibly causing damages. 67% of the carbon dioxide would be released in the vapour phase, 30% as solid CO_2 snow at the site of the rupture (occupying ~7400m^3), and 3% would remain as CO_2 snow inside the pipe. The temperature resulting from the rapid expansion of liquid CO_2 to atmospheric pressure would be –56°C. It is obvious that a reduced distance between (costly) safety valves would decrease the amount of CO_2 released in an accident. However, safety

[26] Recent research suggests that MEA degradation depends on the quality of the flue gas, that is, degradation is higher at a coal power plant that at a natural gas combusting facility. [Wilson et al. 2004b]

valves are a major source of pipeline failure themselves. Therefore, there is no simple trade-off between safety and costs. [Holloway et al. 1996, 120-121; Gale and Davison 2002; Kruse and Tekiela 1996]

In another model, the dispersion of CO_2 from a 10mm hole in a 1m diameter pipeline (1.5 kg/s discharge rate) at wind speeds of 1 m/s and 10 m/s was simulated. Dangerous concentrations of CO_2 (3-5%) were reached at ground level within 50m of the source. [Holloway et al. 1996, 121]

An analysis of European gas pipeline performance revealed that between 1970 and 1987, in a length-time period of ~970,000 km*years, a total of 664 incidents occurred. [Holloway et al. 1996, 121] The following typical reasons for pipeline failure were identified:

- External interference: breach of the transmission pipeline by some external agency, e.g. accident or agricultural activity.
- Hot tapping: breaches of the pipe by utility workers mistaking the pipe for e.g. a water pipe.
- Corrosion (more prevalent in older pipes).[27]
- Construction defect (including defects in materials; prevalent in pipes constructed before 1970)
- Ground movement (only in areas of high geological activity)

The numbers of incidents by reasons and orders of magnitude are displayed in Table 2.3. In general, larger pipes are much less prone to damage by external interference. More specifically, for a 250mm diameter pipeline 60 ruptures per million km*years can be inferred from existing data, which is 70% of the average value of 89 ruptures for all pipeline types.

*Table 2.3: Natural gas pipeline failures in Europe during ~1 million km*years in the period 1970-1987. Source: Holloway et al. [1996, 121], citing Pipes and Pipelines International [1988].*

Cause	Pinhole	Hole	Rupture	Total
External Interference	70	170	89	329
Hot tapping	12	10	0	22
Corrosion	100	2	1	103
Construction defect	74	37	11	122
Ground movement	6	15	13	34
Other	44	4	6	54
Total	306	238	120	664

Gale and Davison [2003] summarized pipeline incidents in the USA between 1986 and 2001 for natural gas and hazardous liquids pipelines and compared them to incidents at US CO_2 pipelines. Corresponding fatalities, injuries and property damages are also given (see Table

[27] State-of-the-art CO_2 pipelines are thought to be hardly prone to corrosion. [Heinrich et al. 2003, 7, citing a personal interview with S. Wehner from Kinder Morgan CO2 company, 2002]

2.4). To put these numbers into perspective, in the USA in 2000 there were ~514,000km natural gas transmission pipelines, ~248,000km hazardous liquid pipelines, and ~2,800km CO_2 pipelines.

Table 2.4: Statistics of pipeline incidents in the USA. Source: Gale and Davison [2003].

Pipelines	Natural gas (1986-2001)	Hazardous liquids (1986-2001)	CO_2 (1990-2001)
Incidents	1287	3035	10
Fatalities	58	36	0
Injuries	217	249	0
Property Damage (mill. US$)	285	764	0.469
Incidents per 1000km pipeline per year	0.17	0.82	0.32
Property damage per 1000km pipeline per year (US$)	37,000	205,400	15,200

While it is difficult to draw general conclusions due to the shorter pipeline network and hence lower total numbers of incidents for CO_2 pipelines, it seems appropriate to assume that CO_2 pipelines are roughly as prone to incidents as natural gas and hazardous liquid pipelines. Property damage payments will constitute a cost factor of CO_2 pipelines, although it appears difficult to derive specific numbers from the data presented here. 94 people have been killed, and 466 were injured in 15 years of natural gas and hazardous liquid pipeline operations. While no injuries or fatalities from a CO_2 pipeline have been reported, it must be taken into account that current CO_2 pipelines in the USA are mainly sited in unpopulated areas. [Gale and Davison 2003] If taking into account the model simulations above and population densities of Europe, for example, it appears reasonable to assume that despite (or due to) the different nature of CO_2, people will be killed in CO_2 pipeline incidents if their network is extended due to large-scale implementation of CCGS.

The Union of Concerned Scientists remarks that setting up and maintaining an extensive pipeline network and the associated facilities does involve considerable adverse environmental impacts. [Union of Concerned Scientists, 2002,4]

It is worth noting that in the US the Department of Transportation Office of Pipeline Safety funds a range of activities including enforcement programmes, state pipeline safety programmes and R&D for natural gas and hazardous waste pipelines. Expenditure from the fund has been US$ ~47 million in fiscal year 2001. [Rothberg and Hassan 2002]

2.4.5 Injection

Surface installation and well preparation

There are some risks associated with the surface structures required for CO_2 injection. These include leaking connectors and appendages, unsuitable and leaking materials, unsuitable construction and execution, decay of materials through time and external damage to pipes caused by, for example, digging or building activities. However, in the event of a destructive failure of the surface system, only a small quantity of CO_2 should be released to the atmosphere, as routinely applied automatic failure detection systems should shut-down the failing subsystem, and safety-valves can be implemented to decrease the overall risks. Generally, the presence of H_2S in the CO_2 stream would increase the risk of material failure in case inappropriate materials are used. [Holloway et al. 1996, 123]

When drilling an injection well, it is crucial that the cementing around the casing has a high quality especially at the cap rock, in order to prevent degrading reaction of CO_2 with the cement which ultimately might lead to leakage to overburden formations. It is also crucial that no faults or fractures intersect the borehole, because this may lead to casing collapse in the event of seismic activity. [Holloway et al. 1996, 124; 136]

Injection phase

The packer, back flow preventer and especially the emergency shutdown valve inside the injection well should prevent the injected CO_2 from emerging the reservoir through the injection well during the injection phase. Failure of all of these safety mechanisms would lead to well blow-out, implying large sudden releases of CO_2 and the related risks to humans and ecosystem around the well. [Holloway et al. 1996, 124] In general, the overall operational risk of injection will increase with the number of wells used. [Stenhouse et al. 2004, 5]

Operators will have to demonstrate their ability to deal with these issues through modeling exercises. All of these issues have been dealt with in gas and oil production in the past, but it is expected that GS will have to meet more rigorous requirements. [Stenhouse et al. 2004, 5]

During the first years after injection a reservoir will be overpressured which implies increased risks of leakage from the injection well. This is due to the higher strains imposed on the well and surrounding geological structures. Therefore, Stenhouse et al. [2004, 5] propose to monitor the injection well at least until the pressure in the injection zone has decreased.

However, geochemical interactions between the CO_2, reservoir fluids and the well cement may impose long-term risks for disintegration of the cement[28] and would, in fact, increase with storage time. This latter risk would then develop counter current to the former (overpressurization), rendering the decision for an optimal monitoring scheme more difficult.

2.4.6 In-situ migration and surface leakage mechanims

It is widely believed that in case of an hermetically sealed cap rock and overburden geological layers with a very low-permeability, upward molecular diffusion of CO_2 from a reservoir would take several thousands of years. [Holloway et al. 1996, 151-159; summarizing: Gale 2003]

[28] Bennaceur [2004, 16] from Schlumberger states that current cementing practices (for US class I and II wells) do not address long-term storage requirements of CO_2, and that they might pose a significant risk of leakage.

However, several mechanisms can disturb the impermeability of the confining strata. In addition, other mechanisms including horizontal mobility of CO_2 and formation fluids may render in-situ migration and surface leakage of CO_2 (and other substances) possible. Such processes will be described in the following subsections.

It is generally worth noting that depending on its in-situ location, the injected CO_2 will remain in a supercritical phase below 800m, switch to gaseous form when migrating above 800m depth (involving expansion in volume), and can in any state mix and migrate along with other substances (e.g., H_2O, CH_4).

In addition, it is possible that CO_2 leaking out of a reservoir slowly due to one or several of the processes described below will accumulate in shallow formations (karst caverns) and leak out abruptly due to another of the following mechanisms. [Wilson et al. 2003, 3477]

Fractures and faults

Fractures are planes along which a rock lost its cohesion. Distinction is made between fractures with or without offset by shearing along the fracture surface. Faults are fractures along which there is visible offset. Faulting occurs under compressive stress. Different kinds of faults are distinguished depending on the direction of displacement and compression mechanisms. [see Holloway et al. 1996, 128]

Joints are surfaces along which there has been imperceptible movement. Joints can be generated by tensional stresses, e.g. from rock shrinkage due to dehydration (for example, mud cracks) or cooling. Open, unfilled joints are called fissures that allow for penetration of the formation by surface water, for example. Fissures can be filled by rock particles. Under natural circumstances, fissures will not be formed in the deeper subsurface. Holloway et al. [1996, 129] terms joints to be a special case of fractures, and here only the terms fractures and faults will be used. [Holloway et al. 1996, 128-129]

Fractures can be induced by CO_2 injection operations if the injection rates are too high and injection zone or reservoir pressures exceed tolerable values. While fractures within the reservoir might actually enhance reservoir performance due to increased permeability (this is routinely applied in order to enhance oil and gas production), it is vital that the integrity of the cap rock is not affected. This would allow migration of CO_2 and/or brine to adjacent formations. [Holloway et al. 1996, 129]

Holloway et al. [1996, 129-130] identify three mechanisms that can reduce the permeability of faults. These are (a) clay-smearing, which involves the smearing of the fault plane by clay present in the formation; (b) cataclase (grain-pulverization) leading to the formation of gouge or mylonite (=milled rock), thus reducing the permeability of the fault zone; and (c) mineral precipitation, which refers to cementation of secondary mineral deposits in the open pore space in the fault, thus rendering the fault impermeable. Open fractures that are filled are commonly known as veins.

It is worth noting that Holloway et al. [1996, 130] remark that it is difficult to determine the exact location of faults and to establish the sealing capacity of the entire fault plane. Present 3-D seismic data allow for the location of faults on a scale of several meters, only. It is considered difficult if impossible to assess the overall sealing performance of a fault plane, which is commonly done by taking some core samples of the plane and extrapolation of the results. The integrity of fault planes can vary considerably.

Examples for outgassing of CO_2 through fractures include volcanic sources, for example in the carbogaseous perialpin province including the Perrier, Vichy and Badoit formations. [Stevens et al. 2001]

Cap rock failure

The most obvious migration and leakage mechanism would be cap rock failure. Several processes could lead to cap rock failure, including fracturing, capillary leakage, molecular diffusion, and changes in the cap rock structure due to geochemical interactions. The basic mechanisms involved in fracturing have been discussed in the previous subsection. It is worth noting that if faulting occurs at the highest point of a cap rock seal, CO_2 migrating towards this point due to its strong buoyancy could migrate several km before leaking through the fault. This process is displayed in Figure 2.2, which shows results of a simulated CO_2 injection operation at the Carnarvon Basin aquifer, located off-shore Western Australia. [Ennis-King et al. 2004] It was assumed that 4.7Mt/y would be injected over 20 years. The impermeable cap rock has an updip angle of 2.5°, and 30km away from the injection site on the top end of this slope there is a major fault. A high aquifer permeability was assumed, and while some CO_2 dissolved, considerable amounts remained as a very mobile plume of supercritical CO_2. 30 years after start of the operations this plume would reach the fault due to considerable migration speed (~1km per year).

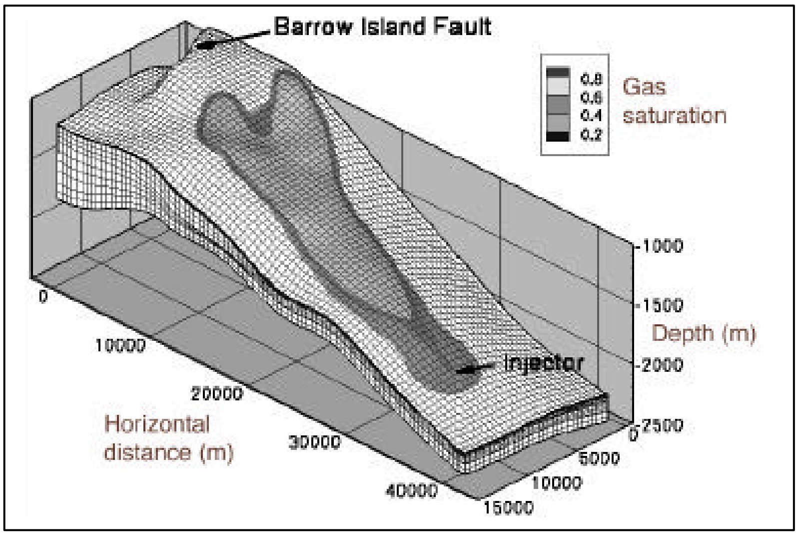

Figure 2.2: Simulated CO_2 migration in Carnarvon Basin aquifer toward a fault in the cap rock. Source: Ennis-King et al. [2004].

Capillary leakage occurs when the pressure of the fluid phase adjacent to the cap rock is higher than the capillary entry pressure of the cap rock. In this case, CO_2 might slowly migrate through the rock. It is considered to be unlikely that this will occur, and the timescale involved render it unlikely that this process will be of significance. [Jimenez and Chalaturnyk 2003]

Molecular diffusion through the cap rock refers to the migration of fluids from areas of high fluid concentration to areas of low fluid concentration. Diffusion is inevitable, but a very slow process. It will take place over geological timescales. The relevance for CCGS operations remains to be clarified. [Jimenez and Chalaturnyk 2003]

Geochemical interaction of CO_2 with the cap rock might cause the cap rock to dissolve. This would increase the cap rock permeability (and the likelihood of fractures, capillary leakage, and molecular diffusion). Geochemical depreciation of the cap rock depends on cap rock properties, formation fluids and CO_2 behavior. Some research activities suggests that for an appropriate cap rock this process should not be a problem. [Jimenez and Chalaturnyk 2003; Okamoto et al. 2003; SACS 2003]

Diffuse outgassing through soil could result from cap rock failure. Soil gas measurements taken at the Rangely Weber oil field, where CO_2 is injected for EOR, indicates that about 3,800t/y of CO_2 leak out of the reservoir over an area of 78 km^2, which corresponds to 0.012% of the overall annual CO_2 injection rate. The mechanisms involved are not understood. [Klusman 2003; Damen et al. 2003, 7]

Brine flow

Brine contained in aquifers naturally flows at a slow pace, usually 1-10cm/y. [Bachu et al. 1994] Injected supercritical CO_2 will migrate either (a) along with or (b) within these brine currents. In the former case (a) CO_2 will be dissolved in brine which is an intended effect in order to (i) displace the injected CO_2 from the injection zone, thus increasing injection capacity, and (ii) to enhance the storage safety of CO_2 (hydrodynamic trapping). In the latter case (b) supercritical CO_2 bubbles that do not dissolve would migrate upwards towards the highest point of the cap rock driven by their buoyancy, possibly for several hundred meters and kilometers. [SACS 2003] Wilson et al. [2004a, 2], for example, calculate that a CO_2 bubble in an aquifer might spread up to 100km^2.

The injection of CO_2 might also cause migration of brine towards adjacent formations due to increased brine reservoir pressures and migration pathways like faults, fractures, boreholes, etc.

Migration through spill point

A spill point refers to the structurally lowest point of a curved cap rock of a depleted gas or oil field. When a hydrocarbon trap has been filled to its spill point, all additionally injected substances will not be confined within the trap but will migrate into (first horizontally, then possibly vertically) adjacent structures.

Seismicity

The occurrence of (micro) earth tremors due to CO_2 injection is in itself an undesirable event. In addition, it could lead to migration of CO_2 and/or fluids through emerging fractures.

Two kinds of seismicity relevant for the geological storage of CO_2 can be distinguished: naturally occurring seismicity due to tectonical processes, and induced seismicity resulting from CO_2 injection. While naturally occuring seismicity is an important issue in tectonically active regions, e.g. Japan and California, the focus here will be on induced seismicity. [Damen et al. 2003, 4]

Examples of induced seismicity are common in many fields, including rock withdrawal in mines, artificial reservoir impoundments (e.g., dams), hydrocarbon extraction in oil or gas fields, deep-well fluid waste injection, or re-injection of geothermal production. The injection of large amounts of a fluid modifies the mechanical state of a sediment layer or fractured rock due to changes in reservoir pressure. High pore-pressure gradients in or around the reservoir may induce micro- or even damaging earthquakes. The process may be enhanced by contraction of the rocks due to cooling by 'cold' injection fluids. In general, structures with already existing fractures are considered to be more prone to induced seismicity. Seismicity could lead to the formation of faults or fractures that allow for the migration of subsurface fluids, e.g. supercritical CO_2. [Holloway et al. 1996, 119 ; 128; Damen et al. 2003, 10]

At the Rocky Mountain Arsenal well (Colorado, USA) maintained by the US army, 625,000m^3 of fluid waste have been injected during discontinuous periods from 1962 to 1966. The injection took place into a highly fractured Precambrian Gneiss at 3650m depth. The last earthquake before injection had occurred in 1882, at a magnitude around 5. Between April 1962, shortly after the start of the injection programme, and August 1967, more than 1,500 earthquakes were recorded. Some exceeded magnitudes of 3-4, and in 1967 three major earthquakes each with a magnitude greater than 5 occurred caused minor damages at surface facilities. Injection activities were terminated in 1966. The seismic activity continued on a lower level until the mid-eighties, when it virtually ceased.[29] [Holloway et al. 1996, 130-131; Perrow 1992, 290-291]

Holloway et al. [1996, 128] remark that damaging earthquakes have been detected in and around hydrocarbon reservoirs after some tens of years of exploitation. Even if final evaluation of seismic hazards after termination of injection operation shows that it is an irrelevant side-effect, the long term aspect should not be neglected.[30]

Ground movement

Subsidence or rise of the earth surface (absidence) could occur as a consequence of pressure changes induced by CO_2 injection. Several cases of subsidence have been documented mainly during exploitation of oil and gas fields. [Holloway et al. 1996, 119]

Another mechanism for subsidence at CO_2 injection operations are chemical reactions between aqueous CO_2 and the cap rock, possibly causing dissolution (chemical compaction) of the cap rock; as a consequence, the reservoir may cave in under the weight of the overburden formation. Prediction of subsidence is found to be difficult. It is considered to be an unlikely event. [Holloway et al. 1996, 119]

Absidence (rise of earth surface) could occur if storage pressure would exceed overburden pressure, but this event is considered to be unlikely. [Holloway et al. 1996, 119]

In reservoirs under high tectonic stress, reduction of the grain pressure (which acts between individual rock particles, and against the overburden pressure) may trigger faults. This may

[29] For more examples of induced seismicity, see Holloway et al. [1996, 130-135].

[30] An induced earthquake bibliography is available at the internet. [Cypser 2004]

lead to uplifting or down-faulting of the surface, depending on the nature of the local tectonic regime. [Holloway et al. 1996, 119]

Leakage through abandoned wells

Leakage through abandoned wells can either occur through the wells that have been used for CO_2 injection, or through older wells which have already been in place before the CO_2 injection operations.

In general, disintegration of the well casing or deterioration of well cement due to geochemical processes constitute the main risks of abandoned wells. Combined with increases in reservoir pressure, inadequate well casing or cement material (esp. in case of older wells) could very likely corrode in a CO_2/H_2O environment which acts as an aggressive solvent, eventually leading to upward migration of CO_2 and/or brine. It is uncertain how well casing and cement will be affected by continuous (>100 years) exposure to CO_2. [Damen et al. 2003, 6; Jimenez and Chalaturnyk 2003; Celia and Bachu 2003; Allison 2001]

Also, older oil, gas and water wells have often been abandoned without proper closing procedures. In the Hutchinson gas explosions, natural gas burst out preferentially through wells that had been abandoned many years ago by simply putting some sand or rock into them, and which were sometimes located in the cellars of houses.[31] [Allison 2001]

In addition, especially abandoned oil and gas fields are often punctured by a large number of non-operative exploration and production wells, some of them in bad condition. In Texas, for example, a total of more than 1.5 million wells have been drilled. In the Province of Alberta, Canada, more than 350,000 wells have been drilled, and ~15,000 new wells are drilled every year. A single resevoir in the Alberta Basin, the Viking formation, is punctured by ~200,000 wells, resulting in 4 wells per km^2 in densely drilled areas. Celia et al. [2004] state that in geological CO_2 storage operations in Western Canada the injected CO_2 plumes are expected to contact several tens to several hundred existing injection wells. Aquifers have often been subject to exploration and production wellbore drilling as well. In addition, Jimenez and Chalaturnyk [2003] add that a wellbore must not necessarily penetrate the reservoir in order to constitute a potential leakage path. As long as there is hydraulic communication between the well and the reservoir, CO_2 may migrate along this path. [Celia and Bachu 2003; Damen et al. 2003, 6-7]

2.4.7 Local risks of CO_2 in-situ migration and surface leakage

After in-situ migration and leakage mechanisms have been described in the previous section, the following subsections will focus on features and impacts of problematic events that might be associated with CCGS.

[31] Allison [2001] also indicates that it is very difficult to localize these wells. It was attempted to map all abandoned wells in Hutchinson in order to avoid future accidents, but no feasible approach for localization is available.

Containment of toxic substances in the CO_2 stream

At some sources of CO_2 (e.g., coal power plants) the flue gas of CO_2-delivering facilities will often contain toxic substances (e.g., H_2S, SO_x, NO_x, and inorganic oxides[32]). Depending on the use of recovery technologies (e.g., MEA stripping, oxy-fuel approaches) and flue gas and/or CO_2 stream cleaning applications, the injected CO_2 stream may contain some of these toxic substances. [Celia and Bachu 2003; Wilson et al. 2004b] In case of subsurface migration or surface leakage, they could impose risks to ecosystems and/or humans, e.g. when migrating into potable groundwater aquifers, or into the soil, or towards the surface.

Mobilization of toxic substances

Subsurface CO_2 migration might lead to dissolution of minerals, heavy metals or organic compounds in the aqueous phase due to the strong solvent properties of supercritical and/or dissolved CO_2 in H_2O. Especially heavy metals are toxic already at low concentrations. The rates, likelihood, and potential significance of such mobilization processes are not well understood. Migration of heavy metals or other toxic substances might contaminate groundwater, soil or surface areas. [Benson et al. 2002, 30; Holloway et al. 1996, 267]

Impacts on soil and sub-soil ecosystems

Migrating CO_2 could diffuse through the soil if leakage from a geological reservoir occurs. At Mammoth Mountain, California, outgassing of >1,200t CO_2 per day stemming from magmatic processes through the soil is observed in an area of 30 hectares. Tree killings have been observed and are attributed to the elevated CO_2 concentrations in the soil. However, the precise mechanisms involved in the tree killing are not understood. Suppression of root-zone respiration via hypoxia, hypercapnia, or acidification of the soil environment are assumed to be the most likely causes. Long-term exposure (weeks or months) to 20% or more CO_2 in soil gas resulted in dead zones where no macroscopic flora survived. The distribution of effects in relation to observed CO_2 concentration levels suggests that 20-30% are a critical threshold for plants and ecosystems in general. [Farrar et al. 1995; Benson et al. 2002, 29]

[32] For example SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O and P_2O_5. [Bauer 2005, Ch.5]

Figure 2.3: Impact of soil outgassing of >1,200t CO_2 per day in a 30 hectar area on local ecosystems at Mammoth Mountain, California. Source: Friberg [2004].

Johnston and Santillo [2002, 105] remark that while surficial terrestrial systems have been extensively researched in terms of their microbial ecology and relations to other soil organisms, far less work has been carried out to investigate deep, sub-soil microbial communities and their ecological interactions. Their overall functions are unknown and subject to debate. Impacts upon these ecosystem due to CO_2 storage might be substantial, but the consequences are largely unknown. [Union of Concerned Scientists 2002, 12; Fredrickson and Onstott 1996]

Heinrich et al. [2003, 10] consider the risks for deep microbial communities to be neglible by citing Benson et al. [2002] (without a page specification). However, no statement rendering the related risks negligible is made by Benson et al. [2002]. Instead it is stated that

> "The distribution and physiology of microbes in the subsurface is not well known, so a projection of their response to elevated CO_2 is not yet possible […]. A survey of the range of known responses to CO_2 by a representative cross section of single-celled and colonial organisms would be useful." [Benson et al. 2002, 24]

In their executive summary, Benson et al. [2002, 2] point out that

> "the identity and physiology of microorganisms dwelling in deep geological formations is largely unknown, so the effects of CO_2 on subsurface microbes are uncertain."

In general, little knowledge is available on the impacts that CO_2 injection and migration may have on soil and sub-soil ecosystems. It is suggested that considerable research is required in this area. [Benson et al. 2002, 30]

Contamination of aquatic ecosystems

Although no literature on possible contaminations of surface aquatic ecosystems risks was found, it appears realistic that migration of CO_2, brine and/or other substances along with it (e.g., heavy metals, SO_x) into aquatic ecosystems such as rivers or lakes would have considerable impacts. CO_2 intrusion would change pH-level, and other substances are likely to cause harm to fish, plants and other living beings.

Contamination of groundwater

Potable groundwater aquifers are generally found in the top 100-200m of the subsurface. Potable groundwater must be fresh. Migrating CO_2 or displacement of brine fluids could lead to contamination of groundwater.

In principle, two potable groundwater contamination mechanisms can be distinguished. First, the groundwater pH-level could decrease due to CO_2 mixing with groundwater. Due to the low pressures and specific temperatures of ground water, intruding CO_2 would be in the gaseous phase. Second, substances in the CO_2 containing fluid and/or displaced saline brine water from adjacent formations might contaminate drinking water.

Only a few possible impact schemes will be discussed here, although more are thinkable. Apart from the adverse effects of increased salinity of groundwater, brine often also contains potentially harmful substances, e.g. trace/heavy metals, dissolved minerals, and organic matter (e.g., from hydrocarbon resources). As supercritical CO_2 acts as a solvent on many of these harmful substances, they might be preferentially transported along with the CO_2 or brine flow.

Another (though related) mechanism involves rising dissolution of carbonates due to lower pH-levels (resulting from CO_2 presence), which in case of leakage might lead to increased hardness of groundwater, potentially exceeding regulatory guidelines. Also, carbonates often accommodate significant amounts of pollutants such as heavy metals; these would be dissolved and transported into drinking water. Analogically, silicates may be dissolved due to decreasing pH levels, thereby also potentially releasing pollutants. [Holloway et al. 1996, 145-146]

Finally, groundwater contains microbials which obtain their energy exclusively from inorganic sources ('rock eaters') and metabolize substances like H_2S, for example. It is completely unknown which effect intrusion of CO_2 into groundwater resources would have on these microbials and on groundwater quality. [Fredrickson and Onstott 1996]

It is important to note that, because many potable groundwaters contain heavy metals already near to the maximum admissible concentrations, only a relative small addition may possibly be sufficient to render a water impotable. [Holloway et al. 1996, 144-150]

The specific risk of migration processes towards groundwater reservoirs would have to be analyzed for each project site. As noted above, annual underground injection of 500Mt municipal sewage in Florida has led to contamination of drinking water aquifers. Contamination of drinking water is strictly banned by law in the USA and Europe. [Damen et al. 2003, 11; CRUST 2001]

Monitoring schemes can be installed in order to control the intrusion of CO_2 and/or brine into groundwater reservoirs (see section 2.2.4).

Holloway et al. [1996, 151] conclude that even small leaks of CO_2 from underground disposal sites may possibly cause significant deteriorations in the quality of potable groundwaters. They recommend to take into account the economic consequences of possible groundwater contamination when assessing CCGS projects. Research on the effects of migration of fluids that may result from CCGS operations is found difficult as the risks are relatively site-specific. Possible groundwater contamination mechanisms and effects are not comprehensively understood today. [Holloway et al. 1996, 139]

Contamination of hydrocarbon resources

If CO_2 and/or other fluids would migrate into hydrocarbon and/or mineral resources, this could lead to contamination of these resources in the sense that their subsequent extraction would be inhibited. The associated economic effects as well as the legal issues that could arise in case of specified property rights should be taken into account in CCGS project calculations. [Wilson et al. 2004a, 2]

CH_4 leakage

Methane CH_4 and light alkanes are ubiquitous in depleted gas and oil storage reservoirs and coal seams, and moderately common in deep saline aquifers. An important feature of CH_4 is that it is more mobile than supercritical CO_2. Soil gas measurements at the Rangeley Weber field EOR operations indicate annual leakage of 400t thermogenic CH_4 from deep sources over an area of $78km^2$. [Klusman 2003]

On a local scale, CH_4 implies similar risks to CO_2, that is, reduced water quality and lethality when accumulating in confined spaces or areas. In addition, CH_4 is highly flammable. Contrary to CO_2 it is lighter than air and therefore usually disperses into the air. With respect to global risks, the global warming potential (radiative forcing) of CH_4 is about 24.5 times that of CO_2 over a period of 100 years. [Schwarze 2000, 29; Damen et al. 2003; Klusman 2003]

Catastrophic surface leakage

Catastrophic surface leakage refers to large-scale and quick outgassing of CO_2 into the atmosphere. It is generally believed that the likelihood for such an event in a geological CO_2 storage operation is very small. The major danger is formed by potential suffocation of humans and animals. Damages to vegetation could also result. Another risk related to CO_2 escape is instant freezing of plants, animals or human beings in the direct vicinity of the leak, due to the temperature drop caused by rapid expansion of liquid CO_2.

Holloway et al. [1996, 118] calculate an instantaneous release of 100 Mt CO_2 (~25 years CO_2 production from a 500 MW coal fired power plant). The size of the resulting CO_2 cloud would reach $\sim 50km^3$. With a cloud thickness of 3m, an area of roughly 18,000 km^2 would be covered. The disastrous effects of such a cloud in densely populated areas are obvious. The probability of such an event is considered to be low due to the various trapping mechanisms in geologic reservoirs discussed above. Also, if the leakage would occur through a single well, the release rate of CO_2 would be limited, as it has been the case with the burning oil and gas wells in Kuwait. A significant leakage from a single well might be partly obstructed by the formation of dry ice. Also, CO_2 accumulates only under specific circumstances. For example, wind leads to dispersion.

However, it is thinkable, for example, that injected CO_2 remain in supercritical condition forming a strongly buoyant plume; that increasing reservoir pressures cause a seismic event; and that sudden surface release of large amounts of CO_2 occur through resulting fractures, at a site and under conditions that favor accumulation. While the likelihood of such an event may be small, the potential impacts, especially in highly populated areas, are not.

Holloway et al. [1996, 321] conclude that risks to man and terrestrial ecosystems would be much reduced if geological CO_2 storage took place off-shore (apparently, this would transfer the risk to marine ecosystems). Another conclusion is to avoid siting geological CO_2 storage projects in populated areas.

Slow surface leakage

Several examples for slow surface leakage have already been discussed in the subsections "Natural analogues" and "Impacts on soil ecosystems" of this subchapter 2.3. It was illustrated that slow outgassing of CO_2 might lead to local accumulations that may be lethal. Also, ecosystems may be damaged.

However, the main risk related to slow outgassing may be global, that is, increasing atmospheric CO_2 concentrations induce global warming. This issue and related socio-economic aspects will be discussed in 2.5.

2.4.8 Local risks associated with fossil fuel extraction and combustion

The Union of Concerned Scientists [2002, 4] and Hawkins [2001] argue that continued and possibly increased reliance on fossil fuels will have adverse environmental impacts at fossil-fuel extraction sites, particularly in ecologically sensitive areas.

Hawkins [2001] reports impacts of coal extraction and combustion in the US. Coal mining has contaminated more than 12,000 miles of US streams and rivers from heavy metals, acid mine drainage and polluted sediments, leading to the killing of fish, vegetation and wildlife. Over the last 30 years, only half of the millions of acres of land that coal mining has disturbed have been reclaimed to even minimum standards. More than 264,000 acres of cropland, 135,000 acres of pasture, and 128,000 acres of forest have been lost. Mountaintop mining practices impose significant hazards for local communities resulting from the explosive charges being used that can lead to landslides and rocks destroying houses and killing people. More than 75% (over 100 million tons per year) of sludge and coal ash resulting from sulfur scrubbing is dumped into quarries, lagoons, unlined landfills and abandoned mines with few safeguards.[33] Although the content of sludge and dry ash includes lead, arsenic, cadmium, selenium, chromium, molybdenum, beryllium, and other toxins, these wastes are exempted from hazardous waste regulation. Therefore, the EPA is unaware of the procedures and whereabouts of dumping sites the number of which is estimated at 600. Waste from a coal plant in North Carolina dumped into Lake Belews (a popular fishing site) has lead to the extinction of 16 out of the 20 previously existing species and made two of the remaining species sterile. In three recreational areas in Texas the state has begun to warn the public to not eat fish due to intoxication from selenium stemming from the dumped ash of nearby coal power plants.

Perrow [1992, 369] calculated the annual number of fatalities related to the US fossil fuel industry (extraction, transportation, impacts of emissions) in the 1980s to be 10,000. It would

[33] A typical 500MW coal fired power plant produces about 125,000 tons of ash and 193,000 tons of sludge per year if the flue gas stream is scrubbed for sulfur.

be highly desirable to attain more actual numbers that also comprise the methodology applied for calculation.[34]

2.4.9 Social distribution of local risks

The social distribution of the local risks of CCGS can be analyzed using a classification developed by Perrow [1992, 100-104]. Perrow distinguishes four categories of risks (in the case an accident had not yet happened) and victims (in case an accidents has happened[35]) of industrial large-scale technological applications:

1. First order victims are the operation personnel of a failing technological system.[36]
2. Second order victims are all those who do not directly operate a failing system but who are actively engaged in its reproduction, and who are usually able to decide whether they are willing to bear a risk or not. Examples include passengers in an airplane, or a driver delivering goods to a factory or plant.
3. Third order victims do not stand in any relation to a failing industrial operation except for being affected by its consequences. People in urban areas with nearby nuclear power plants or the two inhabitants of the trailer which exploded in the Hutchinson natural gas leakage would be examples. In contrast to first and second order victims they do not derive any direct benefits from the operation that triggered the accident.
4. Fourth order victims are all unborn persons who are affected by accidents and/or risks stemming from industrial facilities. For example, foetae whose mothers have been exerted to nuclear radiation, or unborn children who will be affected by contaminations of their food chain, e.g. by heavy metals in the soil.

First order risks of CCGS apply to the operational personnel of CO_2 capture, compression, transport and storage processes. In particular, these include risk of suffocation, and injury or death from technical devices in accidents (e.g., explosions). As there are no data from past experience with CCGS it is difficult to assess how large the associated risks in the different process steps really are. It can be asumed that in the capturing phase the risks will be similar to standard risks at respective facilities (power plants, cement works, etc.). It has been pointed out that in case of MEA absorption processes MEA degradation may lead to an increased number of shut-downs, which increase the risk of accidents involving injury or death of operation personnel. During storage activities, well blowouts or slow leakage at the injection site constitute the most obvious first order risks.

[34] If these figures should become part of a calculus in energy policy – and from a moral point of view, nothing speaks against this – the number of injuries and fatalities in alternative energy production chains would be of equal interest. Unfortunately, no such figures are available.
[35] It can also be argued that a victim is a person who has to bear a specific risk.
[36] It is worth noting that according to Perrow in case of accidents it is common industrial practice to delegate responsibility to the operation personnel responsible by labelling the cause of an accident 'human error'. [Perrow 1992, 101-102] The idea is that this strategy mitigates the need for (potentially costly) adjustments of the process routine. However, (a) humans will always make mistakes, and (b) those actually making a 'mistake' very often cannot be held responsible, e.g. when forced to work irregularly long hours which result in an operating mistake, or if the process materials are not properly maintained.

Potential first order victims of CCGS operations are also all those who are directly engaged in CCGS and who are affected by related risks such as contamination of aquatic ecosystems, contamination of the food chain, etc. Beck [1986, 48-50] terms this the ‘boomerang effect’ of industrial risks, that is, the producers of risks are also affected by them. However, for most local risks of CCGS this would only apply if the operational personnel, managers and scientists (and their families) would live in the vicinity of CCGS applications, which appears improbable, especially long term.

If geological injection of CO_2 leads to contamination of hydrocarbon resources that are owned by the company operating the injection facilities, this can be regarded as a boomerang effect as well.

Also, all operational personnel that are victims of accidents at fossil fuel extraction and processing sites may be classified first order victims if CCGS became applied at a large scale, because CCGS would enable prolonged extraction and use of fossil fuels. However, due to the indirect character of the relation between CCGS and fossil fuel extraction and transport (this group does not work at CCGS sites) these bearers of risks may also be categorized potential second order victims.

Second order victims of CCGS may be drivers delivering goods, or office personnel at capture or storage sites. Also, someone selling property to a CCGS company and affected by adverse impacts of CCGS operations would bear second order risks and impacts.

Possible third order victims are all those who are affected by adverse consequences (risks and accidents) of CCGS without being involved in CCGS operations and/or deriving direct benefits from it. This includes people suffocated due to CO_2 leakage, especially those living in communities near CO_2 storage sites; children, adults and elderly people drinking contaminated groundwater; anyone in the immediate vicinity of a pipeline explosion; anyone holding property that is nearby CCGS sites and which is devalued due to these activities; the holder of a mining license of a contaminated adjacent underground resource, e.g. groundwater. Beck [1986, 50-52] terms the latter two aspects ‘ecological expropriation’.

Many other risks and accidents are principally thinkable that can create third order victims. Decisive here is that anyone living in the surroundings[37] of a CCGS operation or having stakes in adjacent surface and/or underground property is affected by local risks.

Finally, *fourth order victims* are all those unborn who will have to deal with the adverse future impacts of CCGS, e.g. contamination of groundwater resources, contamination of aquatic ecosystems, or CO_2 leakages. Also, the foetus whose mother is drinking contaminated groundwater is a fourth order victim. Related to this it is worth considering, for example, who will assume institutional responsibility for monitoring CO_2 injection sites in the long-run in order to mitigate such adverse impacts, if possible, and what will happen in case of political destabilization, e.g., if there are no responsibilities or engineering capabilities to manage abandoned and failing CO_2 storage sites. Taking serious the interests of future generations renders an ethical debate about the risks of CCGS inevitable. Closely related to this is the issue of long-term monitoring and management of abandoned injection sites.

[37] As it has been noted above, a CO_2 injection plume may stretch out up to $100km^2$. Anyone living within this area bears local risks of CCGS.

2.5 Global risks and opportunities

The global environmental risks of CCGS arise from leakage of CO_2 (or CH_4) from CCGS surface processes or geologic reservoirs to the atmosphere and the resulting increase in atmospheric CO_2 concentration levels, which contribute to global warming. If all of the injected CO_2 would leak into the atmosphere, the application of CCGS would actually increase global CO_2 emission levels relative to a BAU scenario. This is due to the additional energy needs of CO_2 capture, transport and storage (energy penalty). [Union of Concerned Scientists 2002] However, it is argued that if leakage occurs relatively slowly and some CO_2 remains stored forever, it could delay CO_2 peak emissions during the 21st century, thus mitigating the worst climate change impacts. [e.g., Herzog et al. 2003] This argument depends on two notions: first, the reservoir leakage rate should be sufficiently low to delay CO_2 emissions 'long enough', that is, to stabilize atmospheric CO_2 concentrations at a level that renders climate change unlikely or less harmful. Second, renewable energies are going to be introduced on a very large scale in the course of the 21st century, because eventually geological reservoirs for CO_2 (and/or fossil resources) are going to deplete.

In addition to global environmental risks, CCGS involves economic risks due to the considerable costs (e.g. if 400Gt CO_2, would be stored underground at average costs of 50US$/t CO_2, this would imply overall costs of US$ 20 trillion[38]). These R&D, investment and operational (energy penalty) expenditures for CCGS could also could be spent on R&D and investments within the renewable energy sector, which would make renewable energy technologies economically efficient within a shorter timespan. The implementation of CCGS could inhibit the development of renewables. From a global climate change point of view this may be irrelevant as long as renewables will eventually become sufficiently developed, and the CO_2 from fossil fuel point sources is efficiently kept away from the atmosphere in CCGS operations (leakage rate ? 0). If, however, leakage from geological reservoirs will exceed critical thresholds and CCGS is rendered ineffective in terms of reducing global CO_2 emission levels, the investments into CCGS have to be written off and had better been allocated to the development of renewables in the first place (opportunity costs of CCGS). In this case, CCGS will involve considerable welfare losses.

From both a climate change and an economical point of view it is therefore crucial to determine a 'critical leakage' rate (including intertemporal development of leakage) that constitutes a critical threshold that should not be exceeded in CCGS operations. If a CCGS project cannot guarantee that its leakage rate will lie below this threshold, it should not be carried out at all.

The following factors determine the global ecologic and economic effectiveness of CCGS in current integrated assessment models [e.g., Bauer et al. 2004]:

(i) intertemporal atmospheric GHG concentration stabilization target,

(ii) amounts and development of atmospheric GHG emissions from fossil fuel use without CCGS (including dynamics of energy demand and availability of coal, oil, gas reserves) and natural system dynamics,

---

[38] To put this into perspective, the world GDP in 2000 was US$ ~26 trillion. [SRES 2000]

(iii) marginal costs and availablility (incl. technical progress and dynamic constraints) of CCGS,

(iv) marginal costs and availability (incl. technical progress and dynamic constraints) of renewables, and

(v) intertemporal leakage rates from CCGS operations.

Several studies have been undertaken in order to assess the global risks of CCGS and to define a critical threshold for a critical leakage rate. The following section 2.5.1 presents the results of studies that assess leakage rates and their implications for the global climate, economy and energy system. After that, studies analyzing the impacts of leakage rates on global climate change and global welfare are discussed.[39]

2.5.1 Assessing the impacts of leakage on climate change and economic efficiency

Leakage rates and climate change

Hepple and Benson [2002] explored the question of what would be an acceptable annual leakage rate from CCGS operations. They first estimated the total requirement for CCGS operations by calculating the difference between the IPCC SRES emission scenarios and an allowable emission pathway including several emission targets for the next 300 years (only 100 year forecasts were available; these were extrapolated in linear fashion). It was found that in most scenarios at least some CCGS was required in order to achieve emission targets, especially in the 350, 450 and 550ppm cases. Even for the 650 and 750ppm scenarios CCGS was required in scenarios representing a significant reliance on fossil fuels. Depending on emissions scenarios, for the 450ppm target, for example, cumulated CCGS amounts ranging from 1,000Gt CO_2 to 15,000Gt CO_2 were calculated.

In order to assess acceptable leakage rates, specific values were assumed for the various storage scenarios. It turned out that at an annual leakage rate of 1% after 300 years only ~40% of the injected CO_2 would still be confined within the reservoir, with slight variations (+/- 0.7%) between the different scenarios (that is, energy use and emission target assumptions). A leakage rate of 0.1% lead to confinement of ~85% of the injected CO_2; 0.01% leakage implied ~98% confinement. In this case, annual leakage rates never exceed 1.8Gt CO_2 per year. Finally, 0.001% leakage would imply ~99.8% of the injected carbon dioxide remaining within the reservoirs. Hepple and Benson conclude that only leakage rates in the range of 0.01% and lower are worth considering for CCGS operations.

Leakage rates, climate change and economics

Dooley and Wise [2002] analyzed how much additional annual CO_2 emission reductions would be required in order to meet the atmospheric CO_2 concentration targets articulated in the UNFCCC if overall leakage rates of 0.1% and 1% are assumed. Also, the additional mitigation costs due to leakages were calculated. Using the MiniCAM 2001 integrated assessment model, they expected modest economic growth with continued use of fossil fuels and significant penetration of renewable energies in a BAU scenario, resulting in an

[39] It should be mentioned that some studies treating these subjects are not discussed here, including Pacala [2003], Riahi et al. [2004], Herzog et al. [2003], and Bode and Jung [2004].

emission pathways analogical to the B2 scenario in the IPCC Special Report on Emission Scenarios. CCGS is implemented in the year 2035. In order to achieve atmospheric CO_2 concentration targets of 650, 550 and 450 ppm until 2100, a cumulated amount of ~370Gt, ~730Gt, or ~1250Gt CO_2 emissions respectively would have to be stored in media other than the atmosphere. In the 650ppm case, in the year 2095 an average leakage rate of 1% would make additional (compared to 0% leakage) annual emission reductions of ~3.67Gt CO_2 necessary. This figure would be minimal in case of 0.1% leakage (~0.3Gt CO_2). For the 550ppm scenario, ~7Gt CO_2 annual emissions would have to be avoided additionally in 2095 in the 1% leakage case. Again, the number is far lower for 0.1% average leakage, about 0.5Gt CO_2. If 450ppm were to be achieved, at a leakage rate of 1%in the year 2095 there would have to be negative emissions of about 7.34Gt CO_2 per anno, that is, more emission would have to be stored than emitted; in case of moderate leakage, emissions could be positive and should be ~1.5Gt CO_2 lower if compared to the 0% leakage case. From an economic point of view these scenarios imply that in case of 0.1% leakage and 650 and 550ppm emission targets climate change mitigation costs in 2095 would be ~5% higher than in a 0% leakage case. In the 450ppm scenario, mitigation costs would be 15% higher. With a 1% leakage rate, costs of leakage would increase considerably, e.g. 67% in a 550ppm scenario. Dooley and Wise conclude that only very low leakage rates (~0.1%) will be tolerable in CCGS operations. They suggest that without monitoring technology being able to quantify leakages at such low orders of magnitude (from the point of view of individual CCGS projects), it may be difficult to integrate CCGS in a global emission regulation framework at all due to the related economic and climatic inefficiencies.

Ha-Duong and Keith [2003] analyze the impacts of varying leakage rates, discount rates, CCGS costs, and energy penalties on the effectiveness of CCGS efforts (the focus here will be put on their analysis of leakage rates). For doing so, they adopt two point of views: in a 'microeconomic' approach they calculate CCGS mitigation costs at varying leakage rates and conclude that leakage rates up to 1% would render CCGS an effective mitigation option. In a long run cost-benefit model, using the DIAM integrated assessment model, they assess the optimal leakage rate of CCGS operations in case these should become a major mitigation option. This is done by assuming a cost curve representing the assumed costs of climate change and assuming two emission abatement activities, CCGS and renewables. Then the discounted intertemporal sum of expected intertemporal utility is maximized. Single technologies and capital turnover are not represented in the model. In the year 2150, in case of perfect containment (0% leakage) 48% of the energy would be produced in CCGS operations. With a leakage rate of 0.1%, the share of CCGS would still be 39%. At 0.5%, however, only 7% of energy supply would be produced in CCGS operations and at 1% leakage no CCGS would be implemented at all. It can be concluded that 1% leakage will render CCGS economically inefficient.

The most comprehensive analysis of the economic implications of CCGS is available from Bauer et al. [2004]. Using the integrated assessment model MIND the economic impacts of transforming the current global energy system towards a sustainable state are analyzed. The model comprises a macroeconomic endogenous growth module which computes the intertemporally optimal investment decisions for various climate change mitigation options which are endogenously determined. For the renewables learning rates of 15% are assumed, that is, investment costs for renewables energy technologies decrease by 15% every time the installed capacity doubles. In the CCGS sector several capture and storage approaches are distinguished. The economic module is coupled with a climate module which emulates the IPCC TAR atmosphere-ocean circulation model. Aerosols are taken into account (e.g., CO_2 capture operations reduce aerosol emissions). The sensitivity of the climate system is set at 2.8° C for a doubling of CO_2 concentrations from 280ppm. In the adapted climate policy scenarios this limit restricts the economy to GHG emissions that do not induce temperature changes exceeding this threshold (tolerable window approach).

Three global energy system scenarios are calculated by Bauer et al. [2004]. The BAU-case involves no climate policy at all, the CPP° case implements a climate policy without CCGS, and the CPP^+ implies climate policy including CCGS as a mitigation option. In the BAU-case, the world-GDP rises by factor 14 until 2100 and renewables are starting to become implemented at the end of the century due to beginning scarcity of fossil fuels. As displayed in the right panel of Figure 2.4, in the CPP° case global welfare losses rise to a maximum of 1.56%/y of the BAU GDP in 2040, and decline thereafter. If CCGS is part of the climate policy portfolio (CCP^+), welfare losses peak at ~1.4% of the global GDP, and are principally delayed. CCGS lowers the costs of climate change by 0.16% of the total GDP at peak times, thus reducing total mitigation costs by about 10%. In the CPP° case fossil energy use will rise slowly until ~2025 and will then fall to a low level at the end of the century. Renewable energy use will surpass the amount of fossil fuel energy supply in the middle of the century. If CCGS is allowed (CPP^+), more fossil fuels will be used, peaking in ~2030 and remaining on a higher level relative to the CCP° case until ~2070. This renders the transition of the energy system slightly cheaper (global welfare losses are lower – discounting the GDP paths with 5% results in 0.54% GDP losses relative to BAU for CPP° and 0.53% for CPP^+ over the 21st century – and are delayed, which appears to be the more important effect due to the very small overall decrease in mitigation costs; see right panel Figure 2.4). A reservoir leakage rate of ~0.25% is assumed. The cumulative amount of stored CO_2 is 430Gt CO_2. CCGS may hence be regarded as an option to buy time. During the timespan of elevated use of fossil fuels (due to CCGS), the introduction of renewable energies is delayed (surpassing the amount of fossil fuel supply only in the year 2045). Bauer et al. [2004] term this the crowding-out effect of CCGS on renewables. CCGS is becoming implemented in 2010 for industrial hydrogen production processes, and in 2015 for capture at coal fired power plants. CCGS capacities peak in 2040 with 15.8Gt CO_2 per year, declining towards zero (year 2100) aft

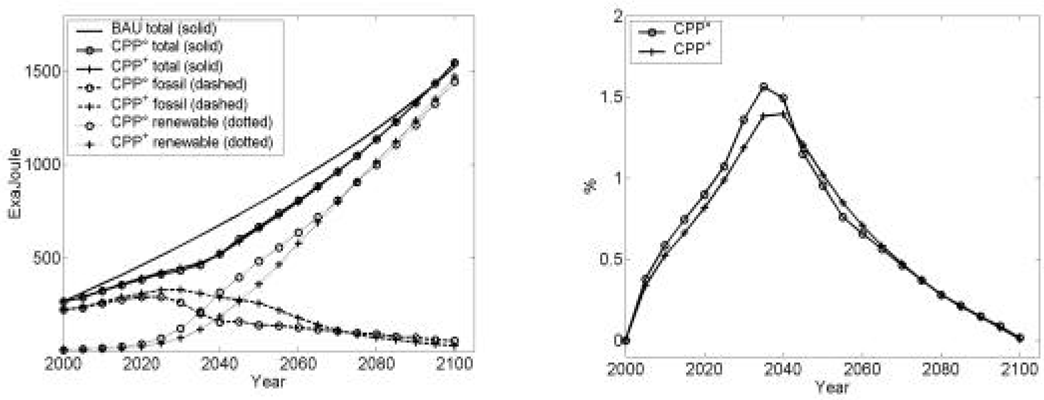

Figure 2.4: Secondary energy production for different policy scenarios (left panel). GDP losses relative to BAU, in the period 2000 – 2100 (right panel). Source: Bauer et al. [2004].

It is important to note that sensitivity analyses show that the impact of reservoir leakage rates on cumulative CCGS amounts is closely connected to renewable energies learning rates. This is displayed in Figure 2.5. If the learning rate for renewables will be low, and the CCGS leakage rate is high (1%), still considerable amounts of CCGS are recommendable from an economic point of view in a climate policy regime (up to ~350Gt CO_2 cumulated); welfare losses would be about 1.1% of GDP relative to the BAU case. If learning rates for renewables are very high and leakage rates from CCGS still ~1%, then no CCGS is recommendable at all, and overall mitigation welfare losses will be relatively low with ~0.5% GDP.

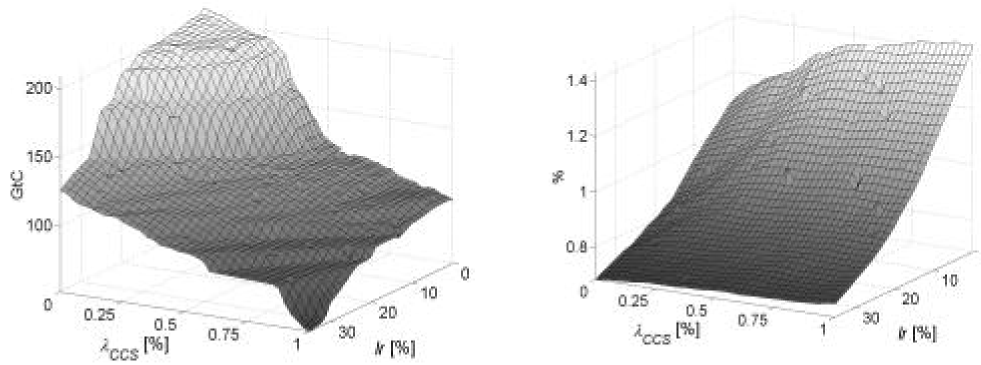

Figure 2.5: Sensitivity of cumulative CCS (left panel) and cumulative discounted GDP losses (right panel) with respect to renewables learning rate (lr), and leakage rate of sequestration sites (CCS ?), in the period 2000 – 2050. Source: Bauer et al. [2004].

It can be concluded that even at higher leakage rates (~1 %) CCGS could be economically and ecologically efficient if the renewables fail to develop quickly. However, if their performance is very well, then less to zero CCGS will be desirable. In general, assuming

0.25% leakage and 15% learning, 430Gt CO_2 might be stored underground, reducing mitigation costs by maximal 10%, which is certainly not outrageous.

Summary

The studies presented here agree that CCGS could become an option to buy time if reservoir leakage rates are sufficiently low. In case of large-scale deployment of CCGS a leakage rate exceeding 1% seems to be ineffective both with respect to stabilizing atmospheric GHG concentrations and in terms of welfare losses. In fact, it appears that 1% is regarded to be the maximal threshold that is still considered worth calculation in model exercises.

A leakage rate of 0% would render CCGS and attractive mitigation option in all studies, with the recommended cumulated amounts considerably varying depending on policy targets (and assumption about renewable learning rates in case of Bauer et al. [2004]). In case of very low leakage rates (0.01%), all studies agree that these may be acceptable. The sensitivity analyses conducted by Bauer et al. [2004] suggests that even higher leakage rates (e.g., 0.25%) may render CCGS effective both in terms of mitigating climate change and reducing the costs of the mitigation process, although these reductions do not appear overwhelming with 10%. Hepple and Benson [2002] recommend that only leakage rates of 0.01% are worth considering.

In general, from a global risks point of view it may be reasonable to implement some early CCGS projects, at least in order to be able to quantify preliminary leakage rates. Depending on the performance of reservoirs and renewables, more CCGS may be introduced or it may be generally cancelled.

2.5.2 Social distribution of global risks

As pointed out in the previous sections, two global risks associated with CCGS can be distinguished. I will first discuss the risks of global climate change arising to specific groups due to CCGS (although the specific contribution of CCGS may be difficult to quantify). For this purpose, the level of analyzing the risks and actions of particular individuals is abandoned in favour of analysis of the behavior of and impacts on whole nation states.[40]

In the second subsection the social distribution of global economic risks will be reviewed. For this purpose it seems necessary to increase the resolution of the analysis and to distinguish between single industries (fossil/CCGS industry, renewable industry, insurances), groups of taxpayers (the public), and nation states.

I would like to emphasize that this chapter constitutes, to my knowledge, the first sociological treatment of the social distribution of global risks associated with CCGS. By no means do the preliminary considerations laid out here exhaust the issues involved. In fact, they do require a comprehensive and empirical treatment of their own. The first subsection on risks stemming from global climate change, for example, could certainly be improved by drawing on research into vulnerability and adaptation; in general, these questions heavily relate to global energy politics and conflicts and suggest a scope of analysis which cannot be adopted here.

Risks of global climate change

There are several uncertainties related to an attempt to specify a social distribution of the risks of climate change triggered by CCGS operations. First of all, it appears be very difficult to establish a causal link between leaking CO_2 reservoirs and climate change, because these reservoirs might only release a fraction of their content. Quantification of 'how much' CO_2 emissions actually triggered adverse climate change events seems to be difficult. In addition, the development of renewable energies is subject to heavy uncertainties. That is, if CCGS were implemented, and if reservoirs would leak and climate change occur, it may still be argued that without CCGS global welfare losses would have been even higher because of the uncertainties related to trusting the renewable energies to solve the global energy crisis resulting from the greenhouse effect.

In addition, it is generally unclear which specific impacts climate change will have in which regions on which groups. It is therefore difficult to identify specific distribution lines of the risks involved in leakage from CCGS operations. However, in very general terms there are some mechanisms and phenomena that are well understood, although the likelihood of their appearance is subject to uncertainties. These climate change related events include sea-level rise of the oceans, melting of glaciers, changes in monsoon dynamics, changes in thermohaline circulations (THC) of the ocean, increase in extreme weather events (hurricanes, floodings, dry periods), loss of biodiversity (in marine, aquatic, soil, and surface

[40] This need arises (a) from the global character of the climate change risks which will affect whole regions, and (b) because nation states are the most important single political actors in climate change policy. A higher resolution analysis may distinguish between regions, industries, and economic classes (e.g., with respect to different adaptive capacities), but would considerably increase the complexity of the analysis.

ecosystems), desertification, melting of permafrost soils and emission of CO_2 and CH_4 from these soils. More specifically, the impacts on human communities include changes in productivity and usage of natural resources, use and availability of water resources, agriculture, infrastructure, increase of catastrophic extreme weather events, and ultimately impacts on human health and life expectation. [Schwarze 2000, 60-69]

As from a global point of view the adoption of CCGS technology can be viewed as a societal decision (in the political organization order of today: of national states), first order victims of CCGS and climate change would be those societies (nation states) who run significantly leaking CCGS operations and who are affected by the induced impacts of global climate change. This is corresponds to Beck's notion of a 'boomerang effect', which arises from global character of the risk. [41] [Beck 1986, 48-50]

The same basic considerations hold true for potential second order victims of leaking CCGS operations and resulting global climate change. These would be societies which, while not themselves conducting CCGS operations, would materially support them (for example by delivering facilities and/or parts). This case could be particularly interesting if CCGS were implemented through CDM mechanisms, especially to countries where technological standards in engineering geology and monitoring are insufficient. If leakage from such reservoirs would occur, the impact could be induced at the country delivering the technology and resources.[42]

Third order victims would be all those who have no influence on the implementation of CCGS and leakage rates but who are affected by climate change. In case of sea level rise, small island states and societies would be an example. In general, any nation that lacks the international prestige and power to have an influence on the adoption of CCGS by other nations, and that is affected by climate change due to leakage from CO_2 reservoirs, would be a third order victim. This could hold particularly true for development countries.

Fourth order victims would be all future nation states and individuals who are affected by climate change triggered by leaking CCGS operations and/or the possibly related failure to sufficiently invest in renewable energies.

---

[41] The situation of operational personnel, management and scientists at leaking CCGS applications who are affected by climate change related incidents might be of particular interest, as such analysis leaves the level of nation states. Such analysis may be – to some extent – useful with regard to the action motivating forces that may result from being aware of participating in a (potentially) leaking CCGS operation. For example, leakage may be perceived as a professional or moral failure (especially if the risk and likelihood of leakage had been well known in advance). Such considerations may act as a strong motivation on operational personnel to run CCGS facilities in an effective way, that is, without leakage. However, such aspects should neither be over- nor understated. Material benefits from running and/or being employed in CCGS operations may exceed the motivational power of uncertain and diffuse individual climate change risks and moral considerations (actually, local risks may be more stimulating with this respect to influence individual action of CCGS employees). In addition, it is very likely that eventual leakage cannot be foreseen (or even detected), and that operational personnel are in fact convinced to help mitigate the risks of global climate change.

[42] Global best-practice requirements for CCGS operations may constitute an approach to mitigate such risks, and would likely find support from the group of potential second order victims involved in CDM.

Economic risks

Analysing the distribution of economic risks of CCGS appears difficult because few studies are available even on the global economic impacts of carbon dioxide capture and geological storage technologies. Still, while it is not possible to deliver quantitative amounts, some basic structures of the distribution of economic risks may be perceivable. It will be assumed that these (and potentially resulting conflicts) will unfold along the lines of the issues 'who bears the risk of costs of CCGS' and 'who may benefit from CCGS, and how much risks does he bear'?

First order economic risks of CCGS refer to the fossil fuel industry[43] bearing the economic risks of CCGS. This would be the case if leakage from reservoirs would exceed critical thresholds and be penalized; if local accidents or devaluation of property rights would systematically lead to liability claims by the affected persons; if environmental law would be systematically violated due to migration and leakage processes and penalties would arise; if an emission regulation framework would become implemented and it would turn out that renewable energy sources are becoming economically superior to CCGS quickly; if CCGS would be implemented via CDM but would not be efficient in terms of investment costs, O&M, and leakage rates.

Alternatively, the fossil fuel industry could transfer these (or some of these) risks to insurance companies, if these are willing to bear them. Insurance companies would in turn have a vital interest in efficient CCGS operations and would be likely to conduct strict controls of the operations.[44]

Second order risks arise if the economic costs of CCGS are born by other parties than the fossil fuel industry. This is – at least to some extent – very likely because there is a broad consensus that R&D should be conducted and sponsored by public funds. Therefore, if CCGS fails, public resources (that could also have been allocated to R&D on renewable energies) will be written off. In this sense the public might bear some economic risks of CCGS.

However, even if no public resources were spent on CCGS, it is highly likely that the fossil fuel industry would completely pass on the costs to consumers, that is, the public. Therefore, even if the public (or individual consumers) do not agree to the implementation of CCGS it will bear economic risks due to (potential) increases in electricity costs and the costs of other fossil fuel related consumer goods (e.g., gasoline) – as long the consumer (the public) cannot or does not decide to purchase electricity or consumer goods from renewable energy sources alternatively (and thereby actively contributes to the reproduction of the fossil fuel sector).

Third order victims of the economic risks of CCGS could be all those groups and individuals who do not actively support CCGS but who are affected by either (a) the implementation of CCGS, even it turns out to be an efficient option from global and local point of views, or (b) if CCGS fails as a climate change mitigation option e.g. due to high leakage rates, or due to

---

[43] Covering all fossil fuel processing aspects of extraction, refining, combustion, and possibly capture and storage. That is: oil, gas and coal companies, refineries, the traditional electricity industry, cement industry, ammonia production etc., and possibly newly arising specialized CCGS companies (e.g., Kinder Morgan CO2 company).

[44] This may be an interesting constellation for considerations concerning a regulatory framework for CCGS.

superior performance of renewables. Another group may be those who do not support CCGS but who would have encountered more welfare if CCGS had not become implemented. For example, within CCGS nation states low income groups receiving state welfare may be affected. Internationally, development aid may be reduced in case of significant economic losses due to CCGS.

The case of the emerging renewable energy industry could be of particular interest. On the one hand it is possible that it will encounter considerable losses if CCGS is becoming accepted and deployed as a climate change mitigation option (opportunity costs of CCGS), on the other hand it may actually propose the implementation of some CCGS in order to increase the acceptability and ratio of public R&D into climate change mitigation options (see 3.1.1).

The nuclear energy industry might be affected in that successful deployment of CCGS might render nuclear power plants uncompetitive as climate change mitigation options, because the current advantage of the low emissions of nuclear power plants relative to fossil fuel technologies would be lost.[45]

Finally, fourth order risks arise from the potential failure (significant leakage) of large scale CCGS installations which might considerably decrease the welfare of future generations.

Quantifying these economic risks is difficult and depends heavily on the development of renewables and empirical leakage rates from CCGS operations. Analysis by Bauer et al. [2004] suggests that potential welfare losses due to CCGS are relatively low (in the order of magnitude of ~0.6% of global GDP in 2100, which is estimated to be 14 times that of today's global GDP), but other calculations assume heavier impacts [e.g., Dooley and Wise 2001]. Also, if leakage rates would exceed 1% and CCGS were implemented on a very large scale, significant economic losses would result.

[45] From the point of view of global energy and security policy this might imply that proliferation of nuclear power could not be justified with global climate change issues.

2.6 Summary and conclusions

Capturing CO_2 from large point sources is a technically feasible option and is routinely performed at many industrial applications. MEA absorption is the best-known approach, but relatively costly and there seems to be little potential for significant future cost reductions by technical progress. Also, MEA degradation and losses in the flue gas impose environmental risks (and economic costs) which are not understood. New solvents might enhance the performance of the absorption approach. None of the other capture approaches has been performed at a significant commercial scale yet. Therefore, performance and costs of these concepts are inherently subject to heavy uncertainties.

Transport of CO_2 is an industrial standard practice and should not encounter significant technical or economic problems. However, there are considerable risks related to CO_2 pipeline transportation. Although no significant accidents have been reported, it must be taken into account that existing pipelines do not run through populated areas. Also, the experience with CO_2 pipelines is small compared to natural gas and liquid waste transport. Experience from these analogues suggests that pipeline transportation schemes do imply risks to human life and health. Affected communities will have to decide whether they are willing to bear these risks. Adding mercaptans to CO_2 analogically to standard procedures in natural gas handling would enhance detectability of CO_2 and could decrease associated risks.

Despite experiences from analogical operations, the geological injection and storage of CO_2 is subject to considerable lacks of knowledge, particularly concerning the details of trapping and migration mechanisms as well as environmental impacts. No proven estimates of reservoir leakage rates from CCGS or related activities are available. More generally, it will be difficult if impossible to attain reliable knowledge on reservoir leakage rates both due to shortcomings of available monitoring technology. The use of tracers and combination of several monitoring technologies could help to improve available monitoring capabilities. In addition, any monitoring approach will have to rely on model simulations. These are facing their own specific problems (e.g., trade-off between computational capacities and reservoir resolution). However, analyses of the overall efficiency of CCGS suggest that leakage rates should be as low as 0.01-0.25% in order to minimize the global risks of CCGS, and it appears questionable whether monitoring resolutions at such low orders of magnitude can be achieved.

It is difficult to assess global geological storage capacities because for a reliable account extended (and expensive) site-by-site analyses would be required. It may well be that most of the estimated reservoirs do not have sufficient trapping capacities. In general, it can be expected that more detailed analyses will lead to the establishment of a ‘portfolio’ of reservoirs, ranging from very well suited to lower performance sites. The former are likely to be used first, implying that leakage risks will increase with cumulating injection of CO_2, as subsequently reservoirs of less quality will have to be used. The ‘reservoir depletion rate’ may develop similar to that of oil or gas extraction, that is, new fields will be discovered and/or rendered usable through technological progress in geological injection and reservoir management technologies (analogical to technical progess in hydrocarbon extraction technology). It is very likely that the potential for EOR operations would be exhausted first, as this activity carries the prospect of economic benefits offsetting costs. The same might hold true for ECBM, which has the drawback of being a relatively unproven technology. Depleted oil and gas reservoirs may be the next storage sites of choice due to their historical record in containing hydrocarbons; however, the presence of abandoned wells and possible structural changes must not be neglected. Aquifers with an impermeable structural trap may also be an attractive storage option due to often vast capacities. Finally, aquifers without structural trapping seem to be the least desirable storage option, as their confining qualities are highly uncertain.

Concerning the local risks of the geological storage of CO_2, it is worth noting that CCGS implies some significant differences to analogical processes and involves certain features that may be crucial for leakage rates. These include the large quantities involved, the strong buoyancy of CO_2, the solvent proporties of supercritical and/or mixed CO_2 in H_2O, the long timescale of desired storage reservoir containment, and the necessity of monitoring due to verification and accounting requirements within an emissions control framework. These issues will each be treated at some more detail in the subsequent paragraphs.

Quantities – The CO_2 injection quantities involved in CCGS exceed those of current standard practices and can affect large areas. Considerable upscaling is required relative to existing or analogical processes. A 1GW coal-fired power plant would produce ~10Mt of CO_2 per year. In comparison, at Sleipner field only 1Mt CO_2 is injected annually. CO_2 from hundreds of fossil fuel combusting facilities would have to be injected. Often, CO_2 from several facilities will be collected and injected into a single reservoir. Modeling simulations suggest that 300Mt CO_2 injected over a 30 year period into a 100m thick receiving horizon could expand over ~100km^2, with pressure effects occurring over areas as large as 1000km^2. [Wilson et al. 2004b, 2]

With respect to regulation efforts this could imply that in certain areas (e.g., Europe) international regulation frameworks for CCGS could be required. There coulde also be problems in regions with high population density.

Buoyancy – The strong buoyancy of CO_2 calls for special considerations concerning trapping mechanisms and methodology. The injectant in liquid industrial waste disposal, for example, usually has no upwards buoyancy at all. Therefore these operations cannot be considered a proper analogue to CCGS with respect to reservoir integrity. While natural gas also has a strong upwards drive, the quantities involved are much lower. However, experience has shown that due to a combination of buoyancy and large quantities serious accidents have occurred in underground injection activities. The only analogue equal in scope (500Mt/y injection rates) and buoyant properties are municipal waste disposal operations in Florida. There, leakage does occur due to a combination of malpractice and the large quantities and buoyancy of the injectant.

With respect to regulation, it is worth noting that current regulation in the USA, for example, is concerned with fluids that show weak or negative buoyancy. New regulation and technical methods will probably be required to assess the trapping mechanisms in the large areas involved in CO_2 injection and to make sure that only safe reservoirs are used. This will be especially important in regions with a more complex geology, and/or other subsurface operations, and/or with many abandoned wells.

Timescale – The timescale of reservoir containment of CO_2 should exceed at least several centuries. This makes very careful selection of appropriate sites necessary. Little experience is available on the very long-term storage of large quantities of potentially harmful substances. The problems associated with nuclear waste disposal may provide hints for future difficulties with CCGS storage schemes. Regulation requirements will be very different to analogues, e.g. buffer storage of natural gas. The regulation framework will have to deal with long-term migration, chemo-physical interactions, leakage, monitoring, and liability. Except for nuclear waste storage (there are only two permitted final nuclear waste storage sites in the world), no long-term regulation scheme for underground injection operations does exist.

Leakage – There are no empirically confirmed accounts of leakage rates from long-term CO_2 storage available. Most demonstration projects are still in their early stages, and both their number and scale (quantities) is limited. Risks of geological storage differ widely between individual sites. Also, the results of laboratory experiments cannot simply be extrapolated to field conditions. [Damen et al. 2003, 15] In general, leakages along or through wells, faults and fractures are widely considered to be the most important leakage pathways. [Damen et al. 2003, 7] It is not contended that there will be *some* leakage from CO_2 reservoirs:

> "Given that wells have been drilled, and abandoned, for more than a century, and available records are highly variable in their information content, characterization of existing wells will necessarily involve significant uncertainties. Coupled with uncertainties associated with geological and hydraulic properties of the natural formation materials, there appears to be little chance over the long term for complete avoidance of leakage of CO_2. Therefore the risk assessment problem associated with deep CO_2 injection is one of estimating leakage probabilities, and determining maximum allowable amounts of leakage, both of which will be *clearly greater than zero*." [Celia and Bachu 2003; ital. in original]

> [On leakage from an aquifer, C.F.] "Even with receptor formations of adequate capacity, some of the injected CO_2 is expected to leak. […] Even with detailed subsurface characterization, leaks cannot be ruled out in some formations because of the buoyancy of the separate-phase CO_2, the induced pressure gradients from injection, and the variable nature of strata serving as barriers to upward migration." [Bruant et al. 2002]

> "[…] it will be impossible to reduce the risk of CO_2 leaking from the reservoir to zero." [Holloway et al. 1996, 126]

Therefore, the question is rather: how large will leakage rates be?

> "Given the large number of existing wells, the lack of detailed information on many of those wells, and the spatial and temporal scales of the carbon storage problem, complete avoidance of leakage over long periods of time appears to be impossible. While initially this may appear to imply that geological storage is a bad idea, we believe the important question to be answered is not whether there will be any leakage, but whether the expected leakage is acceptable in terms of timing and amount, with 'acceptable' being defined in terms of environmental consequences." [Celia and Bachu 2003]

None of the existing analogical operations has a monitoring scheme in place that would allow for a safe assessment of future leakage rates in CCGS operations. With respect to an integration of CCGS into an emission abatement framework it is worth noting that while the UNFCCC mentions the need of using sinks for reducing greenhouse gas emissions, it does also explicitly enjoin parties to manage such sinks in a sustainable manner. [Johnston and Santillo 2002, 96; see also 5.2]

Monitoring – The central technical problems associated with monitoring of the injected CO_2 have been mentioned above. With regard to the integration of CCGS into a global emission regulation framework they constitute a very significant problem: if verification and accounting for mitigated CO_2 emission can solely depend on measuring injection quantities at the wellhead (and not on monitoring of leakage rates), and quantitatively exact and at least in principle undisputable accounts of CO_2 leakage rates are impossible, it is questionable whether CCGS can become a climate change mitigation strategy at all. It is worth noting that accounting problems associated with the exact quantification of the sequestration capacities of natural sinks have led to significant disputes within the UNFCCC process in the past.

From a global point of view the risks associated with CCGS basically refer to the leakage rate, the resulting impacts on climate change and the economic efficiency of CCGS both in case of leakage or perfect containment. Climate change risks imply that leaking reservoirs will increase atmospheric GHG concentrations. In addition, if all CO_2 from CCGS operations would leak out, more CO_2 would be emitted relative to a BAU case due to the energy penalty from CCGS. Also, in this case the adoption of renewables would have been favourable from a climate protection point of view. Similar considerations apply for the economic risks of CCGS. If leakage is too high, CCGS should not become implemented because investments would not help in mitigating climate change. Also, if the renewable energies will develop quickly, little CCGS will be required.

Analyses of the social distribution of local and global risks provide a hint for lines conflict that may possibly arise in the issue of CCGS. These will be analyzed at more detail in the following chapter 3.

The following Table 2.5 provides an overview of the main risks that have been identified for CCGS operations.

Current R&D addresses many of these problematic issues. [for an overview of some research efforts as of 2003, see Damen et al. 2003] However, e.g. Damen et al. [2003, 17] state that it is unlikely that all risks will be completely understood and quantified after the existing and planned R&D programmes have been finished.

Table 2.5: Overview of some risks associated with CO_2 capture, transport and geological storage. Source: based on Damen et al. [2003, 20], own compilation.

Issue	Chance	Potential consequences/effects
Risks of CO_2 capture		
Increased process vulnerability due to higher complexity	unknown	Increased process stillstands (economic losses), and increased risk of harm to operational personnel
MEA emission along with flue gas	known, high	Unknown
Risks of transport at, surface installations and injection operations		
Pipeline failure	known, moderate	Suffocation, injuries to humans & animals in surroundings, damages to vegetation
Surface equipment failure	known, moderate	Suffocation, injuries of operational personnel
Well failure during injection	known, moderate	Suffocation, injuries of operational personnel
Risks of in-situ migration and surface leakage		
Seismicity and/or ground heave	unknown	Damage to surface facilities and resulting costs, harm to humans, animals, ecosystems
Contamination of soil or sub-soil ecosystems	unknown	Killing, damage of soil and sub-soil ecology due to changing pH-value, toxic substances [1]
Contamination of aquatic ecosystems	unknown	Killing, damage of lake or marine ecosystems due to changes in pH-value, toxic substances [1]
Contamination of groundwater	unknown	Unknown harm to population, esp. children, elderly, due to contamination with toxic substances [1]. Economic losses due to impotable groundwater resources
Contamination of hydrocarbon resources	unknown	Intrusion of CO_2 and/or brine may render adjacent hydrocarbon reservoirs unusable, thus incurring costs
Catastrophic surface leakage	unknown	Suffocation, injuries to humans & animals in surroundings, damages to vegetation, possible damages due to spread of toxic substances [1]
Slow surface leakage	unknown	If critical CO_2 concentrations can accumulate, suffocation, injuries to humans & animals in surroundings, damages to vegetation, possible damages due to spread of toxic substances [1]
Global risk of climate change	unknown	Climate change due to leakage of stored CO_2 or mobilized CH_4 into the atmosphere
Macroeconomic risks	unknown	Loss in global welfare, distributed among different groups and generations

[1] including: H_2S, SO_x, No_x, SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O and P_2O_5, and heavy metals.

3. Social aspects of CO_2 capture and geological storage

This chapter is the central part of this thesis. The most important social aspects and determinants of the viability of carbon dioxide capture and geological storage technology systems are identified and analyzed. In 3.1 elements for a theoretical framework are presented, and 3.2 provides empirically biased analysis of CCGS, including identification of the crucial social determinants of its actual implementation.

3.1 A theoretical framework

Section 3.1.1 introduces Ulrich Beck's theoretical approach which conceptualizes global climate change as a specific risk of (reflexive) modernization. In section 3.1.2, John Dewey's theory of the public is discussed in order to gain a policy framework for dealing with modernization risks in modern industrialized democracies. In 3.1.3 an account of conflict theory is given by drawing on the syntheses provided by Randall Collins [1990, 1975]. In 3.1.4 two approaches aiming at understanding the social conditions of endogenous technological change are presented.

3.1.1 Modernization risks

The industrial sector of modern societies produces both commodities for investment and consumption and risks which are fundamentally different from those that mankind has come to know in its pre-industrial history. This is the basic notion of Ulrich Beck's '*Risikogesellschaft*' of 1986. Kaufmann [1992, 15-20] distinguishes three distinct kind of industrial modernization risks which are implicitly addressed by Beck. First, modern high technologies involve a considerable potential for catastrophic events (e.g., nuclear power plants; Tschernobyl). Second, the cumulation of specific routine industrial processes leads to potentially dangerous changes in ecological processes (e.g., large-scale combustion of fossil fuels leads to climate change). Third, modern biotechnologies and especially technologies aiming at the manipulation of the genetical code of living beings (e.g., humans) involve risks which are not fully understood today. The focus here is on the first two kinds of risks.

In the past, most dangers (risks) did arise from entities external to society (nature, gods). Modernization risks, however, arise from the internalization of nature into the industrial production process and the scale of human interaction with nature. Modernization, set out to abolish the risks and dangers imposed by nature (and gods) onto humans, does now – by achieving its aims – create risks and dangers of its own. Beck coins the term 'reflexive modernization' to conceptualize this phenomenon. In contrast to traditional risks, modernization risks are inherent to society, that is, they are produced by human beings in social formations. [Beck 1986, 107; 254]

Beck characterizes modernization risks as follows:

- Modernization risks are not exterior, but interior to society, and result from the close interaction of a large-scale industrial system with natural ecosystems (e.g., resource extraction, waste dumpage in various media, infrastructural (spatial) requirements of industrial facilities).

- Modernization risks can potentially affect everybody (all plants, animals, and humans) everywhere, that is, they show a tendency for globalization.
- Modernization risks cannot be detected by human senses. Scientific methods and instruments are required for their detection. They are therefore perceived as socially constructed phenomena.[46]
- Modernization risks are irreversible.

On could assume that the risks of modernization, being external to society, should be easier to resolve and abolish than traditional dangers and risks. However, the concept of reflexive modernization comprises two additional issues which explain why this is a more complicated issue. First, the emergence of modernization risks in industrial society gives rise to novel lines of conflict that are distinct from those of traditional and industrializing societies. That is, lines of conflict are determined by the social distribution of risks rather than the social distribution of wealth and power. Therefore, existing and institutionalized modes for conflict resolution are inappropriate for dealing with modernization risks. Second, reflexive modernization changes the character of science from a social system which presents itself as relatively uniform to the general public (i.e. criticism remains within system boundaries) towards an appearance marked by conflicting and contradicting statements equally claiming validity. Science does not provide a single integrated account of the (social and natural) world, but offers differing world-views depending on the methodological (and value) decisions of researchers. The increase of the human potential for (inter-) action in and with nature and social systems (increasing complexity) allows multiple scientific perspective to claim validity and plausibility, and society as a whole is faced with an increasing number of options among which it has to choose. Modernization, by realizing its own aims (including increase of the human potential for self-determination of the human conduct of life), is turning reflexive. [Beck 1986, 251-253]

Due to these fundamental structural changes, Beck states that a second phase of modernization is required in order complete the project of modernity and to overcome its current shortcomings (e.g., the systematic production of modernization risks). However, he is not very optimistic about the possibility of that prospect. The reason for this is that some social groups (e.g., industrial corporations) currently do have strong vested interests in having the status quo of industrial procedures remain unaltered. This leads to the (historically) new lines of societal conflict and cooperation that have been mentioned above (e.g., between those deriving benefits from the generation of modernization risks, and those who are affected by their impacts, without deriving direct benefits). Classical and institutionalized lines of conflict and cooperation (e.g., capital versus labor, nation states versus each other) are likely to be inappropriate for dealing with modernization risks. [Beck 1986, 61]

[46] Beck derives two conclusions from this: first, mass media can play a crucial role in propagating or not propagating certain definitions of risks. Second, science should be institutionalized in a way that allows for a competition of different scientific perspectives. [Beck 1986, 61-62]

Beck remarks that the generation and regulation of modernization risks is currently subject to a 'subpolitics' that is not negotiated in classical institutions of representative democracy (parliament, professional politicians) but in informal conflicts between industrial corporations, citizen movements, and environmental NGOs (for example). While Beck concedes that these subpolitical processes imply a potential for an improvement of democratic culture, and that the principal and guiding idea of future political procedures for dealing with modernization risks should be to incorporate subpolitics into a legitimate democratical process that deals with the problems and opportunities that arise from competing claims of knowledge within the sciences, Beck can not offer a comprehensive view of such a democratical set of institutional arrangements.[47]

Therefore, in the following section John Dewey's conceptualization of public problems and public inquiries as means for dealing with public problems will be discussed.

3.1.2 Modernization risks as public problems

Sixty years before Beck's *'Risikogesellschaft'*, John Dewey (1859-1952), next to Charles Sanders Peirce (1839-1914) and William James (1842-1910) the most reknown representative of the American philosophy of (classical) pragmatism, published a booklet with the title *'The public and its problems'* (1928). In this book Dewey develops – at the begin of the 20th century – a political philosophy which has surprisingly much in common with the requirements to a political framework able to deal with the consequences of modernity as put forward by Beck. Dewey personally experienced the consequences of a unregulated process of industrialization and modernization (systematically leading to modernization risks) in Chicago at the turn of the 20th century, when large-scale migration, impoverishment and environmental degradation resulted from the massive social and physical transformations commonly referred to as urbanization and industrialization. [Westbrook 1991; Rost 2003]

Like Beck, Dewey assumes that the project of modernity in its current state has not been completed yet. A second phase of modernization has to meet and overcome the shortcomings of the first. Dewey also aims at finding a democratical political form to achieve this goal. However, unlike Beck, Dewey develops a systematic approach of how modern industrialized democratical societies might deal with the social and technical forces that have been unleashed by the process of industrialization.

The systematic starting point of Dewey's framework is the concept of indirect consequences of actions which concern third parties who are not directly involved in transaction between agents (or actions of an individual agent). All those who are affected by indirect consequences of actions constitute a public, as opposed to a private sphere which is

---

[47] This is because Beck remains bound to the concepts he does critize himself: for Beck, classical politics has a strong connotation of exerting (monarchical) central power. [Beck 1986, 312] Subpolitics, in the contrary, are perceived to have an inherently strongly anti-hierarchical bias. Because Beck contends that the modernization risks shaping subpolitics cannot be dealt with through the institutional framework of classical politics, he doubts whether there can be any viable political framework for dealing with modernization risks at all. This follows from his lack of an alternative conceptualization of politics that may allow for an integrated application of both centralized power and truly democratic procedures (institutions).

constituted through the direct consequences of transactions of agents that do not affect third parties.[48]

If indirect consequences of actions can be identified, a society may – depending on the evaluation of their respective character – seek to either stabilize or avoid such consequences. If the indirect consequences are identified and regulation is introduced in order to either stabilize (public goods) or avoid them (public problems), the first step towards the formation of a state has been done. If officials and public institutions are implemented in order to regulate indirect consequences of actions in the interest of the public, and common property (*res publica*) is assembled by the public (*populus*) in order to enable the officials to reach these goals, the basic features of a state are at hand. The government is not the state, as the state also principally comprises the public; but the public is organized in and through officials. Therefore, the state represents an important, but specific and limited societal interest.

Dewey notes that this view of the state does not comprise a belief in any particular form of a political system. Instead, continuous monitoring of indirect consequences of actions, behavior of officials, institutions, and affected individuals and groups, as well as the impacts of changing technology on social arrangements and the development of new ways of thinking and observing (monitoring) social processes enables and makes necessary changes in the specific character of the regulation of public affairs. Therefore, Dewey also speaks of 'democratic experimentalism' which involves the idea that organization of the public as a state is never finite, and that roles of officials and related institutions should principally be regarded to be merely hypothetical. This should enable steady adaption of the institutions and roles of officials to the changing conditions of the social and physical world.

According to Dewey, (interdisciplinary oriented) social sciences could play a major role in identifying indirect consequences of actions and proposing institutional role sets for officials in order to enable the regulation of desirable or avoidable consequences of actions in efficient ways (political counseling). It has to be ensured, for example, that officials do in fact represent the interests of the public and do not make use of their power in order to serve personal interests. Changing means of thinking about institutional arrangements (e.g., new social science theories), or changing circumstances (e.g., globalization, technological change) may enable new designs of rolesets for officials and institutions. Therefore, Dewey refrains from proposing particular schemes for regulating public affairs (apart from the classical concept of checks and balances of power) and states that these questions should be left open for treatment in particular socio-cultural and historical situations.

However, the social sciences can only be one part of a more general social process that identifies and regulates public goods and problems. In his later epistemological work *'Logic. The theory of Inquiry'* (1938), Dewey designs a social process of public inquiry which has little to do with classical epistemology, but is concerned with the question of how modern societies can establish forms of communication that allow to collectively establish and share a view of public goods and problems. The process of public inquiry developed by Dewey comprises several phases: First, a problematic situation has to be qualified and described. A

[48] Hence, the terms public and private do not correspond to the concepts 'social' and 'individual'. The private is (can be) social, and the public can arise from individual phenomena (action) as well.

situation is problematic if there is a tension between a living being (living beings) and their environment and if this tension cannot be resolved by means of habitualized modes of conduct or readily available means and methods. Second, the problem is formulated.[49] Third, a solution hypothesis is constructed. Fourth, rational deduction involves the semiotic interplay of solution hypothesis and problem formulation, and if required, the generation of new hypotheses. Fifth, empirical facts and theoretical concepts (hypotheses) are combined experimentally and operationally. Then, real operations can be carried out to restructure the empirical environment. Finally, judgements are made which have the ontological status of warranted assertions, that is, they are results of specific research that can be modified at any time, but which for the time being enable to settle the initial problematic situation by their implementation. Within the inquiry, several loops allow for starting the process over by using differing guiding ideas or hypotheses. Throughout the process, an intercommunication of lay and expert cultures is to take place integrating common sense views and scientific discourse. Communication is the methodological basis of Dewey's concept. Art can play a crucial role in supporting the intercommunication of lay and expert cultures, for example by communicating findings of the natural and social sciences to the general public. [Rost 2003; Krüger 2000]

Dewey's historical diagnosis in *'The public and its problems'* runs as follows. Industrialization involved the introduction of new technologies which lead to a fundamental revolution in social affairs. Without announcement or intention, local communities found themselves dependent on distant and invisible organizations. The rise of the 'Great Society' is characterized by a remarkable increase in the production of commodities and the introduction of relatively mechanical and unpersonal forms of living into local communities. Dewey's specific analyses of these impacts is of less interest here than his principal conclusion that the riches produced by the means of the Great Society have the potential to make the human condition on earth more humane than ever, which is due to the superior productivity achieved in the Great Society. Unlike a line of thought running from Plato to Rousseau, Dewey's reaction towards the Great Society is not to long for an imagined idyll of 'primitive' ways of life, but to overcome the shortcomings of the Great Society while preserving its potential of improving the general human condition.

The systematic considerations that aim at accomplishing this have been summarized in the paragraphs above. In order to bring these concepts into relation with the Great Society – that makes them both possible and necessary – Dewey introduces the concept of the 'Great Community'. The Great Society can be transformed into a Great Community if public goods and problems can be identified and regulated as outlined above. The very constitution of a public dealing with the implications of the Great Society marks the rise of the Great Community. The Great Community has little in common with local communities. While these are based on face-to-face relations, the Great Community is formed by communication via impersonal media. According to Dewey, the Great Community (public) is currently distracted and unable to constitute itself due to its disparancy and mobility. This is not to assume Dewey aims at establishing a monolithic singular culture – in the contrary, his is a

[49] This is a very crucial step because it determines the selection of aspects which are considered relevant for solving a problem.

concept of tolerance that exceeds the notions of mere negative freedom but embraces the cultural potentials of a pluralistic society. Dewey's notion is rather that those who are affected by indirect consequences of actions today are not able to identify their common interests due to the current conditions of the Great Society, a state that can be overcome by the means of processes of societal communication.

As noted by Dewey, social science analyses in particular historical and socio-cultural situations require particular theories and concepts. Therefore, in order to analyze the social implications of CCGS in the following subchapter 3.2, some theoretical concepts are required that enable such analysis. In the following section the basic notions of conflict theory as currently represented by Randall Collins are presented. The final section of this subchapter will then introduce two theoretical perspectives for gaining an understanding of the social conditions of technological change.[50]

3.1.3 Conflict theory

Conflict theory[51] aims at analyzing the organization of society and the behavior of people and groups and at explaining why structures take the forms they do at various historical times as well as in local situations, and how and what kind of changes do occur. It has emerged from attempts to strip Marxism off its political bias towards socialism as well as the strict focus on the analytical category of class conflict.[52] For conflict theory, socialism, capitalism or anarchism are societal structures which all are equally subject to theoretical analysis, and class conflict is an analytical category no more important than that of power, property or status structures. [Collins 1990]

The focus of conflict theory on geopolitics (military and international politics), politics (states),[53] status (culture/ ideology) and class structures/ property (economics) as primordial analytical categories reflects the incorporation of Weberian ideas into the body of theoretical positions that has been formulated by Marx and Engels.[54] Michels, Pareto, Mosca, Simmel are other thinkers that have formulated some of the positions put forward by contemporary conflict sociology, which has first been formulated and elaborated as such in the 1950s and

---

[50] With respect to Dewey's conception of the role of social sciences in dealing with public problems, the chapters 2, 4 and 5 of this thesis can be regarded as contributions to a process of public communication about how to deal with climate change in general, and the prospect of implementing CCGS as a mitigation option in particular.

[51] Collins [1990] implicitly argues that conflict theory comprises (or can comprise) application in several academic disciplines, including sociology, history, economics, ethnology etc. It can be assumed that this is the reason his terminology in Collins [1990] is one of conflict *theory* rather than conflict *sociology*, which is the title of Collins' major contribution on the issue (Collins [1975]). Joas and Knöbl [2004, 253] argue that conflict theory has historically emerged from conflict sociology, and prefer the term theory because it underpins that this approach is a genuinely distinct theoretical approach.

[52] Collins states that in fact „it is fair to say that modern conflict theory emerged as an effort to produce a nonideological version of Marxism." [Collins 1990, 68] Joas and Knöbl [2004, 251-283] argue that the emergence of conflict sociology in the 1950s and 1960s must be viewed in context of the dominance of the structural functionalist paradigm developed by Talcott Parsons, which emphasizes social order rather than social conflicts.

[53] Geopolitics/ military and state politics are two aspects of the Weberian category of power.

[54] Collins [1990, 68] even claims that "conflict theory has been implicit in historiography and social thought since at least the time of Thucydides."

1960s by Ralf Dahrendorf, Reinhard Bendix, C. Wright Mills, Lewis Coser, David Lockwood, and John Rex.[55] [Collins 1990, Joas and Knöbl 2004]

The basic theses of conflict sociology are the following [Collins 1990, 68]:

1) The central feature of social organization is stratification, the kind and degree of inequality among groups and individuals and their domination over one another.
2) The causes of what happens in society are to be sought in the interests of groups and individuals; above all, their interests in maintaining their positions of domination or evading domination by others.[56]
3) Who wins what in these struggles depends on the resources controlled by the different factions, including material resources for violence and for economic exchange, but also resources for social organization and for shaping emotions and ideas.
4) Social change is driven especially by conflict; hence long periods of relatively stable domination are punctuated by intense and dramatic episodes of group mobilization.

This is not to say that conflict theory does not take into account patterns of solidarity (cooperation) that tie social groups together. [Collins 1990] Cooperation is pre-requisite to conflict between groups insofar as groups can act as such only if cooperating internally in some way; also, conflict often occurs within principally cooperating groups. In addition, conflicts carried out through communication processes can often lead to learning processes on behalf of all participating parties, which enable solutions which are encountered as valuable by all participating parties.[57] [Joas and Knöbl 2004, 277-283] When analysing social settings, both aspects (cooperation and conflict) have to be taken into account, although the focus of conflict theory – as implied by the term – usually is on conflict.[58]

The analysis of organizations can be regarded to be one of the most important applications of conflict theory and has been developed in this sense first by Max Weber and Robert Michels. Organizations are the building blocks of capitalist enterprises, parties, states, armies, churches, and virtually every other contemporary (and historical) social phenomena. [Collins 1990] In order to understand society, understanding of organizations can be regarded as a central key.

Collins [1990] claims that conflict sociology is predominantly empirical in its bias. The basic themes of domination, interests, resources for control and mobilization, and the episodic and

---

[55] There are, of course, different strands within conflict sociology itself. Coser, for example, remained within the framework of structural functionalism. [Joas and Knöbl 2004, 257] The position presented here is based on the perspective formulated by Collins [1975, 1990].

[56] It is important to note that while it is acknowledged here that struggle for domination is an important factor for motivating social action, it is not the only factor. Values e.g. can be important driving forces for social action as well. [this approach has most notoriously been put forward by Charles Taylor. See Taylor 1999, 1992; Rosa 1998; Honneth 1999; Schubert 2002]

[57] Joas and Knöbl [2004, 277-283] identify the lack of recognition of this aspect (role of culture and values in generating social consent and hence cooperation) to have been a central reason for the decreasing significance of conflict theory in sociology (except for historical macrosociology) since the 1970s. It is assumed here that conflict sociology is not principally irreconcilable with this notion.

[58] Which may be attributed to the historical emergence of conflict theory as opposed to structural functionalism.

conflictual nature of change are applied in political sociology,[59] social movement theory, sociology of professions, sociology of education, criminology, and studies of stratification and social change.

Conflict theory envisions a future in which both cooperation and a variety of conflicts – military, organizational, economic, and ideological – will continue according to their respective rythms, without an end. [Collins 1990]

3.1.4 Endogenous technological change

The following two citations characterize the contemporary state of affairs in the understanding of technological change in the social sciences:

> "Technology is one of the unexplored dark spots in the social sciences." [Collins 1986, 77]

> "The theories and models of technical and institutional change available to us at the present time are not well articulated. In attempting to understand the generation and adoption transfer of new technology and institutions, we are confronted with a kit of loose tools and a body of historical generalizations." [Ruttan 2001, 61]

However, despite the absence of an integrated and comprehensive theory of technological change, there are theoretical considerations available that facilitate an understanding of the social dynamics driving technological change. First, the approach of Randall Collins is presented who sketches some central sociological conditions that have to be met in order to render development of a technology a success in terms of high market diffusion rates. Second, the basic theoretical framework developed for the Integrated Assessment Model MIND is presented in order to gain an understanding of the economic forces driving technological change.

Randall Collins – Sociological conditions of technological change

Collins aims at a general (transhistorical, intercultural) understanding of the genesis and social diffusion of technology. While he takes notice of economic theories of technology including modeling of profitability and costs of technology in relation to growth, interindustry productivity, rates of diffusion, evolution of particular technologies and the behavior of particular firms,[60] he criticizes that these approaches lack historical and macrosociological explanatory leverage because they assume the prior social and economic complex that makes up the modern market economy. [Collins 1986, 77] Collins therefore undertakes some historical comparisons in order to develop a broader sociological theory of technology. The focus here will be on his central findings.

Collins distinguishes two phases of technology development: innovation and diffusion. The process of innovation is not problematic from his point of view:

> "It appears that innovation is relatively easy, as far as the production of new ideas is concerned. The initial idea itself is rarely the crucial part of any invention, and, indeed, possible ideas seem to be far more widely available than their utilization. (...) It follows that

---

[59] Including geopolitical analyses based on Weberian theory as put forward by Kennedy [1989] and Collins [1986], for example.

[60] Such approaches are discussed more extensively in Ruttan [2001]. One such particular approach is presented in the following subsection.

whenever there is the social pressure to innovate, solutions will always be found. The possibility of future inventions, at any point in history, always extends to infinity." [Collins 1986, 115]

Collins argues that innovations usually arise from (a) incremental extensions of previous technologies and by (b) responses to crossovers and problems that occur during the process of expansion and diffusion of a technology.[61]

According to Collins, it is the process of social diffusion of a technology which is crucial for its successful and sustained development. Whether or not a technology will be widely adopted depends on the respective social conditions. The most important social conditions and their implications for technology deployment can be summarized in four points:

1) Competition in a specific social field (e.g., military, or energy use) fosters the development and adoption of innovative technologies by social actors who want to sustain or improve their relative position in such competitions. Economical markets are but one institutionalized form of competition and increase the rate of innovation and diffusion of new technologies. Other forms of competition (e.g., religious, political, military) can foster innovation and diffusion as well.[62]
2) The tighter the bonds of communication between social actors are, the faster the rates of diffusion.
3) If functionally equivalent technologies are available, the technology with lower costs is preferred because the resources saved can be spent otherwise (e.g., for improving the relative position of an actor in another area of competition).
4) A particular innovative technology will become socially adopted (diffuse) if there are agents with the necessary resources (e.g., economical, political, military, ideological) and the temporally sustained motivation to implement the innovation. Motivation to implement a technology can arise from the relative position of agents within a competition and the advantage they expect from adoption of the technology within that competition, for example.

These principal considerations should suffice to provide a general picture of the social conditions for technological change. In the next subsection, a more particular economic approach is presented which narrows the social conditions of technological change to the issue of intertemporal investment decisions of agents in market competitions under conditions of uncertainy.

MIND – Economic conditions of technological change

The Integrated Assessment Model MIND developed by Edenhofer et al. [2005] comprises a macroeconmic growth module with endogenously represented technological change and is

[61] Collins' optimistic perspective on the abundant availability of innovative concepts appears very questionable. It is very likely that historical situations in which there was social pressure to innovate but where it did not happen could easily be identified. However, this point is not of importance here.

[62] More generally, innovation is more likely to happen in areas of greater geopolitical importance. This is because these areas are subject to increased competition from other areas of less geopolitical relevance which aim at achieving the dominant geopolitical position.

based on a number of theoretical considerations which allow for a more detailed understanding of technological change than the principal considerations of Collins outlined above.

The first basic claim put forward by Edenhofer et al. is that investments render particular technologies more cheaply due to "learning by doing" effects. That is, the more capacity of a technology is installed, the lower will its economic costs get. This effect is quantified by a "learning rate" which denotes how much costs per performance units installed decrease if capacity increases.

The second basic claim is that investments are reactions of economic agents to scarcities. Faced with a particular factor scarcity (e.g., labor), economic agents invest into reducing the constraint resulting from that scarcity (e.g., by conducting investments that increase labor productivity).

Historically, there has been no principal scarcity in the energy sector. It can be held that fossil fuel resources are going to be available at relatively low cost until late in the 21st century due to technological progress in the fossil fuel extraction sector. [Rogner 1997] However, climate change imposes an indirect constraint on the use of fossil fuels for combustion already today.

In model runs the model MIND assumes that the global economy will remain within a tolerable window of global climate change, that is, current GHG emissions will have to be reduced substantially. MIND then calculates the intertemporally optimal investment path that renders meeting such a climate "guardrail" cheapest from a social planner point of view. It can be shown that endogenous modeling of renewables (including learning by doing) and CCS as climate change mitigation options (as well as intertemporal investment strategies) considerably decreases the costs of meeting a relatively safe global emission path. According to simulation results meeting such a path will consume only 0.81% of the global GDP. The key to keep climate change mitigation costs low is early allocation of investments to renewable energy technologies and CCS. [Edenhofer et al. 2005]

3.2 A social science perspective on CO_2 capture and geological storage

In this subchapter empirical aspects of CCGS will be investigated. First, relevant stakeholders for the implementation of CCGS are identified and their respective positions discussed (3.2.1). Then, the available studies of public perceptions and acceptance of CCGS are presented (3.2.2). After that some geopolitical aspects of CCGS are investigated (3.2.3). Finally, social determinants of the viability of CCGS are identified and discussed (3.2.4), and the chapter is concluded with a brief assessment of the gains that the theoretical concepts presented in 3.1 can yield in their application to CCGS.

3.2.1 Relevant stakeholders

In the following, relevant stakeholders that are or may become important with respect to the implementation of CCGS are identified and some remarks concerning their position are made. However, much more detailed and empirical research would be required in order to be able to present valid results. Therefore, the notions presented here should rather be regarded as an assemblance of preliminary hypothese that can enable future empirical (e.g., expert interviews) sociological analyses.

The stakeholders discussed are:

- Fossil resource extraction and energy industries
- Renewable energy industries
- Finance
- Public Authorities
- Public
- Academia and Science
- Environmental NGOs (ENGO)

Fossil resource extraction and energy industries – With climate change being a widely accepted public problem today, and efforts for mitigating climate change being subject to international political negotiations, the fossil fuel extraction and energy industries are in a difficult situation because their core business is the very source of this public problem. If renewable energy carriers can crowd out fossil fuels due to political measures in the future, this will imply an expropriation of the fossil fuel industries. Therefore, CCGS is of particular interest for the fossil fuel industries[63] because it may allow for both continued use of fossil fuels and global climate protection, thereby allowing to avoid expropriation and public pressure that could arise if fossil fuels would be continuously burnt in the face of future climate change events.

The fossil fuel energy (electrical power) sector is increasingly facing political measures of market liberalization, e.g. in Europe. This increases the pressure on companies to keep their costs low. If CCGS were to become a large-scale climate change mitigation option, this pressure may hinder firms to adopt CCGS because they might fear competitive

---

[63] Especially the coal industries, due to the high ratio of CO_2 emissions per unit of energy in coal.

disadvantages. [Senior et al. 2004] If faced with (for example) an emission cap and trade regime, however, CCGS may in fact become a way to actually increase the economic efficiency of fossil fuel use. On the other hand, Senior et al. [2004] state that the power industry is principally risk averse due to the steady and modest returns of the industry's operations combined with a high proportion of debt financing. This could reduce the willingness to invest into new technology like CCGS. Therefore, Senior et al. [2004] point out that as long as the regulatory environment for CCGS (i.e. regulation of risks and economic incentives) remains uncertain, there will be no (short-term) large-scale investment into CCGS by the power industry at all.

Already, firms are emerging today that may engage in CCGS as professional 'CCGS-companies' offering capture technologies, CO_2 transport and geological storage services to energy providers or other companies producing CO_2 streams at large point sources (for example, Kinder Morgan CO2 Company, or ABB). Apparently, these companies do have a considerable interest in the introduction of CCGS because a new field of business opportunities would be generated. [Fischedick et al. 2004, 17]

Renewable energy industries – While at first sight it may appear that the position of renewable energy industries towards CCGS should clearly be negative because the fossil fuel energy sector is the direct and dominant competitor with superior resources, the relation of renewable and fossil fuel industries may in fact be a more complicated issue. First, the renewable industries might be faced with a similar problem as Environmental NGOs (see below). That is, as they may blame the use of fossil fuels for triggering climate change and could use this argument to substantiate the claim that their business – contrary to that of the fossil energy industry – is for the good of society (and that doing good for society is an important motivation for their business), this claim could lose credibility if CCGS would be attacked as a climate change mitigation option right away. At least, this consideration may keep the renewable energy sector from attacking CCGS too sharply, as such polemic is likely to be perceived by the public as the same 'egoistic' (and morally illegitimate) behavior that is often associated with the fossil fuel industries. To sum up, CCGS could impose a challenge to the moral credibility of the renewable energy sector.

Another consideration may keep the renewable energy industries from attacking CCGS too sharply. If renewable energy firms are unsure whether they are going to be able to deliver the amounts of energy required by society in the next 50 to 100 years, they may in fact be interested in fossil fuels being used in the future – to some extent – in order to reduce the performance pressure on renewables. Imagine a society trusting the renewables to be able to meet its future (rising) energy demands and implementing regulation accordingly, but renewables not being able to deliver the energy quantities required, thereby hindering economic development. Such a scenario would impose significant public pressure on renewable energy firms. While the scope of significance of these considerations should not be overstated, they may still motivate the renewable energy sector to not criticize CCGS as strongly as it may initially be expected.

Finance sector – there are two major groups of financial agents that could be of importance for CCGS: investment fonds and banks will be required for providing capital, and insurances may come into play for insuring risks of CCGS operations, depending on regulatory schemes.

Senior et al. [2004] remark that access to capital may be a critical factor in the fossil energy sector, as US$ ~4 trillion investment will be required for new electricity generation capacity over the next 30 years. The adoption of CCGS may increase capital costs by a non-trivial 15-20%. The added capital requirements may create additional pressure on financial markets and energy companies in a liberalized market. In addition, renewable energies will also require considerable amounts of capital if they are to compete with the fossil fuel sector. Investment fonds and banks could therefore play an important role in allocating investments either towards fossil or the renewable energy technologies.

Concerning insurances, these could play an interesting role in a future regulatory framework for CCGS if they are willing to engage in these operations. In case insurances refuse to become involved in CCGS e.g. due to high or uncertain risks, this may turn into an important argument for opponents of CCGS. In this case, it could be argued that market forces rule out the implementation of CCGS. Also, insurances are interested in mitigating climate change in order to avoid the related damages.

Public authorities – Four kinds of public bodies are likely to become involved in CCGS: governments, legislatory bodies, jurisdiction, and regulatory authorities. Because CCGS is a strategic technology option with respect to its significant scale (costs) and social meaning (climate change mitigation) and will require political regulation, governments will have some influence of the adoption of CCGS. It appears likely that within governments tensions will arise between different groups, e.g. economic and environmental ministries and, of course, different political parties.[64]

Legislatory institutions may become important for implementing regulation for CCGS.

Jurisdictional bodies, that is, courts (judges, and state attorneys) may become important in case of damages or setting up of individual CCGS operation sites. Jurisdiction could create precedents that could foster or hinder the adoption of CCGS in a specific society/region.

Regulatory authorities may be required for the implementation of CCGS, e.g. an environmental authority, or a technical assessment authority (in Germany, for example, Technischer Überwachungsverein TÜV).

Public – Following the definition of Dewey (see 3.1.2) in case of CCGS the general public is constituted by all those who are thirds affected by the transactions and processes involved in CCGS. In fact, different publics can be distinguished with respect to different aspects of CCGS. The local public is constituted by all those who are affected by local risks of CCGS (see 2.4.9). A regional public is constituted by all those forming a tax union and who therefore may be affected by subsidization of CCGS (e.g., nation state level), and more generally, by all those who are affected by economic risks of CCGS. Finally, there is a

[64] Fischedick et al. [2004, 84-85] conducted a survey of the attitude of german parties towards CCGS. The governing party SPD has not published a statement concerning CCGS yet. The green party (Bündnis 90/ Die Grünen) has a mixed attitude but considers CCGS technologically immature and therefore proposes to focus on alternative climate change mitigation options. The CDU is very much in favour of CCGS and calls it one of the substantial 'cornerstones' of its energy policy. The FDP considers CCGS an option both worth and requiring more research. The PDS refuses CCGS because it aims at a complete switch to renewables until 2050.

global public with respect to CCGS because this technology aims at resolving the global problem of anthropogenic climate change.

Empirically, protests to CCGS operations or analogues have often been started by local communities in the vicinity of the respective industrial or research applications. Experience in US industrial waste injection has shown that opposition from communities near operating injection facilities can be strong, especially when the wastes are not generated near the injection site. [see Heddle 2003; Benson et al. 2002, appendix 14; de Figueiredo et al. 2002] Benson et al. [2002, 7] list the following critical issues that often arise in such conflicts: (i) decrease in nearby property values, (ii) local accidents associated with mixing wastes, (iii) leaking surface impoundments, (iv) air pollution, and (v) transportational hazards. Facilities far from population centres are generally subject to less local opposition. [Benson et al. 2002, 7]

It can be assumed that in general the public will aim at minimizing the risks and maximizing the opportunities of CCGS, although there will be trade-offs. Other than that, it appears difficult to define the interests of the public in CCGS before a public process of communication has been established identifying these interests.

Science and Academia – Science and Academia here is defined as all researchers and students dealing with CCGS in some way. A simple distinction may be made between those researchers working towards making CCGS a feasible technology option and those having a more detached position. While the former are likely to promote the development CCGS in order to make it a success story, and might therefore focus on the opportunities of CCGS (as such a strategy will be in line with their personal interests, e.g., increase research funds), the latter may be more reluctant to promote CCGS. For them a success of CCGS might not be coupled with their personal interest. In fact, they may derive peronal benefits from adopting a critical perspective towards CCGS.

The academic and scientific disciplines involved in CCGS include engineering, geology, biology, economics, political sciences, and sociology, each with specific subfields. Therefore, dealing with CCGS makes an interdisciplinary approach inevitable.

Environmental NGOs – Environmental NGOs[65] (ENGO) are in a similar strategic situation with respect to their position towards CCGS as the renewable energy sector, but for ENGOs the issue of moral credibility is of even greater importance: it is their most important resource (enabling them to shape public ideas and convictions). If environmental NGOs would attack CCGS as a climate change mitigation option and the fossil fuel industries would succeed in framing CCGS a viable way to mitigate climate change, environmental NGOs could suffer a severe loss of public credibility.

In less 'ideology critical' (conflict sociological) terms it can be argued that if environmental NGOs are in fact interested in mitigating climate change, CCGS could be an interesting option for them, too, under the condition that the global and local risks are very low (and the worst-case scenario for CCGS involves relatively low risks). The difficult position for ENGOs arises – to some extent – from the fact that the fossil fuel industries have traditionally been the concept of the 'enemy' (next to the nuclear power industry) of the

[65] For example, Greenpeace and WWF on an international scale, and NABU, BUND, and Germanwatch in Germany.

environmental movement from which the ENGOs have emerged. Also, ENGOs explicitly support the introduction of renewable energies and increases in energy efficiency as climate change mitigation options. However, if e.g. leakage rates from CCGS operations are negligible, costs low, and (public) investments into the renewable sector not reduced, there would be little reason to refuse CCGS.[66] This would be different, of course, if risks and costs were (perceived to be) relatively high. In this case, environmental NGOs could be a very important opponent in a conflict about the implementation of CCGS. [for the mixed feelings of environmental NGOs towards CCGS, see e.g., Greenpeace 2004a, 2004b[67]; WWF unknown; Union of Concerned Scientists 2002; Anderson 2003; Hawkins 2001; Germanwatch 2004; Fischedick et al. 2004, 83-84; Keith and Morgan 2000, 22-23]

In addition, environmental NGOs may regard CCGS as a strategic opportunity to make higher emission reduction goals politically viable. However, if NGOs perceive CCGS as a means used by the fossil fuel industries and public authorities to delay negotiations of emission reductions targets, they are very likely to strongly oppose it. [Hawkins 2001]

3.2.2 Public perceptions of CCGS

In general, very little research has been conducted so far on public perceptions of CCGS. Such research is facing two central challenges: first, the relatively technical and 'remote' nature of the issue, meaning that there are few immediate points of connection in the lay public's frame of reference to many of the key concepts. Second, the early stage of the technology, with very few examples and experiences in the public domain to draw upon as illustratios. [Shackley et al. 2004, 12] In the following, the available studies on the public perceptions of CCGS are summarized and presented.

Curry et al. [2004] conducted an internet survey of 1,205 people (representing 70% of the 1,710 persons approached) in the US in September-October 2003. They found that only 4% (n=46) had heard of CCS in the past year. Education level was the only demographic indicator distinguishing those who had heard of CCS. However, only 0.5% of the entire sample – i.e. not all of those who had claimed to have heard about it – knew that CCS is a technology that aims at mitigating climate change.

Environmental policy ranked 13th in a list of policy priorities of US citizens at that time. Of environmental concerns, global warming ranked sixth out of the issues asked in the survey. Among those who listed the environment as one of their top three policy concerns, global warming was ranked third highest among environmental issues.

It can be concluded that in the US, global warming is not perceived to be a top policy issue (terrorism was found to be the top issue) and is not a top environmental concern. CCS is unknown to the general public.

---

[66] Some environmental NGOs in the Netherlands have declared their conditional support for an experimental GS project. [Huijts 2003, 24]

[67] In these papers Greenpeace Germany has adopted a critical perspective on CCGS, that is, only if increases in energy efficiency and implementation of renewables are not sufficiently successful, the risky option of CCGS is thought to be worth further considerations. A similar position is adopted by WWF.

Itaoka et al. [2004] investigated the public perceptions of CCS in two cities in Japan, Tokyo and Sapporo. 1,006 people (64% of those addressed) responded to a questionnaire, 504 in Tokyo and 502 in Sapporo. 31% of the persons asked were familiar with CCS. Of those who had heard of CCS, 36% indicated TV and another 36% newspapers as the source of information. 17.6% of all persons interviewed stated that they principally reject CCS technology.

The study also investigated the impact of differing levels of information. Two information sheets on CCS were introduced after asking the initial questions concerning CCS, one containing little and the other more extensive information on different CCS options. For all CCS options presented (mainly various ocean disposal concepts, but also off- and onshore geological storage) the level of acceptance rose with increasing amount of information, except for – interestingly – onshore geological storage (CCGS): it appears that increased levels of information for CCGS decrease its acceptance, whereas acceptance of ocean storage options (both direct and geological) increased with more information being provided.

Also, factor analyses were conducted identifying four 'underlying' factors that principally determined acceptance of CCS options. In addition, multiple regression analysis was carried out in order to determine the impact of the respective factors on the acceptance of CCS. The focus here will be on the findings for onshore geological storage. Factor 1 comprises concerns about risks and leakage and has the strongest and a negative impact on acceptance of CCGS. Factor 2 is labelled 'understanding of effectiveness of CCS' by Itakao et al. but the respective statements are maybe more accurately labeled 'trust in CCS as a feasible climate change mitigation option'. Apparently, this factor shows a positive correlation with acceptance. Factor 3 is 'social responsibility' and summarizes statements that suggest that climatic change is an important issue that should be addressed immediately, that richer countries should deal with it first, and that current generation should not pass on economic and environmental burdens to following generations. This factor has a slightly negative impact (the lowest of all factors) on the acceptance of CCGS, that is, the higher the feeling of social responsibility, the lower the acceptance of CCGS. Factor 4 integrates statements of concern about the continued use of fossil fuels and has a negative impact on the acceptance of CCGS. In addition, the multiple regression analyses revealed that women are slightly more prone to reject onshore CCGS than men.

Shackley et al. [2004] conducted both focus group analyses and a face-to-face survey. The focus group analyses are presented first. Two citizen panels of 8 and 9 members in Manchester and York met five times for two hours. While the Manchester panel consisted of women only, the York panel exclusively consisted of men.[68] The initial perception of CCS was positive in the Manchester panel after presentation of the technology by a geologist but got more differentiated when the panel was confronted with more skeptical expert opinions. It appears that the York panel was more skeptical in a general sense because some participants challenged the whole idea of global climate change (nobody in the Manchester panel did). At the end of the focus group process, three positions in each group could be

[68] It can be argued that rhis was in part reflected in the results as the Manchester panel focused on individual contributions to climate change mitigation through lifestyle changes, whereas the York panel put an emphasis on large-scale technology system transformations. Also, men were better informed about climate change science and more skeptical towards scientific experts than women.

distinguished. A minority in each group regarded CCS as either morally questionable (i.e. there were concerns if CCS as an end-of-the-pipe technology would keep society from treating the causes of climate change and implementing fundamental changes) or posing too great a risk in terms of geological integrity. A further minority (one or two individuals in each panel) regarded CCS quite positive. The majority, however, was rather lukewarm about CCS but considered it one of many necessary options in a portfolio of options for mitigating climate change (including decarbonization technologies, policies, lifestyle changes). Three underlying reasons for accepting CCS as part of a portfolio were identified by Shackley et al.: first, no single technology could meet an envisioned emission reduction goal of 60%. Second, lifestyle change was regarded an insufficient and unreliable means to mitigate climate change. Third, the risks of CCS were considered to be unknown at the present time, but the panels were reassured by a geologist's interpretation of the potential risks. Within each group, ambiguity in the statements of individuals could be observed. For example, some individuals that were principally not supportive of CCS would express a more positive attitude when expressing their skepticism about the potential of other climate change mitigation options. Others would express general support for CCS on technical and economic grounds, but in other contexts they did raise moral concerns.

In the survey of Shackley et al., 212 persons were interviewed face-to-face at John Lennon Airport (Liverpool) departure hall. A broadly (though not statistically) representative sample of the UK public (in terms of age, qualifications, household income and gender) has been obtained, though with an under-representation of low-income households and individuals with no qualifications. When first prompted with the idea of CCS (little information), 38% were against it, 13% in support, and the rest undecided. This changed in the course of the interview as more information was provided and CCS was put into perspective with other climate change mitigation technologies. In the end, 34% were against CCS and 38% in favour. That is, providing some information on CCS significantly improved the perception of it (although it cannot be derived from the study what kind of information was provided to the interviewed persons). Asked about their spontaneous concern about CCS, 49% answered 'leakage', and 36% regarded it as a means of treating symptoms rather than reasons of CO_2 emissions. Ecosystem impacts with 31% was the next issue raised most. Asked about who should fund CCS, 71% responded 'the oil industry', followed by 'the government' (54%).[69] Asked about who should regulate CCS, Government was the most frequent answer (46%), followed by the Environmental Agency (43%), Environmental Groups (34%) and the oil industry (32%). 16% were in support of a completely new governmental regulatory agency for CCS.

In general, Shackley et al. concluded that CCS is not as well liked as wind, wave, tidal and solar power, and energy efficiency measures, but there is slight support for it and CCS is certainly preferred to nuclear power and higher energy bills.

Huijts [2003] employs sociological (role of groups) and psychological (role of analytical and heuristic evaluation, trust and affect) approaches to the study of public perceptions of CCS. Three basic research aims were formulated: first to investigate the attitude of people when they are faced with CCS and the possibility of implementation of CCS operations in their

[69] Multiple answers were possible for this and the following question.

vicinity, second to understand determinants of attitude formation, and third to explore citizen's trust in different groups related to CCS (government, oil industry, environmental NGOs).

Citizens from three residential areas in the Netherlands, nearby Amsterdam were approached. All areas do have in common that they lie above gas fields and that light earthquakes have occurred in 1994 and 2001 (inducing no damages) which have been attributed to natural gas mining. Therefore, a higher awareness of geological underground operations could be expected (84% of respondents were aware of living above a gas field). Of 191 questionnaires handed out, 112 were returned (58%). The sample had a higher average education level than the general Dutch population. Brief information on CCS and the risks and opportunities involves was given, along with information on the attitudes of the Dutch government, oil industry, and environmental NGOs towards CCS.

Before reading the information, only 3% of the sample stated to know 'reasonably much' about CCS, and 58% said they knew 'almost nothing' ('a little': 21%; 'very little': 18%). After reading the (quite balanced) information, 46% stated that CCGS is a good solution to the climate problem, 25% considered it a bad solution, and 29% were undecided. While 55% considered CCS projects implemented further away from their homes desirable, only 25% thought so about projects in their immediate vicinity. Huijts labels this effect NUMBY (not-under-my-backyard), relating to the known concept of NIMBY (not-in-my-backyard).

Concerning affects towards CCS, the main reaction was 'worried', followed by 'powerlessness', 'feeling of annoyance', 'aversion', and 'calmness'. 'Trust', 'fear', 'satisfaction', and 'hope' were felt to a lesser extent, and 'joyfulness', 'pride', and 'stress' were hardly felt at all. While negative feelings are prevalent, CCS does not seem arouse people strongly because (a) calmness was an affect shared by many and (b) all average ratings did not lie at extreme points of the 7-point scale that was used, but indicated only slight tendencies. This is displayed in Figure 3.1.

Concerning trust, environmental NGOs were found to be trusted most, followed by government and industry. However, only trust in government or industry showed a (positive) correlation with the attitude towards CCS. This can be attributed to the marginal role NGOs play in actually implementing and running (regulating) CCS operations.

In general, people rated the perceived risks of CCS higher than the perceived benefits to society. Some people did not see any societal benefits at all. The perceived personal benefits were rated even lower. This reflects the fact that CCS is a locally implemented solution to a global problem.

Huijts [2003, 51] therefore concludes that local opposition might arise at CCS operations that are implemented under residential areas. Adoption in uninhabited areas may hence be preferable. However, acceptance of particular projects might be improved by increasing citizen's trust towards government and industry. Building trust, however, "should not only be aimed at proving the competence of the involved actors, but should also be aimed at showing that involved actors have goals that are similar to the goals of the citizens and that their intentions can therefore be trusted." [Huijts 2003, 62]

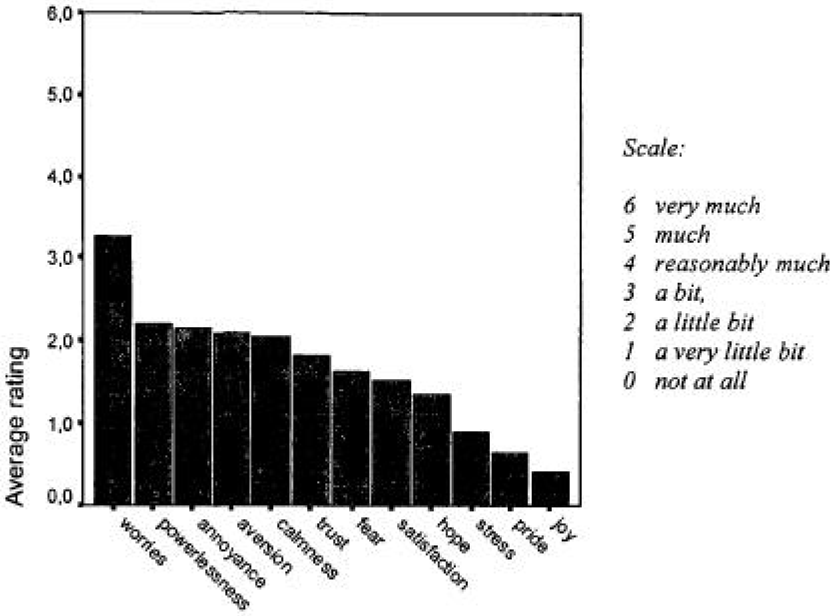

Figure 3.1: Average rating of twelve feelings when thinking about geological CO_2 storage. Source: Huijts [2003, 59].

Palmgren et al. [2004] conducted two studies in Pittsburgh (US), one comprising 18 semi-structured face-to-face interviews of about 45 minutes each, and a second in which 126 individuals were asked about their perceptions of CCGS and oceanic CO_2 disposal in a closed-form survey. The sample was older and more educated than the average american public. The design of the questionnaire for the second study was based on the findings of the first.

In the 18 interviews it emerged that the interviewed had a strong desire to frame CCS in the context of alternatives for climate change mitigation. Second, the interviewed were at unease with the idea that CCS may involve trading one problem (climate change) for another (leaky reservoirs, risks).

Study two revealed a considerable lack of support for CCS, with geological storage being favoured over oceanic disposal. Providing information on the technical aspects, risks and opportunities of CCS approaches even lead to a decrease in support, in particular for oceanic disposal.[70] Also, the general willingness to pay for CCS technologies was very low in relative terms (the interviewed persons were asked to rank 9 technology mixes that would reduce CO_2 emissions by 50%), and providing information decreased willingness to pay for oceanic disposal while slightly increasing it for GS. Both results are displayed in Figure 3.2.

[70] It seems worth noting that the informations provided on the risks of GS did not comprise the risk of groundwater contamination.

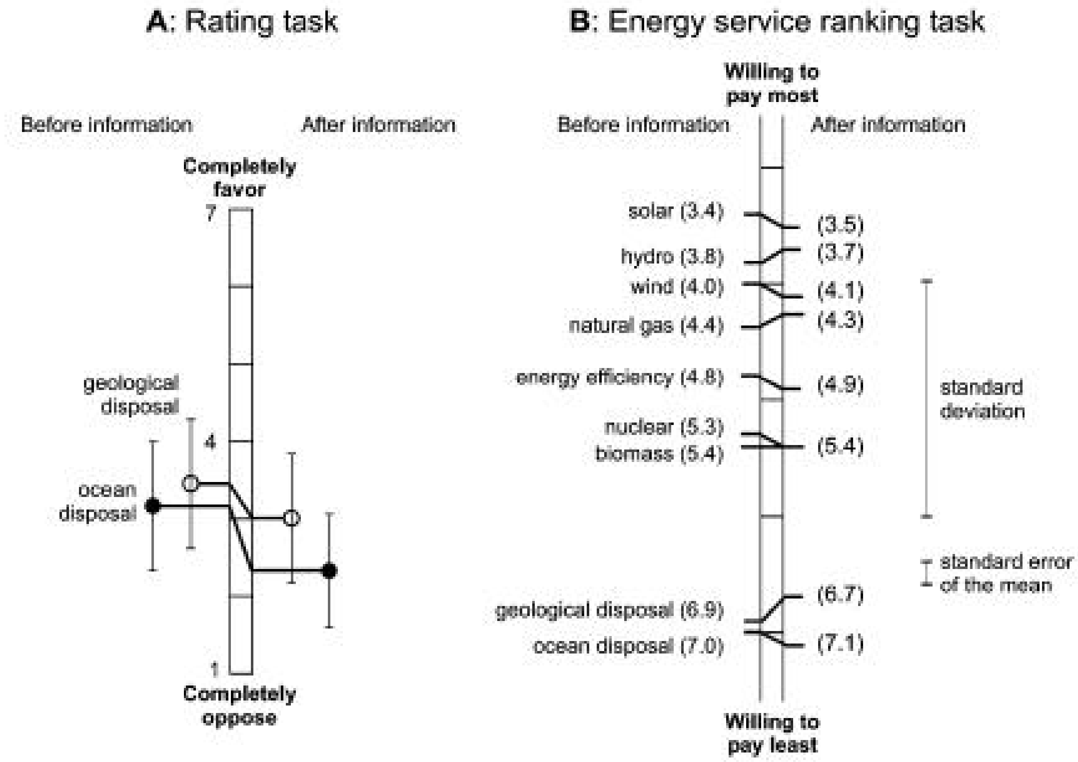

Figure 3.2: (A) Mean ratings of geologic disposal (open circles) and ocean disposal (solid circles) before (left) and after (right) receiving information about the technologies. Circles are mean rating scores and are approximately the size of the standard error of the mean. Bars are standard deviations. (B) Mean ranks, in terms of relative willingness-to-pay, of nine options for reducing 50% of CO_2 emissions. The left side shows ranking before, the right side after information was provided. Source: Palmgren et al. [2004, 6447].

Persons who were more pro-environmental were less inclined to support CCS. Palmgren et al. assume that the principal rejection of CCS could be due to the low awareness of climate change as a pressing problem with the interviewed persons. They conclude that there will very likely be severe difficulties for fostering public support for CCS in the US and identify some determinants for the outcome of such debates:

> "On the basis of (...) earlier studies, one might have anticipated that carbon separation with geological sequestration will be acceptable to the U.S. public. But the results (...), in which even nuclear power ranks as a more preferred option, should be enough to give one pause, and at a minimum, suggest that the way in which the public becomes informed about this technology, the way the technology itself performs, and the way in which the public debate gets framed could dramatically shape future public perceptions. (...)
>
> The results of this study suggest that, at best, the public is likely to view this technology with mixed feelings. High levels of public acceptance will almost certainly require: broader public understanding of the need to limit carbon dioxide emissions and of the costs and risks of alternative options for carbon management; a much stronger scientific understanding and a larger empirical base for claims about the likely efficacy and safety of disposal; and an approach to public communication, regulation, monitoring, and emergency response that is

> open and respectful of public concerns. (...) an arrogant approach such as the one adopted in the past by the industries responsible for nuclear power and genetically modified crops could create a level of public distrust that makes the widespread implementation of carbon sequestration in the United States difficult, if not impossible." [Palmgren et al. 2004, 6449]

Finally, it is worth remarking that May et al. [2003, 171] argue that in Germany the introduction of natural gas storage could serve as an example of how to introduce a risk-bearing geo-technology without problems concerning the acceptance of that technology by the public. However, CCGS has a significantly different character if compared to natural gas storage because it is related to the issue of global climate change, a topic receiving – at least in Germany – considerable public and media interest, quite opposed to the question of securing steady energy supply, which constitutes the background for natural gas storage activities. In addition, climate change is per se perceived as a problematic issue, while natural gas supply is not. Therefore, the issues of CCGS and underground storage of natural gas are framed in completely different ways, and it seems highly unlikely that the approach applied for introducing underground natural gas storage could work for the introduction of CCGS.

3.2.3 Some geopolitical implications of CCGS

Applying the considerations put forward by Collins [1990, 1986, see 3.1.3] it can be argued that dimate change has become a serious matter in international politics today. [Oberthür and Ott 2000] Within the geopolitical arena, the governments of the countries representing today's geopolitical centre (USA, European Union, Japan) are competing to present themselves as being active in climate change mitigation efforts as long as this will generate domestic legitimacy. This is currently the case – to varying degrees – because the public in these countries has an awareness of climate change as a public problem. For the EU, for example, establishing the first large-scale CO_2 emission trading scheme in the world (see 5.1.2) is an internationally prestigious enterprise.

For several reasons (economic concerns, fossil fuel industry interests) the USA – the leading nation in the geopolitical arena – does currently not play an active role in international climate change policy, which has lowered the international prestige of the USA. For any US government it will therefore be attractive to find a way to play a more active role in climate change policy in order to underpin the leading role of the USA in all areas of global politics. CCGS may allow the USA to play an active role in climate change policy without having to surrender its general position of the recent years. Also, it would not have to agree to the European Union's strategy (renewables) of the last years, which could be perceived to be problematic as it may imply a loss in relative geopolitical prestige.

Other than that, if CCGS can enable the large scale use of coal as primary energy carrier, CCGS may mitigate geopolitical conflict potential which arises from the current reliance on oil of the world's major industries on oil. The world's largest oil reserves are concentrated in the middle east, rendering this region strategically important. However, almost all countries with large or growing economies (e.g., USA, China, India, Europe) do have abundant coal reserves. Using locally available coal is (a) not economical today and would (b) considerably increase the problem of climate change. However, if a global emission reduction regime would be installed, coal could (a) become economically competitive and (b) in case of implementation of CCGS could be used without threatening the current global climate equilibrium, thereby reducing the global dependence on oil and possibly increasing geopolitical safety. On the other hand it may be argued that interdependence of nation states due to resource dependencies may also be a stabilizing factor in geopolitical relations. Completely independent nations may more prone to conflicts.[71]

Finally, the economies of some countries are heavily reliant on coal. Australia, for example, is a leading export nation for coal and has interests in maintaining this situation. Implementation of CCGS is therefore of interest for Australia in order to enable continued world-wide use and stabilize the global demand for australian coal.

[71] I would like to thank Ottmar Edenhofer and Bill Hare for pointing out these issues.

3.2.4 Social determinants of the viability of CO_2 capture and storage technology

Industrialization[72] has been a central aspect of the project of modernity[73] for at least the last 200 years and will remain to play a key role in it. There are no hints today indicating that the industrial sector in modern societies is going to lose any of its importance in the future. It appears that no other mode of material production can yield higher levels of productivity and hence a superior material standard of living.

Industrialization involves the large-scale introduction of technologies that increase the scale and change the quality of human interaction with nature. In order to work, these technologies require considerable amounts of energy. Fossil fuels (coal, oil, gas) have replaced wood, watermills, windmills, animals, and the human effort as energy sources used by society for its material reproduction process. However, burning fossil fuels at a very large scale leads to problematic indirect (and unintended) consequences that threaten the ecological equilibrium of the earth: CO_2 resulting from fossil fuel combustion induces the so-called greenhouse effect that is leading to a rise in global surface mean temperature.

This effect as well as possible consequences have been identified and formulated by the scientific sector of modern societies (e.g., Tyndall and Arrhenius in the 19th century; IPCC 2001 more recently, in an institutional form reflecting the features of modernity). This has been (and still is) necessary because global climate change cannot be observed directly, that is, without scientific means and methods.

In the face of global climate change mankind[74] is currently conducting a process of global communication that shows features of the process of inquiry proposed for dealing with such situations by Dewey (see 3.1.2): the situation has been qualified and the problem formulated, including the identification of crucial causal chains [IPCC 2001]; and hypotheses for solving the problem of climate change (including both mitigation and adaptation measures) have been and still are continuously constructed and discussed, some being experimentally implemented and tested in the real-world.

Among mitigation measures being discussed are changes in the industrial energy infrastructure, with specific proposals including the increase of efficiency in energy use, introduction of CO_2-neutral biofuels, windmills, different forms of solar power, geothermal energy, tidal power plants and other options commonly referred to as renewables, and more recently, CO_2 capture and storage.[75]

The actual real-world and large-scale implementation of each of these technological options depends on a variety of aspects. While they must meet one basic physical requirement, that

[72] A broad concept of industrialization is applied that also includes phenomena like modern means of transport and heating. This can be justified by arguing that although these phenomena are not part of the industrial sector in a narrow sense, they are still an output of it and would not exist without the existence of a large-scale industrial system that enables their continuous reproduction.

[73] Other key aspects of modernity concern changes in social structure and ideas.

[74] It is apparant that not all of mankind can participate in this process e.g. due to poverty. However, in principle all mankind is affected by the consequences of CO_2 emissions and resulting climate change and therefore has an interest in mitigating adverse impacts.

[75] Ironically, while CCS is proposed to abate a specific risk of modernization (climate change), it does itself induce modernization risks (see chapter 2). Based on Beck's notion of 'reflexive modernity', one may speak of a 'double reflexivity' inherent to CCS.

is, function (to some extent) as intended by humans under the physical conditions of space and time, all other determinants of their viability can be described in terms of social factors.

The elements for describing these social factors have been assembled in the previous sections. Figure 3.3 shows a scheme of the social determinants of market diffusion of climate change mitigation technologies.

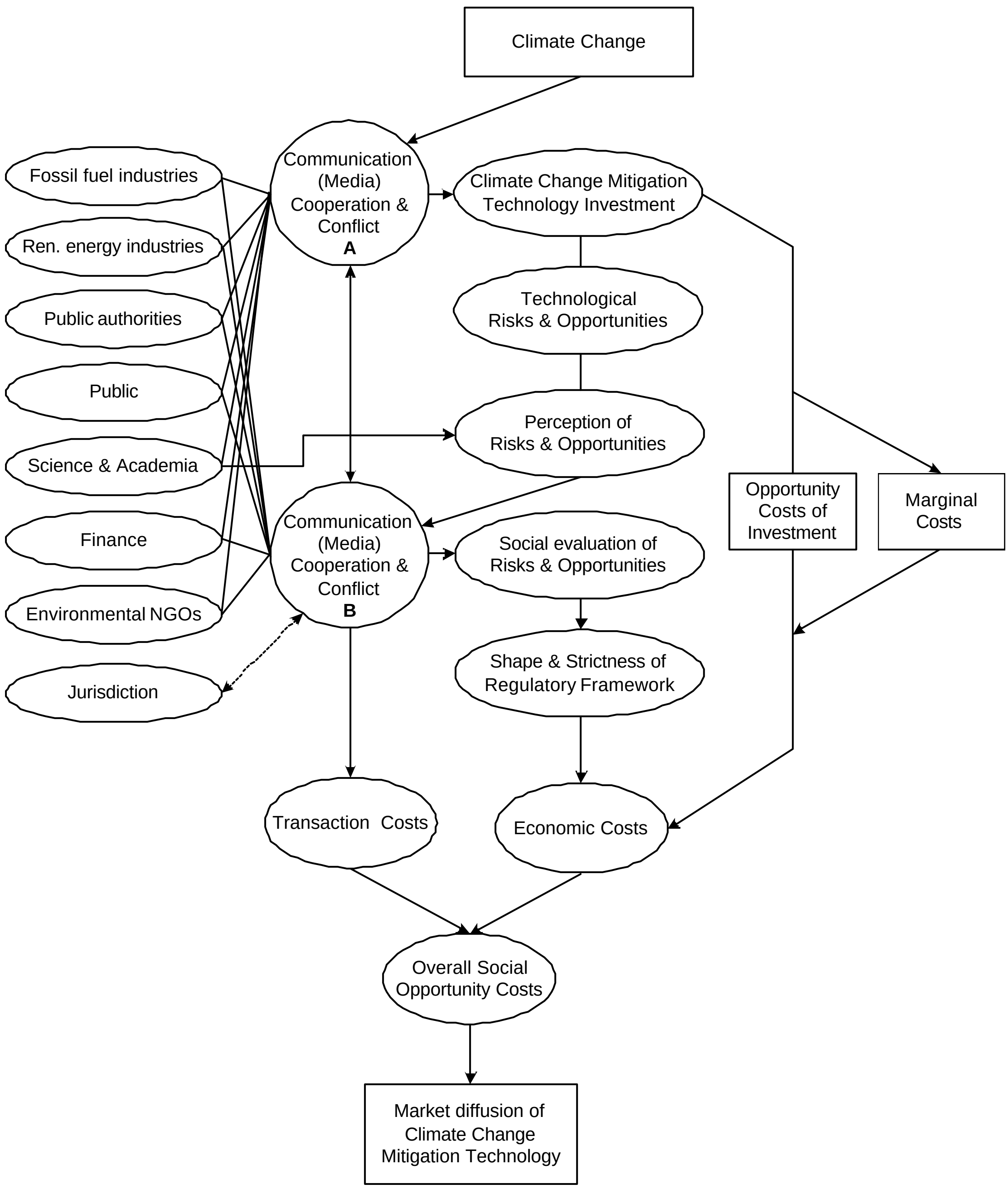

Figure 3.3: Social determinants of market diffusion of climate change mitigation technologies. Source: own.

Starting the discussion of the depicted scheme from the right, the marginal costs of a technology can be reduced by investments and the associated effects of learning by doing. Opportunity costs of investment arise from the fact that investment in one technology makes investment of these resources into an other technology impossible. This is of particular importance under conditions of uncertainty, e.g. when learning rates of different technologies are unknown, or in the particular case of CCS if there is uncertainty about leakage rates and risks (and costs implied). Marginal and opportunity costs of investment are one 'hard' techno-economic determinant of relative economic costs of a technology that are only indirectly – via investment decisions – subject to human influence.

This distinguishes these two determinants from the other elements in the scheme, which are better characterized as being subject to processes of social construction (this in no way reduces their social – and therefore not transcendable – significance). Commencing the discussion from the top of the scheme, climate change is a problem that had (and has) to be constructed in scientific investigations applying scientific methods and has been (to some extent, still is) subject to considerable conflicts. In the scheme it is assumed that an accepted and widely shared definition of climate change as a public problem does exist.

Now, the question of what to do about climate change is conceptualized as being subject to processes of communication involving both cooperation and conflict between different stakeholders. Here, only communication processes regarding investments into energy technologies aiming at mitigating climate change are taken into account. There are several issues that give rise to conflict and cooperation, the most important being that no cheap (in relative terms) and safe large-scale energy technology is available today.[76] Instead, renewable energy technologies (in an integrated portfolio approach) have been regarded as the only feasible climate change mitigation options until recently, and the process of climate change mitigation has basically been described in terms of a switch from a fossil fuel based energy system to renewables. However, renewable energy technologies are currently not able to compete with fossil fuel based technologies because of market imperfections that relate to economies of scale in both sectors. While for renewables the period of cost reductions through learning by doing still lies ahead, the fossil fuel sector has (i) already been through this period and (ii) has written off these expenditures, thereby having a competitive advantage. [Edenhofer et al. 2005b] Therefore, if they are going to be needed in the future, it is necessary that renewables encounter significant investments in order to reduce their competitive disadvantages. However, CCS is now emerging as an additional potential climate change mitigation option that might contribute to mitigating climate change – while allowing for the continued use of fossil fuels.

Under conditions of scarcity, conflict and cooperation arises in this situation between different stakeholders concerning the investment decisions into either renewables or fossil fuel energy technologies (e.g., CCGS). The positions in this process (which is depicted as 'Communication, Cooperation & Conflict A' in the scheme 3.2) can be derived from their respective interests (and to some extent, levels and kinds of information). In the following paragraph, the stakeholders involved and their positions are discussed (the related issues in

[76] It is often suggested that nuclear fusion could be such a technology, but it is not available today or in the foreseeable future.

the case of CCGS have been discussed more extensively in 3.2.1 above). The outcome of this process of communication (A) is allocation of investments to competing climate change mitigation technologies. The relative amount of investments depends on how many material, ideological and emotional resources the respective stakeholders are able to mobilize in the process.[77]

Although traditional fossil fuel-based energy companies do also invest into renewables today, and although both the fossil fuel and renewable energy sectors are internally more divergent than suggested here (different technologies and firms, and different interest groups within firms), it can be generally assumed that these stakeholders both have diverging interests that give rise to conflict when it comes to allocating private and public investments (or subsidies) to mitigation technologies. That is, the fossil fuel industry has vested interests in prolonging the use of fossil fuels, and the renewables industry has an interest in substituting fossil fuel technologies by renewables. Environmental NGOs usually support the renewable energy sector. Public authorities often take mixed positions due to internal lines of conflict (see 3.2.1 above). The finance sector involves different interests groups, with insurances being strongly interested in mitigating climate change in order to reduce damages resulting from climate change, while large investment funds (e.g., pension funds) can exert considerable power in large-scale investment allocation decisions. Interests of science and academia are also strongly divergent internally because different areas of research (e.g., geologists in CCGS; engineers exploring the design of solar panels) compete for limited research funds. Finally, publics also ave multiple interests, including an interest to avoid the negative consequences that may arise from climate change, and to effectively allocate public investments into competing mitigation technologies in order to save scarce resources.

The investment decisions lead to the introduction and testing of new energy technologies that involve both risks and opportunities. Again, these risks and opportunities have to be rendered perceivable, i.e. identified and formulated by scientists. These definitions of risks and opportunities then give rise to a second process of communication involving conflict and cooperation (B) that results in a more or less specific and widely shared social evaluation of these risks and opportunities. Ultimately, the outcome of the social evaluation process will determine the features and strictness of a regulatory regime, which in turn will partially determine the economic viability of a particular technology. [Wilson et al. 2003, 3482; Keith and Morgan 2000, 22; Hawkins 2001] Again, a number of stakeholders will be involved in this process, which will be discussed in the following paragraph with respect to the risks and opportunities of CCGS. Again, these considerations have basically already been developed above.

The fossil fuel industry regards CCGS as a means to prolong the use of fossil fuels while at the same time being able to overtly accept climate change as a public problem. CCGS allows it to undertake efforts for climate change mitigation and thereby improve the legitimacy of the fossil fuel sector. It therefore has a strong short-term interest to put an emphasis on the opportunities of CCGS, and to downplay the risks involved. However, in the long-run it will be in the self-interest of the fossil fuel industry to reduce the associated risks as accidents

[77] In principle, this process could be organized according to the form of a public inquiry proposed by Dewey. The same applies for the communication process B discussed below.

will decrease both legitimacy of CCGS in particular and the fossil fuel sector in general. It has to be assessed empirically whether this is taken into account short-term by the relevant agents in this sector. Renewable energy companies are in principal likely to oppose CCGS on the grounds of related risks because they have to fear reduced public support and subsidies (relative to an absence of CCGS), but their position appears to be somewhat more ambivalent due to their image of 'helping' the public to mitigate climate change. The same ambivalence is of greater importance for environmental NGOs: while they cannot be sure about the intentions of the fossil fuel industry on CCGS, they can hardly attack CCGS right away without losing credibility. However, they are very aware of related risks. Within the finance sector, CCGS could become an interesting financial opportunity in risk investment for investment funds (depending on the regulatory framework; see chapter 5). Insurances may be interested in insuring the risks of CCGS operations, or may refuse to do so due to incalculable risks – a decision which would likely have an impact on the discussion of the risks and opportunities of CCGS. For scientists that are engaged in setting up CCGS operations there is, on the one hand, an incentive to understate the risks involved in order to receive desired research funds; on the other hand, accidents (that become public) would do considerable damage to their reputation. Other scientists may derive benefits (economically, reputation) for adopting a more critical perspective on CCGS. Public authorities have to calculate conflicting ends: on the one hand, CCGS appears to be a promising climate change mitigation technology, on the other hand safety of the public (and the environment) has to be ensured in order to maintain legitimacy. The public authority of jurisdiction, in particular, could play a major role in the implementation of CCGS when the risks of setting up new operations, or damages resulting from accidents are negotiated before a court of law. Depending on the amount of the fines raised and the quality of the decisions made by jurisdiction, the overall viability of CCGS could be strongly affected. The general public could raise their concerns or support for CCGS in various ways. For example, NUMBY phenomena could arise on a local scale due to local risks. Finally, it is worth noting that in both of the processes of communication that have been discussed (A and B) the media plays a crucial role in shaping public perceptions e.g. by granting certain stakeholders more access to discussions, reports etc. than others, or by delivering a biased coverage depending of interests of some kind, or by simply ignoring, or very extensively reporting on CCS. Also, both processes of communication are interrelated, that is, the perception of risks and opportunities has an impact on the discussion (and implementation) of investment decisions, and vice versa.

It is now possible to bring together the central social determinants of the viability of climate change mitigation technologies. First, marginal technological costs and opportunity costs of technology investment determine, in part, the relative economic costs of a technology. Second, economic costs are also determined by the regulatory scheme that is implemented for the respective technology. Third, the very processes of communication, conflict, and cooperation (probably most notably: conflicts, e.g. changing legislation; lawsuits; boycotts) induce transaction costs that should not be neglected when assessing the viability of a technology option.

When looking at the scheme from right to left, it becomes increasingly difficult to quantify the economic costs associated with the respective determinants (i.e. this is relatively easy for marginal costs, but difficult for transaction costs). Together, transaction and economic costs make up for the overall social opportunity costs of a technology, which in relation to the overall costs of other technologies determines the market diffusion rate of a particular technology. The option with least social opportunity costs can be expected to encounter the highest market diffusion rates.

More research would be very desirable to specify the interests and strategies of stakeholders and resulting lines of cooperation and conflict. Also, quantifying the impacts of (a) marginal costs of investment, (b) opportunity costs of investment, (c) costs implied by regulatory schemes, and (d) transaction costs of CCGS as well as of other technologies with the prospect of climate change mitigation would help in assessing the viability of such technologies.

In this thesis, the issue of (a) marginal costs and (b) opportunity costs of investment have already been touched in 2.3 and 2.5, respectively. In the following chapters 4 and 5 issues relating to the regulation of CCGS are going to be discussed. By doing so, the related aspect (d) transaction costs is – to some extent – implicitly addressed as well.

This chapter will be concluded by a discussion of the gains that derive from the application of theoretical conceptions that have been outlined in 3.1 to the issue of CCGS. While the contribution of Beck allows for a description and qualification of the contemporary situation of modernized industrialized societies, including the identification of novel lines of cooperation and conflict and the availability of competing and sometimes incommensurable interpretations of the world provided by the sciences, Beck can not offer a systematic approach on how to deal with this problematic situation. John Dewey can provide some general tools for rendering modernization risks accessible to societal processes of communication that aim at dealing with those risks, but fails to offer particular tools that allow for the organization of publics, for example, or for setting up public inquiries under the conditions (and lines of conflict) within the Great Society. [Westbrook 1991, 300-318] While conflict theory as represented by Collins [1975, 1990] can guide analysis of the social aspects of CCGS towards crucial conflicts which arise from diverging interests of stakeholders, it fails to take into account normative and value guided action (as conceptualized by e.g. Talcott Parsons or Charles Taylor, respectively), and processes of communication that can lead to the establishment of intersubjectively shared norms, values, and interests,[78] which may turn out be crucial for an understanding of the societal adoption or rejection of large-scale technological systems. The limited social science knowledge on the dynamics of technological change directs attention towards the role of power, interest and time (Collins) and investment into scarce production factors (MIND) for the bias and scope of technological change, but a broader understanding of these processes – linked to the theoretical efforts previously discussed – appears highly desirable. However, application of these concepts has allowed for the identification of crucial social factors that determine the viability of CCGS. Further theoretical and empirical research should investigate the relative importance and the specific issues involved in determining these factors.

[78] The work of Juergen Habermas shows a strong tendency towards such an account, but the concepts of George Herbert Mead [1987] and Joas [1997; 1992] may prove more fruitful with respect to these empirical issues.

4. Selected regulatory issues

This chapter aims at discussing some regulatory issues which could turn out to be crucial for the implementation and viability of CCGS. It draws on the technical analyses of chapter 2 and on a review of literature investigating existing regulatory conditions for CCGS, which is provided in appendix A.

4.1 Criteria

In order to identify crucial regulatory issues of CCGS, two assumptions are made. The first has been elaborated in chapter 3 and refers to the prospect of social communication, cooperation, and conflict regarding CCGS. Such a debate is likely to take the form of discussing very specific issues regarding the regulation of CCGS. Interests and concerns about CCGS will probably determine the opinion of stakeholders with regard to specific regulatory issues. The second assumption is that the risks, costs and opportunities associated with such regulatory issues will be the crucial topics in these discussions and are going to be evaluated controversially by conflicting parties. In this chapter regulatory issues will be addressed that are closely connected to the following three aspects, which relate to these two assumptions.

Risks – Concerning risks two remarks can be made. First, if the scope of a regulative framework were to be deducted from the risks that arise from CCGS, the categorical separation of local and global risks which has been applied in chapter 2 of this thesis suggests that it may be subject to discussion whether the scope of a regulatory framework for CCGS should be local, or global, or both. That is, one may either propose separated local and global frameworks which should be linked in some way, or it may be attempted to implement an integrated framework for CCGS, simultaneously covering local and global risks. This issue will be addressed in subchapter 5.1. In the following sections the principal distinction of local and global risks and regulatory approaches should be held in mind in order to facilitate understanding of the problems that will be associated with designing regulation for CCGS. The second remark is rather basic and notes that the need for regulation of CCGS will usually be substantiated with particular risks that are associated with CCGS.

Costs – The concept of costs will be applied in a very broad sense including economic costs, transaction costs, and opportunity costs (see section 3.2.4). While some regulatory issues may principally be agreed on from the point of view of risk management (e.g., extensive monitoring), from a costs point of view they might be rejected by specific stakeholders, thereby rendering them subject to potential conflict.

Opportunities – Finally, there will be some regulatory aspects which will be crucial in order to integrate CCGS into a portfolio of climate change mitigation options at all (e.g., verification and accounting for leakage; economic incentives). These aspects could be indispensable in determining the opportunity of CCGS for becoming a viable climate change mitigation at all, and will therefore also determine the scope of regulation for CCGS.

4.2 Some crucial regulatory issues

Forbes [2002, 3-4] proposes that the regulatory scope for CCGS should comprise the four aspects of (i) project siting, (ii) CO_2 injection, (iii) reservoir monitoring and (iv) verification and accounting for injected CO_2. Stenhouse et al. [2004, 3] identify (a) site selection, (b) reservoir ownership, (c) monitoring and (d) leakage as the four factors in a (long-term) regulatory scheme which mainly determine the costs of regulatory regimes for CCGS. Permitting procedures are often identified as important cost factor for CCGS. [e.g., Vine 2004] In the subsequent sections the following issues will be discussed:

- legal status of CO_2-stream and underground injection,
- site selection, acquisition and permission (incl. pipeline setup),
- definition of an acceptable leakage rate,
- monitoring, leakage and verification/accounting,
- short- and long-term liability (incl. remediation measures),
- the relations between CCGS, renewables and incentives for climate change mitigation technologies, and
- the adoption of CCGS in developing countries and countries in transition.

4.2.1 Legal status of CO_2-stream and underground injection

The legal definition of a captured and liquefied CO_2 stream ready for geological injection could make a significant difference in the strictness of regulation for CCGS operations. [Keith and Morgan 2000, 21] The same holds true for the legal definition of underground injection of CO_2 stemming from large point sources. In the following, the focus will be on the implications of legislation in Europe.

Definition of CO_2-stream

There are three legal definitions that could be appointed to a liquid CO_2 stream for geological injection, each implying different levels and standards of regulation. First, the CO_2 could be regarded to be no waste at all. Second, it could be defined as a waste. Third, it could be defined as a hazardous waste. There is currently no explicit legal definition for CO_2 in CCGS operations available (neither in Europe nor anywhere else). Therefore, Wall et al. [2004] and CRUST [2001] have analyzed the current EU waste legislation, which is laid out in the EU directives on waste and on landfill, with respect to a possible application to CCGS.

It is regarded as very unlikely that liquefied CO_2 bound for geological storage would not be defined as a waste at all. This is due to the EU definition of waste, which states that "(i) any substance or object set out in Annex 1, or (ii) which the holder discards or intends or is required to discard" is to be regarded as waste. The latter would apply for CO_2 in CCGS, as the directive cites as examples "substances that no longer perform satisfactorily, residues of industrial processes, residues from raw material extraction and processing, and products for which the holder has no further use." [both cited after Wall et al. 2004, 3] Therefore, it is very likely that CO_2 in CCGS operations will (at least) be defined as a waste, and regulation will therefore have to follow the relatively strict EU regulation guidelines. [Wall et al. 2004, 3; CRUST 2001, 17] According to these guidelines EU Member States have to ensure recovery or disposal of a waste without endangering human health, without using processes or methods which could harm the environment, and more particularly (for example) without risk to water, air, soil, plants and animals. This requires increased documentation about the waste, and acquisition of permits for transporting and handling wastes. The permission procedure between an authority and a project operator has to cover the following aspects: type and quantities of waste, technical requirements, security precautions, disposal site, treatment methods, and record keeping on quantity, nature, origin, (and where relevant: destination, frequency of collection, and mode of transport). [Wall et al. 2004, 2-3] While these measures may increase the costs of CCGS operations, it appears unlikely that they will render CCGS as a whole unfeasible.

This, however, could be the case if CO_2 would be defined as an hazardous waste, as hazardous waste handling involves relatively strict regulation. Hazardous wastes are defined in the European waste catalogue, which takes into account the origin (e.g., power stations and other combustion plants) and composition of waste and, where necessary, limit values of concentration. Flue gases are not included in this definition. This is due to the fact that flue gases are usually emitted into the atmosphere and thus not defined as wastes. As there is no category for flue gases so far, captured CO_2 could fall under category non-hazardous "wastes not otherwise specified". According to Wall et al. [2004, 3] and CRUST [2001, 17] there is no indication that a pure stream of CO_2 would be classified as hazardous waste. However, if the CO_2 stream – depending on the capture technology – will contain other substances classified as hazardous (e.g., sulphur containing components like SO_2, H_2S, COS, or nitrates as N_2, NO, NO_2, as well as O_2, Ar, H_2, CO, hydrocarbons, metals and particulates), this would be different, depending on the level of concentration of these substances. There is, so far, no definition of what a "high concentration" of such substances would be.[79] [Wall et al. 2004, 4]

Definition of underground injection of captured CO_2

If the CO_2-stream would be defined as a waste, under current EU legislation CCGS as a technological system would be defined as a waste disposal operation. CRUST [2001, 17] quotes the following EU definition of "disposing of wastes":

> "In this act and the stipulations arising out of it, disposing of wastes is taken among other things to mean:
>
> - the useful application or removal of wastes within the organization in which they were created;
> - taking wastes from an organization to an organization located elsewhere that belongs to the same natural or legal person for the purposes of useful application or removal;
> - temporarily handing over wastes for useful application."

[79] Wall et al. [2004, 3] remark that in CCGS research not enough attention has been spent on the issue of hazardous components in the CO_2 stream.

On these grounds Wall et al. [2004, 3] and [CRUST 2001, 17] conclude that under the EU waste directive, geological storage of CO_2 would be defined as waste disposal according to European Law.

This does imply that a site-specific safety assessment has to be carried out, with special emphasis put on proving the existence of a geological barrier and the final aim of preventing leakage of the waste to the biosphere. Identification of risks, receptors, pathways of possible leakages to the biosphere and impact assessments if the substance comes into contact with the biosphere are demanded. If the result of the safety assessments is in the negative, waste disposal may not be allowed. [Wall et al. 2004, 4] While these procedures will add to the costs of CCGS, they will very likely not principally inhibit the implementation of CCGS.

However, that is a possibility that arises from the fact that EU legislation requires that all wastes that may undergo undesired physical, chemical or biological transformation after they have been deposited must not be disposed of in underground storage. This regulation may be applicable to CCGS. In addition, all liquid wastes have been excluded from underground storage. As CO_2 is injected in supercritical phase, that is, as a fluid, its underground disposal may be forbidden (as it would constitute a liquid waste). The decisive question yet to be resolved here is: is a liquid defined to be a liquid under atmospheric pressure and temperature, or in the state where it is actually stored? [Wall et al. 2004, 4]

In general, current European law and regulation does not explicitly cover CCGS. Under current legislation, CO_2 in CCGS is faced with legal incertidudes regarding its status as waste material, and CCGS projects with the explicit aim of mitigating greenhouse gases that exceed the status of R&D efforts would likely require negotiation of legal and safety issues at a court. [Wall et al. 2004, 6]

4.2.2 Site selection, land acquisition and permission

There are at least three crucial aspects to the site selection, land acquisition and permission process. First, selecting appropriate (safe) reservoirs will be crucial in avoiding adverse environmental impacts and atmospheric leakage of injected CO_2.

Second, it will reflect a society's attitude towards CCGS. Scenarios include (but are not exhausted by the examples of) governments requiring little testing and demonstration and citizens approving the implementation of underground injection activities, and protest from citizens and NGOs with prohibition of underground injection of CO_2 by authorities.

Third, the (economic, transaction) costs of this initial phase might have impacts on the economic viability of CCGS. For example, permitting Class I well operations in the USA costs US$ ~2 million (see appendix A), and permitting a CCGS operation in a restrictive regulatory environment may be much more expensive. Knowledge of the costs and impacts of various permitting processes (possibly in different world regions) would be a valuable information in order to appropriately calculate overall investment costs of CCGS.

Site selection

In section 2.2.3 it has been shown that different geological formation types have different properties with respect to reservoir integrity and volume. It appears desirable to choose the safest formations for underground injection first. While it seems to be relatively clear that aquifers without seals have the prospect of the largest storage volumes but lowest safety, an a priori evaluation of the performance of the other formation types is not possible. Therefore, site-specific exploration efforts will be required.

Matching of carbon dioxide sources and sinks will be crucial for reducing costs. For this, tools making use of Geographic Information Systems (GIS), for example, are being developed to identify spatially effective CCGS operations. [IEA GHG 2002; Smith 2004]

There is the possibility that in the site selection (or permission) phase local citizens will protest against the implementation of underground storage of CO_2 in their vicinity. This is often referred to as ‘not-in-my-backyard’ (NIMBY) syndrome, or – more appropriately – NUMBY (not-under-my.backyard) as pointed out by Huijts [2003]. This appears to be particularly likely if the injection operations are planned in densely populated areas. Also, local support by citizens is likely to be lower if CO_2 for injection stems from facilities far away, on contrast to the case where CO_2 e.g. from local coal power plants (usually large local employees) is to be stored in the vic inity of such a facility. In the USA, waste disposal activities via underground injection in the past have sometimes been conducted in areas populated by groups with low social status (high unemployment rates, low incomes, discriminated ethnic groups, for example indian territories), which has sometimes led to intervention of NGOs. [see Benson et al. 2002, appendix 14; for a systematic treatment of this issue, see Heddle 2003]

Such local social conflicts could induce considerable transaction costs, ranging from legal economic costs to significant prolongation of the whole permission process. It has already been mentioned that an ocean injection demonstration project off the coast of Hawaii had to be cancelled due to protests from local citizens. [de Figueiredo et al. 2002]

Concerning the costs of site selection, Stenhouse et al. [2004, 3] assume that the exploration costs will develop analogous to oil and gas exploration: experience and improving technology will tend to drive costs down, while depletion of the best storage sites will drive costs up, although it is unclear how soon “depletion” will occur. Quantifying the exploration costs for CCGS operations would be useful for calculating the overall costs.

Land acquisition

Ownership of a storage reservoir is an important issue in site selection, first because it is often unclear who owns the underground structures into which CO_2 will be injected (the owner of the surface land, or the owner of the mineral rights), and second because purchasing or paying royalties (i.e. compensations for usage, land value depreciation, liabilities) to an owner could constitute a major cost factor of GS. The same holds for acquiring land for a CO_2-pipeline.

In case owners are unwilling to sell their land, authorities could heavily influence the ownership issue depending on their position towards CCGS. They might enforce expropriation of land-owners that are unwilling to sell their land, for example, arguing that CCGS serves the common good (that is, mitigating climate change). [Stenhouse et al. 2004, 3-4; Smith 2004]

Apart from such drastic measures, other means of taking influence on land acqusition (and the implied social distribution of costs of CCGS) include changing (e.g., environmental) law or providing state-owned land for pipelines or underground injection sites.

Permission from authorities

In order to conduct carbon dioxide capture, pipeline transport and underground injection it is likely that operators will have to obtain permissions from authorities (see section 4.2.1). There currently are no legal and regulatory frameworks for CCGS permission anywhere in the world due to the early state of technology development. Principally, permitting CCGS projects will at least take place on a local scale (e.g., nation states). The following considerations relate to the features of future permission regulation.

If an authority has principally banned CCGS, no permissions will be issued. If CCGS is generally accepted, obtaining a permission will be coupled with meeting some requirements of the regulating authority. The scope and content of these requirements will determine the implemented safety measures and costs of setting up a CCGS operation. They may include prescriptions on the extent of pre-injection and injection monitoring of the reservoir, reservoir simulations, environmental risk assessment, and several other procedures which would have to be specified. [Stenhouse et al. 2004, 7]

Usually, permitting requirements for underground injection activities vary from country to country. The permitting procedures for analogous processes (e.g., acid gas injection, EOR) are unlikely to apply to CCGS due to the larger volumes, timescales, and the monitoring problems associated with CCGS. [Stenhouse et al. 2004, 3]

A public permitting process may have to balance competing goals. On the one hand, safety should be maximized, on the other hand, costs should be kept low.

Tying the safety issue of CCGS solely to the permission process would likely create negative incentives for firms to develop, improve and take serious safety measures for CCGS. Experience from nuclear reactor permission processes indicates that if this is the case, the private firm’s safety measures efforts are reduced to achieving formal compliance with the requirements of an authority, the motivation of which in turn is basically to secure its own position. Therefore, safety measure tend to remain sub-optimal. [see 5.3.1; Radkau 1983, 470]

In general, the strictness of guidelines for site permission will have some impact on project costs. Loose guidelines would make site selection cheaper, but projects would be more prone to accidents (and vice versa). This trade-off becomes a more complex issue if the costs of long-term liability for leakages (global framework), public health and ecosystem damages are taken into account, because with respect to this better safety measures could lead to a net-decrease in overall costs. [Stenhouse et al. 2004, 3]

4.2.3 Definition of an acceptable leakage rate

In chapter 2 it has been shown that from a geological point of view it is almost certain that some leakage will occur at CO_2 storage operations. Subchapter 2.5 has elaborated the significance of the average leakage rate from CCGS operations for the overall ecological and economical effectiveness of CCGS as a climate change mitigation option. In subchapter 2.4 several leakage mechanisms and possible impacts were described.

Considering this and that there may be groups critical towards CCGS (section 3.2.1) it follows that for a large-scale implementation of CCGS an acceptable average leakage rate and acceptable leakage rates for individual formations will have to be defined (and agreed on). Wilson et al. [2003, 3482] note :

> "It seems likely that a regulatory regime must accept limited leakage if GS is ever to play a significant role though this could make achieving a regulatory consensus more difficult."

There are some implications and possible consequences of defining an acceptable leakage. If a leakage rate >0% will face severe opposition in a particular society, protests against (maybe even very low) leakage rates may render CCGS unviable, especially when a threshold of 0% leakage (but no principal ban) is adopted in legislation. This is due to the admitted impossibility of guaranteeing 100% confinement. If such a regime were complemented by considerable penalties for leakage, no CCGS will be adopted at all.

Accepting low leakage rates (<0.01%) may not necessarily lead to opposition motivated by the ineffectiveness of CCGS as a climate change mitigation option. Instead, it appears more likely that a legislated acceptable leakage rate of this order of magnitude may give rise to concerns by local communities (possibly including local authorities, ENGOs), especially if pipeline installation and CO_2 injection are to take place in populated areas. European legislation takes such concerns relatively serious. For example, the purpose of the European Water Framework Directive is to protect inland surface waters, transitional waters, coastal waters and groundwater within the EU, with its aims including ensuring the supply of quality surface and groundwater for sustainable use, reducing existing pollutions of groundwater, and protecting marine and territorial waters. Groundwater should not be polluted at all; a precautionary approach is in place that prohibits direct discharges to groundwater, and requires monitoring in injection activities in order to detect changes in the water composition. A river basin approach is applied, that is, Member States must set up appropriate governance structures, if necessary transnational. It is in general unclear how the water framework directive will concern CCGS in detail. However, it is very likely that as goundwater must not be polluted, any leakage of CO_2 into groundwater changing groundwater quality (f.e. a decrease in groundwater pH) – even if such migration would not involve toxic chemicals – would be restricted and forbidden. In addition, a geological storage project would likely have to conduct monitoring of adjacent groundwater aquifers. [Wall et al. 2004, 2] Therefore, even if low average leakage rates are considered acceptable, there are some sensitive areas especially with regard to local risks where currently a strict zero leakage regulation is in place that might have to be changed for CCGS, which appears very unlikely and which could require considerable transaction costs.

The likelihood for conflicts concerning local risks rises with higher leakage rates (>0.01%) being deemed acceptable by legislation (regulation). In addition to concerns about local risks, opposition arguing that CCGS is not a viable climate change mitigation option becomes more likely then, but would heavily depend on (competing) scientific estimates of the ecological and economic effectiveness of CCGS.

In general, public concerns and conflict about acceptable leakage rates is likely to determine, in part, the scope of regulation required at CCGS operations.

4.2.4 Monitoring, leakage, reservoir management and verification/accounting

Monitoring at GS sites has to be conducted for at least two reasons: (i) in order to make sure that no health, safety or ecological damages are incurred locally (and to enable remediation measures in case of accidents), and (ii) to verify or account for the reduction of CO_2 emissions. [Stenhouse et al. 2004, 4]

Concerning (i), monitoring will be pre-requisite for the permitting procedure of CCGS projects (assessment of operational safety). In addition, it seems likely that it will be a necessary condition to render CCGS acceptable for those who are affected by the related risks. Only exi-stence of a monitoring scheme can enable an informed management of the local (and global) risks of CCGS including remediation schemes for accident scenarios.

Concerning (ii), it must be made sure that the amounts of surface leakage of carbon dioxide can be quantified. Setting up a regulation scheme for monitoring touches the issue of verification for mitigated CO_2, which constitutes a central aspect of a potential global CO_2-emission regulation framework.

It appears that the potentially most controversial issue concerning monitoring – apart from the scope and methods for monitoring – is for how long geological CO_2 storage sites will have to be monitored. It seems unlikely that environmental NGOs and the public will accept CCGS without some permanent or at least periodical long-term monitoring scheme. In order to quantify leakages site-specifically with respect to emission permit verification or accounting it seems necessary to install a permanent long-term monitoring scheme. However, extensive long-term monitoring could prove very expensive. Stenhouse et al. [2004, 4] remark that while most CCGS studies assume monitoring costs of less than US$ 0.3 per ton CO_2, actual costs could be much higher if long term monitoring were required. This may actually render CCGS as a whole too costly. On the other hand, it has to be taken into account that extensive monitoring could reduce liability costs associated with CCGS (e.g., by lowering an insurance premium). This appears to be another issue deserving more attention in further research.

According to Stenhouse et al. [2004, 7], a monitoring programme has to take into account the following three aspects: (1) it must include a distinction between ‘acceptable’ (within specifications) and ‘unacceptable’ (outside specifications) behavior of CO_2 and the storage site. This makes (2) exhaustive definitions of specifications of ‘acceptable’ behavior necessary, which have to be based both on safety- and verification/accounting considerations. (3) The specific actions to be taken if unacceptable behavior is identified should also be defined.

In order to meet these requirements, site operators will need relatively detailed models in order to be able to interpret the monitoring data and to identify what corresponds to acceptable behavior, what not, and what to do about it. [Stenhouse et al. 2004, 7] Definition of unacceptable behavior and measures to take in case of such unacceptable behavior will also have significant impact on the costs of monitoring, operations safety, liability, and insurance.

Monitoring will also be a vital aspect of model construction. Early monitoring would provide a baseline against which future monitoring data could be compared. Monitoring should therefore start before CO_2-injection can cause perturbations. [Stenhouse et al. 2004, 6]

Different monitoring schemes may be required for different GS projects. Small projects in proven traps might employ less stringent monitoring systems than very large projects in saline aquifers. Population density or ecological sensitivity may be other factors affecting the stringency of the monitoring scheme. [Wilson et al. 2004, 8]

In the following, specified tasks of a monitoring regime for CCGS will be identified. In the operation injection phase, there appear to be two main aspects of monitoring: (a) controlling the injection process (speed and volume of injection) and (b) to identify leakages (underground and surface leakage). Once a project is complete and the injection wells have been sealed, Stenhouse et al. [2004] identify three reasons for continuing monitoring: (i) to allow for the detection and management of leakage, (ii) to engender public confidence, and (iii) to provide data for verification/accounting for greenhouse gas reduction. [Stenhouse et al. 2004, 6]

From the point of view adapted here, there is no need to distinguish between long-term monitoring allowing for management of risks and monitoring fostering public support; it is assumed that appropriate safety management can engender public confidence, as ‘appropriate’ depends on a social definition resulting from a communication process between the stakeholders involved (including citizens). Therefore, it can be argued that post-injection monitoring has the three specific tasks of (a) identifying (surface and underground) leakages, (b) to allow for safety management (measures), and (c) to enable the integration of CCGS into a possible emission reduction framework (e.g., emissions trading mechanism, Clean Development Mechanism, Joint Implementation).

Hence 6 tasks of a monitoring scheme have been identified, 3 relating to the injection phase and 3 relating to the post-injection phase of CCGS. These are:

(1) optimization of the injection process,
(2) ensuring short-term safety of the injection process,
(3) verification and accounting of GHG reductions within national emission inventories, and CDM or JI, respectively,
(4) assuring long-term safety of the reservoir,
(5) enable mitigative measures in case of accident in the long run, and
(6) enable long-term verification or accounting of GHG reductions.

A central question concerning the regulation of monitoring is who will review and apply the monitoring data that will be obtained. [Stenhouse et al. 2004, 6] It is also related to the issue of who will provide and control (e.g., peer-review) the models used for monitoring the storage sites. IEA [2004, 14] propose that mid-term monitoring (~30 years) could be borne jointly by private firms and the public, and long-term monitoring should be carried out by state authorities. No specific reasons for this proposal are given, e.g. whether public participation may increase safety and acceptance, or reduce cost for private firms, and who will bear the cost of a (semi-)public monitoring scheme.

Also, especially with respect to a potentially performance-based regulative framework (see 5.3.1), it has to be clarified which specific parameters will be monitored. [Stenhouse et al. 2004, 4] This issue is related to the modeling conception and the safety management.

Concerning the relation of monitoring and verification and accounting of injected CO_2, it may happen that monitoring regulation will be implemented on transnational or national (e.g., EU or North America) or even state level (e.g., within USA), while the emission regulation framework motivating CCGS is global (or international, e.g. EU-wide). Local accounting and verification procedures therefore would have to be compatible with international procedures.

Because available monitoring technology is not capable of delivering a perfect account of the behavior of injected CO_2, the ultimate question concerning the regulation of monitoring, verification and accounting will be: how accurate is accurate enough? [Torvanger et al. 2004]

Another issue linked closely to local regulation concepts – if CCGS becomes a large scale GHG mitigation option – is that several GS projects are likely to be adjacent to each other, and in case of subsurface CO_2 migration (e.g. from GS projects at brine aquifers), problems with accounting practice may arise. If the CO_2 stays underground but migrates from the storage site, how will this be treated in the accounting process? If carbon dioxide migrates to another project site, can this movement be adequately tracked and quantified? [Stenhouse et al. 2004, 6] Who, in case of such migration, has the right to hold a potential carbon credit? And in case of leakages from "joined" reservoirs, which project operator is penalized which amount? [Stenhouse et al. 2004, 6]

Record keeping will be necessary not only for financial reasons from the point of view of CCS firms (assessment of royalties, possible government dues, determination of ownership of surface property, and mineral rights) but also for safety reasons (to avoid future drilling of CO_2 storage sites and to remind of abandoned injection wells). Geological and geographic information on GS sites could be included in geographical information systems that cover single nation states or the world. The United States MIDCARB (Mid-continent Interactive Digital Carbon Atlas and Relational dataBase) system[80] is an example for such technology. [Stenhouse et al. 2004, 4-5]

As the time-scale envisaged for geological storage of CO_2 exceeds 100 years, long-term social stability comes into play. In order to minimize the effects of political change, the organization entrusted with archival of CCS should be unpolitical (e.g., a geological survey responsible for compiling and storing geological and related type of information). [Stenhouse et al. 2004, 5]

[80] See www.midcarb.org

4.2.5 Liability and related issues

Short- and long-term liability are critical issues for the large-scale implementation of CCGS because they are closely related to risks, costs and opportunities of CCGS. In addition, liability is closely connected to remediation in case of accidents, and general intergenerational legacy effects that come with CCGS. All of these aspects will be discussed in the following three subsections.

Liability

First, the scarce existing literature on liability for CCGS will be presented, followed by a discussion of specific requirements. It is not attempted to offer solutions. The aim of this section is rather to identify requirements and potential difficulties related to the issue of liability.

De Figueiredo et al. [2003, 1] systematically divide liability issues into 3 areas : (i) operational liability is associated with CO_2 capture, compression, transportation and injection into the storage formation, (ii) in-situ liability which is associated with potential public health impacts and environmental and ecosystem damages as a result of CO_2 leakage from the underground storage reservoir, and (iii) climate liability that is associated with leakage under a future regulatory regime controlling CO_2 emissions. De Figueiredo et al. [2003, 2] assume that climate liability should be dealt with in a global regulatory policy framework for climate change. For the USA, operational liability is no problem in their perspective. De Figueiredo et al. [2003, 1] assume that the issue of in-situ liability will be crucial for the implementation of CCGS, as the potentially associated costs (e.g., in case of groundwater pollution) could deter firms from carrying out CCGS. They therefore call for a specific liability framework for CCGS that reduces the liability risk for firms.

Five approaches to address in-situ liability of CCGS are discussed by de Figueiredo et al. [2003, 5]. The first involves introducing a "liability cap" for CCGS analogous to nuclear power plants and terrorist attacks, where the federal level (or public) takes over liability above a certain amount of damage. This is due to the fact that the associated catastrophic risks are too large to be taken over by insurances. De Figueiredo et al. suggest, however, that such a scheme would likely stigmatize CCGS in public perception. As a second approach, (US) states could take over liability; this, however, has not been working well for dealing with low-radioactive substances in the past. Third, a future CCGS industry as a whole could be held liable for accidents, analogous to the nuclear industry in the USA, where in case of a nuclear accident each power plant reactor operator has to pay up to US$ 88 million if a common insurance pool of US$ 200 million is used up. Fourth, companies could be held liable individually. In the US EPA UIC program, several instruments are available for such a procedure: surety bonds (guarantee by a surety company that a specified obligation will be fulfilled), letters of credit (guarantee that a set amount of money will be available to a specified company under certain conditions), trust funds (repositories of money set aside for a specific purpose), and financial statements (audited information from a company's income statement and balance sheet demonstrating sufficient resources for specific obligations). However, these instruments cannot assure that funds are available in case a firm ceases to exist or declares bankruptcy. Finally, operators could insure their operations if insurances decide that they are willing to bear the risk of CCGS, which will depend heavily on results of future risk assessment studies.

Torvanger et al. [2004, 11] make four proposal for handling liability for injected CO_2. First, authorities could require CCGS firms to fulfill specific minimum requirements. If these are met, the authority assumes the liability for the reservoir after injection. Second, stewardship may be transferred to public authorities after a fixed period of time, for example, 20 years. Third, a company could be credited 80% of the CO_2 injected and all future responsibility for leakage is with the public. This could apparently involve significant costs for the public in case of high leakage rates. Finally, CCGS firms might finance an insurance fund that could cover future expenses of reservoir monitoring and maintenance, or authorities could require a certain amount of money to be paid into such a fund for each ton CO_2 injected.

Marland et al. [2001, 265] discuss regulatory regimes for biosequestration of CO_2 and identify 4 possible (groups of) agents that may bear liability for CO_2 that has been stored in a media other than the atmosphere but which bears the risk of leakage into the atmosphere over time. These are (1) the host party who holds the CO_2 (site operator), (2) a purchasing party that rents emission certificates from a CCGS operator, (3) a third party such as an insurer or the holder of a performance bond, or (4) a collective of purchasers maintaining a risk-adjusted reserve of emission certificates to compensate for premature losses.

Stenhouse at al. [2004, 7] state that “uncertainty about the transference of liability to the public sector could significantly impact the economics of storage in a negative fashion.”

While De Figueiredo et al. [2003] adopt at systematic classification of liability issues, one could also introduce a classification that distinguishes between short- and long-term liability that deals with (i) local risks and (ii) global risks. The rest of this section will focus on short- and long-term liability concerning local risks. It is assumed that liability regarding global risks should be regulated withing a regulatory framework on emission abatement (see 5.2).

Short-term liability can be defined as liability during the injection phase. Long-term liability refers to liability thereafter, involving several hundred years. Designing a short-term regulatory scheme governing liability for injection operations and their consequences does not seem to impose insurmountable barries, as in principle legislation for analogous operations is available. However, the considerable amounts of CO_2 (as well as its buoyancy) in CCGS operations must be taken into account because they exceed those of all analogous operations, thereby increasing the potential of damages (risks) that may lead to liability claims from individuals, groups or organizations.

It can be argued that if liability for CO_2 handling and injection operations and their consequences is with the firm(s) that conduct CCGS, the economic risk related to this will create a strong incentive to maximize reservoir containment and operational safety. Also, if CCGS firms consider this risk to be too high, and do not implement CCGS at all because of liability concerns, it can be claimed that this proves the lack of safety of CCGS operations, and that these should therefore not be implemented at all. A similar argument applies if insurances are not willing to insure CCGS operations, or if the risk premium is too high to render CCGS economically attractive: in this case there would be a clear market signal that CCGS is not a viable climate change mitigation option due to the related risks (the same considerations apply to the issue of long-term liability).

This would be different if liability for CCGS would be transferred to public hands. This would render CCGS more attractive because it would lower the associated economic risks stemming from the liability issue. However, in this case there would also be no incentive to maximize the safety of CCGS operations, because the operator would hold no responsibility. The remarks by De Figueiredo et al. [2003] on experience with such regulation for low-radioactive nuclear wastes suggest that such schemes are not recommendable and have led to problems in analogous cases in the past. It appears unlikely that liability for CCGS operations – especially short-term – will be transferred to public hands, as there is a significant probability that this will lead to protests from environmental NGOs and the public.

Radkau [1983, 467] draws on a comprehensive historical analysis of the genesis of the german nuclear industry, and remarks that as soon as (in 1976) it was made clear that the nuclear industry and not the public would bear liability for the final storage of radioactive wastes, the discussion about costs and risks of nuclear waste disposal in a hearing by the German Bundestag immediately became far more transparent and risk-oriented from the industrial side. This was due to the change in the situation of the private industry compared to a situation where it would hold no liability for storage, which implied no incentive for an open debate of the adverse impacts of nuclear waste storage.

Some [e.g., Wilson et al. 2004, 2] remark that firms are not likely to exist as long as injected CO_2 is intended to remain underground, and that for the sake of safety liability should be transferred to public hands several years after termination of injection operations. However, the same considerations that have been outlined in the previous paragraphs apply: in this case there would be no incentives for CCGS firms to maximize the long-term safety of CO_2 injection. From a safety point of view a guaranteed transfer of liability to the public will therefore generally provide negative incentives for CCGS firms, which from a safety point of view does not seem to be desirable. As the public will likely mainly be concerned about safety of CCGS operations, private liability would foster social support for CCGS as this would be perceived as a signal of trust by CCGS firms into their technology.[81]

Another important issue regarding liability is the clarification of ownership related to CO_2 underground injection operations. The entities with potential property rights include the land surface owner, the mineral interest owner, the royalty owner, and the reversionary interest owner (interest in a reservoir that becomes effective at a specified time in the future). All of these stakeholders might have to be taken into account when regulating the liability for GS. [de Figueiredo et al. 2003, 7]

To sum up, long-term liability has to be addressed for the following reasons:

- Local safety: some actor has to hold responsibility in case of accident (e.g., leakage to adjacent formations, surface leakage) to allow for quick and effective remediation.
- Global safety: site selection and injection should be performed in a way that ensures long storage retention timescales. Private long-term liability – the exact design of which

[81] However, this will also largely depend on the question of the scope of economic penalties that will be implemented in case of accidents. Assessing the economic impacts of liability is therefore another task which would allow for a better understanding of the viability of CCGS.

may vary (e.g. tradable) – could be a strong incentive to do so. Transfer of liability to the public, however, would provide a negative incentive concerning storage safety.

- Accounting within an emissions trading system: in case of leakage after a longer period somebody should be penalized, that is, be forced to buy emission permits for the leakage, in order to maintain the aim of the emission cap regime.

Transferring (long-term) liability to the public would likely induce protest from environmental NGOs and the public. It may be felt that those who derive profits from imposing public risks should be held liable for these risks as well.

Remediation

In case of accidents it will be important from a safety point of view that there are remediation and protection schemes that minimize the impacts of such accidents. With regard to liability, remediation and protection schemes could lower the impact of accidents, thereby reducing the amount of damages. An agent holding liability for a CO_2 reservoir or a related process is likely to be interested in effective remediation and protection schemes that can reduce the scope of potential damages.

Remediation measures in the analogical case of natural gas storage include venting accumulated natural gas from shallower strata, or depressurization of the reservoir by releasing natural gas to the atmosphere. [Benson et al. 2002, 8]

If these measures would be applied in CCGS, there might be strong disincentives not to vent CO_2 to the atmosphere as this would likely be related to a penalty for emitting CO_2. This might result in practices that take such remediation measures only very reluctantly, thus increasing the risk of CCGS operations.

From a safety point of view it also appears desirable that a specific agent with the necessary expertise should hold responsibility for remediation and protection measures in case of accidents in order to make sure that such measures are actually taken (long-term). Such measures still remain to be defined.

Legacy effects

Legacy effects arise from the fact that deploying CCGS implies a transfer of risks to future generations. There are several ethical considerations related to this issues.

While some argue that future generations will be wealthier and technologically more advanced, and therefore better able to deal with the risks imposed by long-term CCGS, others argue that it is not ethical to burden future generations with unknown risks. These considerations are very similar to those surrounding nuclear or hazardous waste storage. [Wilson et al. 2004a, 3]

Leaving the treatment of such questions to CCGS firms would be inappropriate as it is legitimate to assume that the primary motivation of private enterprises in market capitalism is the maximization of profit, and not ethical considerations concerning the welfare of future generations. The issue of legacy (i.e., sustainability) associated with CCGS should (and very likely will) therefore be discussed in a broader public context. The results of this discussion are likely to shape the features of a regulatory framework for CCGS.

4.2.6 CCGS, renewables, and incentives

Principally, without an incentive to avoid CO_2 emissions, be it an emission permit trading system or a CO_2 tax, for example, CCGS will not be deployed by private firms because in the absence of such a regime there is no economic benefit for doing so (except for some EOR or ECBM operations). This is underlined by the fact that existing CCGS operations do either induce economic benefits (EOR, ECBM) and/or are subject to public regulation (incentives for EOR in USA, CO_2 tax in Norway for Sleipner). Therefore, some GHG emission regulation is a necessary condition for CCGS.

In addition to this, CCGS is one of several climate change mitigation options and can be regarded as a competitor to renewable energy production technologies because both technological concepts aim at reducing the GHG emissions of energy production. However, CCGS is widely regarded to be a bridging technology for as long as the supply of renewable energy technologies is insufficient to meet the world's energy demand. As the performance of renewables will increase with cumulated investment and experience, the implementation of CCGS largely depends on investments into renewables. However, the decision to implement CCGS will require considerable investments which otherwise could be used for developing renewables, which will be needed in the long run anyways.[82] As the development rate of renewables is uncertain today (as well as the leakage rate and local risks of CCGS operations), society is currently facing a difficult decision: should all resources available for energy R&D be allocated to developing renewables now, hoping that these will develop quick enough to allow significant reductions in CO_2 emissions, or should some resources be allocated to the deployment of CCGS in order to achieve relatively quick emission reductions (which are associated with uncertainties of their own, that is, unknown leakage rates and local risks)? Under these circumstances it appears desirable to avoid an early lock-in of the energy system into a specific energy infrastructure which is difficult to alter. [Edenhofer et al. 2004a, Edenhofer et al. 2004b, Bauer et al. 2004, Edenhofer et al. 2005b]

Therefore, it seems reasonable to implement an institutional framework that allows for both the reduction of uncertainties associated with the performance of renewables and CCGS, and that launches a sustainability transition of the energy system as soon as possible. In order to achieve this, a comprehensive regulatory framework should at least address the following issues:

- implementation of an emission reduction framework,
- incentives for developing renewables,
- incentives for quantifying leakage rates and local risks of CCGS operations in pilot projects,
- depending on the performance of renewables, incentives for implementing safe CCGS operations.

[82] For this and many other aspects of this section, see subchapter 2.5, especially the discussion of the model of Bauer et al. [2004].

4.2.7 Adoption of CCGS in developing countries and countries in transition

With respect to the current fossil fuel-based energy infrastructure and vast fossil fuel resources (especially coal) in some rapidly developing countries (e.g., China; see 1.1), CCGS could become an interesting CO_2 emission reduction option if such countries were to join a global emission cap and trade system. If these countries would refuse to join such a scheme, Kyoto instruments as the Clean Development Mechanism (CDM) or Joint Implementation (JI) could allow industrialized nations to obtain emission permits by implementing CCGS in such countries. Several aspects would have to be taken into account (see 5.2.1). First, there should be some kind of regulatory framework allowing for such measures. For example, it is currently unclear whether and how CCGS could be integrated into the Kyoto CDM and JI mechanisms. [IEA GHG 2002] Second, it should be ensured that the local and global risks of CCGS operations are minimized in developing countries. There would have to be mechanisms and regulations that ensure that only state-of-the-art technology is being applied.

5. Institutional regulation for CO_2 capture and storage

In this chapter, three issues will be addressed. First, principal regulatory requirements and basic categories are characterized which any future regulatory body for CCGS will have to take into account in some way (5.1). Then, the international regulatory environment for future regulation of CCGS is shortly described and analyzed with respect to the current treatment of CCGS therein (5.2). Finally, concepts for regulating CCGS are outlined (5.3) and systematically discussed.

5.1 Regulatory requirements and basic categories

This subchapter aims at providing an overview of the regulatory requirements of CO_2 capture, transport and geological storage. It is based on the analyses of chapters 2, 3, 4, appendix A, AETF [2004] and Edenhofer et al. [2004a]. It prepares the discussion of implementation of a regulatory framework in subchapter 5.3. It is attempted to facilitate the understanding of the whole of regulatory requirements by introducing a novel categorization for regulatory requirements. Principally, regulatory requirements of CCGS arise from the risks, costs and opportunties of this emerging technological system.

Three basic distinctions are applied here to categorize regulatory reqirements of CCGS. The first distinguishes between *technical* and *social* processes. Technical processes include technological schemes as well as natural processes such as climate change (this category might thus also be labelled 'physical'). Social processes are social activities in which social groups conduct certain activities. With respect to (social) regulatory activities it is worth noting that one can discriminate three principal approaches to regulation, that is, legislatory, policy-based, and economical. In fact, each approach contains some elements of the other. Nevertheless they can be can be distinguished analytically. This is mainly due to the fact that selection of a specific approach usually depends on which social group is preoccupied with setting up the regulation (courts and lawyers, politicians, or economists).[83] While social and technical aspects are often difficult to separate analytically, it can usually be differentiated between processes with a more technical bias and others where the social component is prevalent.

Second, *local* and *global* processes are distinguished. Global processes involve the whole (physical and social) world (earth), whereas local processes are restricted to specified areas (physical/technical) or groups (e.g., nation states, federal states, local communities). Specification of spatial areas usually corresponds to specifying certain social groups.

Third, *long*- and *short-term* processes are discerned. Short-term technical or social processes are those which occur during the operational (injection) period of a CCGS project, whereas long-term processes commence after termination of injection operations and extend to the infinite future, or at least (in order to render this order of magnitude more imaginable) 100 to 1,000 or 10,0000 years and more.

[83] For example, in this thesis the policy and economic perspectives are prevalent while the juridical perspective is neglected (see subchapter 5.3).

In the following, processes that are involved in CCGS regulation are shortly addressed and categorized according to these basic distinctions. The analysis is concluded by a summarizing Table 5.1. It is important to note that this list cannot be regarded to be comprehensive. There may be regulatory requirements that are unknown today (e.g., due to unknown risks). Therefore, such a list can never be considered comprehensive for systematic reasons, although with increasing experience the probability of new requirements can be expected to decrease.

Local short-term requirements

Concerning the social requirements of local short-term regulation, incentives for conducting RD&D on climate change mitigation options may have to be set up in order to reduce the uncertainties of crucial parameters of climate change mitigation options (costs of CCGS, leakage rates, costs of renewables, learning rate of renewables) and expectations of CCGS firms stabilized, the legal status of CCGS and CO_2 may have to be clarified (see section 4.2.1), the site selection and permission process should be designed in a way that minimizes later risks of leakage and accidents while taking into account the costs of this process (4.2.2), a liability regime should be set up that balances the possibly contending aims of minimizing local risks and costs (4.2.5), and it should be ensured that remediation measures in case of accidents are worked out and there are responsible agents to conduct these activities appropriately if required. Also, compliance with established regulation has to be ensured.

The technical aspects of local short-term regulation concern verification of the net amounts of CO_2 avoided and injected (including calculation of fugitive emissions during CO_2 handling from capture to injection, see section 2.1.4), setting up a monitoring scheme and quantifying leakage rates of CO_2 and other substances (see 2.2.4).

Global short-term requirements

From a social activities point of view the global short-term needs of regulation for CCGS include the creation of incentives to avoid emissions of greenhouse gases to the atmosphere (e.g., an emission cap and trade regime, see 5.2), and to do this in a way that minimizes the related global economic risks of implementating CGGS and renewables with uncertain leakage and development rates, for example by implementing an inherent flexibility to such a regime. Institutional schemes that include incentives to minimize leakage from CO_2 reservoirs should be set up (including establishment of some liability) as well as mechanisms which ensure that experiences gained at individual CCGS projects are communicated and applied among all CCGS operators. [Reiner and Herzog 2004, 3; Gale and Read 2004; Perrow, 1992]

From a technical point of view it appears desirable to enable transfer of (state-of-the-art) energy technologies from industrialized nations to developing countries and countries in economic transition (e.g., China and India), although this technical process will, of course, mainly involve setting up a genuinely social mechanism regulating technology transfer.

Local long-term requirements

From a social processes point of view establishment of a long-term liability regime for local risks of CCGS appears necessary, as well as ensuring that remediation measures and responsible and capable agents in case of adverse events at CO_2 reservoirs are available in the long-run (see 4.2.5).

Technically, long-term monitoring may be desirable in order to enable a long-term local liability and remediation regime (as well as global long-term institutional regulations on leakage).

Global long-term requirements

From the social global long-term point of view creating an institutional regime that induces incentives for minimizing the global (climate change) risks of leakage (which is complementary to local requirements), that establishes some kind of liability, and ensures that site operators (agents responsible for long-term monitoring and remediation measures) optimally exchange experiences gained appears necessary.

Table 5.1: Categorization of regulatory requirements of CO_2 capture, transport and storage. Source: own.

		Local	**Global**
Short-term	*Social*	Create incentives for reducing uncertainties on climate change mitigation options through RD&D (CCGS, renewables); stabilize expectations of CCGS firms. Define legal status of CCGS and CO_2. Ensure that site selection & permission process minimize risk of leakage and accidents (costs). Establish liability for local risks of CCGS. Ensure remediation measures and agents are available. Ensure compliance with regulation.	Create incentive to avoid GHG emission to atmosphere (e.g., emission cap and trade), and minimize the global economic risks of this mitigation process. Create an incentive to minimize leakage from CCGS operations (both long- and short-term), including establishment of liability. Enable transfer (and application) of experiences on safety issues among CCGS operators.
	Technical	Verify net amount of injected CO_2 (account for fugitive CO_2 in capture, transport, injection). Install monitoring scheme, quantify leakage rates.	Enable sustainable technology transfer to developing countries
Long-term	*Social*	Establish liability for local risks of reservoir leakage. Ensure remediation measures and agents are available.	Create an incentive to minimize long-term leakage, including establishment of liability. Ensure transfer and application of experience among reservoir operators.
	Technical	Establish long-term monitoring	

Subchapter 5.3 will discuss two proposals for meeting these regulatory requirements. While it is possible (and necessary) to discuss isolated items of specific categories in detail,[84] the approach chosen here is different: regulatory concepts are analyzed that aim at providing an overarching and integrated framework for CCGS.[85] There are two reasons for this. First, there is no global framework for CCGS that is widely discussed today, while the necessity for this widely admitted [e.g., IEA 2003; Wilson et al. 2003; Bengal 2004; de Figueiredo et al. 2003; Reiner and Herzog 2004; Senior et al. 2004]. Second, for discussion of details of regulation (e.g., legal specifications) an overarching framework (or, at least, a principal guiding idea) appears very desirable.

It therefore appears recommendable to start analysis of possible regulatory schemes from the point of view of the global (short- and long-term) regulatory needs of CCGS (which are in fact often inseparably related to local aspects). Having sketched an overarching scheme, it will be possible to treat local requirements. Then, more detailed issues can be discussed (however, this will not be part of this thesis).

The relation between global and local regulation could principally take three forms: (i) granting autonomy to local regulation, (ii) regulating local aspects from a global point of view, or (iii) defining certain minimum standards that local regulation has to meet from the global point of view, the detailed implementation of which is left to social processes at the local level.

Because the primordial perspective chosen here is global, it is necessary to first obtain an overview of the global (international) social processes which relate to regulation of CCGS. These are the United Nations Framework Convention on Climate Change (UNFCCC), and the related Kyoto protocol and European Union Greenhouse Gas Trading Scheme EU (ETS). They will be briefly discussed in the following subchapter 5.2. Designs for a regulatory framework for CCGS will then be discussed in subchapter 5.3.

---

[84] For example, IEA [2004] and Bode and Jung [2004] analyze detailed regulatory issues concerning CCGS by drawing analogies to existing regulations for biosequestration activities under the UNFCCC.

[85] An integrated framework for CCGS is considered desirable by many authors, the most important reason for this being minimization of transaction costs that could arise in case of heterogenous requirements and responsible authorities, with resulting uncertainty and ineffectiveness. [Wilson et al. 2003; Benson et al. 2002; AETF 2004]

5.2 The UNFCCC process

The United Nations Framework Convention on Climate Change (UNFCCC) is the overarching convention in which almost all countries of the world have agreed to take actions in order to ensure the stabilization of the concentration of GHG emissions in the atmosphere to acceptable levels. [IEA GHG 2003] It was inaugurated at the 1992 'Earth Summit' at Rio de Janeiro, Brazil. The primary objective of the UNFCC is

> "(...) the stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a timeframe sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner." [UNFCCC 1992, Article 2]

In order to reach this goal, the Conventions states that participating parties shall

> "promote and cooperate in the development, application and diffusion, including transfer, of technologies, practices and processes that control, reduce or prevent anthropogenic emissions of greenhouse gases […] in all relevant sectors, including the energy […] sectors." [UNFCCC, Article 4c]

The UNFCC has institutionalized regular Conferences of Parties (COP) at which the parties negotiate and decide upon climate policy measures. Also, all Annex I countries (essentially the developed countries) are required to establish national GHG emission inventories. Best Practice Guidelines for keeping these inventories are issued by the IPCC. [IPCC 1996]

5.2.1 The Kyoto Protocol

In 1997, the 3rd Conference of Parties (COP 3) of the UNFCCC at Kyoto adopted the 'Kyoto Protocol'. In the Kyoto Protocol the industrialized nations of the world (listed in Annex B of the Protocol, or Annex I of the UNFCCC[86]) agreed to reduce their combined GHG[87] emissions 5% below 1990 levels in a commitment period from 2008 to 2012. While there has been considerable critique of the Protocol,[88] it is also widely recognized as a breakthrough in international climate negotiations and a signal to markets that climate change is an important policy issue that is going to be addressed by governments in the future. [Schwarze 2000] The Kyoto protocol will come into force on February 16th 2005 after its ratification by Russia in November 2004.[89] [UNFCCC 2004]

---

[86] Annex I and Annex B include all OECD countries and the eastern european nations in economic transition. The two lists are identical apart from Belarus and Turkey which are in Annex I of the UNFCCC, but not in Annex B of the Kyoto Protocol; Croatia, Liechtenstein, Monaco and Slovenia are listed in Annex B, but not in Annex I. [Bode and Jung 2004; Schwarze 2000; Krug 2003]

[87] The following substances are defined greenhouse gases (GHG) within the Kyoto Protocol: CO_2, CH_4, N_2O, SF_6, HFC, and PFC.

[88] Critique focused on the negligible effects of the emission reductions agreed upon in the Protocol, which would have almost no impact at all on global climate change. Another controverse aspect was the inclusion of biological sinks (biosequestration) into the Protocol. For a summary of critique, see e.g. Schwarze [2000].

[89] For the Kyoto protocol to come into force, nations that are responsible for at least 55% of the global emissions had to ratify the contract. [Schwarze 2000, 97]

The Kyoto Protocol's main instrument for meeting the requirements of emission reductions is an emission cap and trade regime, which is complemented by the Clean Development Mechanism (CDM) and Joint implementation (JI) program. Also, so-called regional 'bubbles' can be constituted if several nations establish a common emission cap and trade regime with the cap being based (at least) on the sum of the emission allowances of the participating parties under the Kyoto protocol. The EU is the only emissions trading 'bubble' that has been set up so far (see section 5.2.2 on EU ETS below).

Regarding CCGS and the Kyoto Protocol, there is only one explicit reference which states that Annex-I countries need to research, promote, develop and increasingly use CO_2 sequestration technologies (Art. 2, par a).iv). This note was extended in the Marrakesh Amendments to the Kyoto Protocol. The Marrakesh Accords further clarify the Kyoto Protocol regarding technology cooperation stating that Annex-I countries should indicate how they give priority to cooperation in development and transfer of technologies relating to fossil fuel that capture and store greenhouse gases (Paragraph 26, Decision 5/CP.7). [all cited after IEA GHG 2002]

> "[OECD countries, C.F.] should give priority, in implementing their commitments under Article 3, paragraph 14, of the Kyoto Protocol, to the following actions: (...) d) Co-operating in the development, diffusion and transfer of less greenhouse gas-emitting advanced fossil fuel technologies, and/or technologies relating to fossil fuels that capture and store greenhouse gases, and encouraging their wider use; and facilitating the participation of the least developed countries and other Parties not included in the Annex I in this effort." [article 26 UNFCCC 2001a, cited after IEA GHG 2002, 41]

This means that the OECD countries have an obligation to promote market development of CO_2 capture and storage technologies in developing countries. The exact financing mechanisms for funding technology transfer have not yet been clarified. More generally, no explicit text references to CCS project-based activities can be found in the CDM and JI-related decisions. This may remain so as long as CCS remains more costly than other CO_2 emission reduction technologies. [IEA GHG 2002, 41; IEA 2004b, 23; Torvanger et al. 2004, 6]

The lack of recognition of CCGS in the UNFCCC process has implicitly been acknowledged at the Party of Conferences at Marrakesh where the IPCC was requested to write a technical paper on the subject.

> "[The COP, C.F.] *invites* the Intergovernmental Panel on Climate Change, in cooperation with other relevant organizations, to prepare a technical paper on geological carbon storage technologies, covering current information, and report on it for the considerations of the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol as its second session." [UNFCCC 2001b, cited after IEA GHG 2002, 41]

The publication of this Special Report on Carbon Dioxide Capture and Storage is due in late 2005.

In the following, the three main instruments agreed upon in the Kyoto Protocol – emission cap and trade, CDM and JI – will be shortly discussed.

Emission cap and trade regime

An emission cap and trade regime for greenhouse gas emissions implies that for specific sectors and facilities in participating nations a maximum of the total emissions from these sectors and facilities is defined ('cap'). At the start of the regime, emission permits ('credits', in case of Kyoto: Assigned Amount Units (AAU)) are handed out to the participating nations according to negotiated quotas.[90] The overall number of issued permits equals the defined emission cap. The national authorities may then hand out permits to individual installations according to some allocation concept (e.g., auctioning, grandfathering). [Schwarze 2000, 109-145; Krug 2003]

After that, the emission permits may be traded among the facilities (or countries): each facility has to prove to a climate authority that it holds an amount of permits that equals its volume of actual emissions. If actual emissions from a facility are reduced, superfluous permits can be sold on a market. Therefore, a market price for CO_2 emissions is etablished along with an incentive to reduce the regulated GHG emissions. The basic idea is that the inherent flexibility of the mechanism achieves emission reductions at those facilities where they are cheapest. [Schwarze 2000, 109-145; Krug 2003]

Facilities whose emissions exceed the amount of permits held can buy permits from companies that achieve emission reductions. If a facility fails to book the sufficent amount of emission permits, the regulatory authority that keeps track of emissions and certificate inventories will issue a penalty fine for the amount of GHG emitted without being covered by certificates. [Schwarze 2000, 109-145; Krug 2003]

Such a penalty mechanism would make the seller of a certificate liable for violations of the mechanism. Alternatively, buyers of certificates may be held liable. In this case the value of individual certificates would be subject to uncertainty: if the actual emissions of a seller of certificates exceed his total stock of certificates at the end of a trading period, the certificates he has sold (and which are held by buyers) are devalued, either completely (all certificates sold after the budget has been exceeded), or proportional to the percentage at which the seller has exceeded his budget. In this case, emission certificates of actors with uncertain security will be traded with a risk premium, that is, they are going to be cheaper than 'safe' certificates, but in case they are devalued the buyer will encounter an economic loss. [Schwarze 2002, 117-118]

Introduction of emissions trading into the UNFCCC process and ultimately the Kyoto Protocol is attributed to the USA, who nevertheless pulled out of the treaty in 2001. The United States have already gained experience with an emission cap and trade regime controlling SO_2 emissions in the 1990s. More than 260 of the most polluting power stations were given a maximum emissions allowance, and anyone destined to exceed their limit had to buy an extra credit from those were able to reduce their SO_2 emissions. By 2000 all US coal-fired power stations were integrated into the scheme due to its success: nationwide emissions had fallen from 16Mt in the late 1980s to about 11Mt. [Hopkin 2004, 269]

---

[90] Concepts for allocating emission quotas include per capita allocation and other concepts. Investigating the implications of each allocation scheme has become subject to a substantial body of research.

Clean Development Mechanism

The Clean Development Mechanisms (CDM) was added to the emission trading scheme of the Kyoto Protocol for three reasons. First, not all countries are expected to join the Protocol (especially developing countries, e.g., China, India) because they feel that this could inhibit their economic development. Second, GHG emission reductions can often be achieved cheaper in developing countries than in industrialized nations (by transferring emission reducing technology). Third, technology transfer to development countries may help in developing these countries in a sustainable way.

The basic idea of CDM is simple. A developed country introduces a technology that reduces GHG emissions into a developing country and receives a Certified Emission Reduction (CER) for the emissions reduced. It has to be ensured that the implementation process increases the sustainability of the host country. The emission reduction of each project is verified by an independent operating entity which remains to be specified. It has to be ensured that a CDM project incurs additional investments that otherwise would not have been made. It is currently unclear whether CERs can be traded on a market. Developed countries can credit CERs against their national emission inventories (that is, their AAUs).

However, there are several problems associated with CDM, some of which shall be briefly addressed. First, it is difficult to calculate the emissions avoided by a CDM project. Both parties involved have a strong incentive to overstate the actual emission reductions.[91] In order to calculate the actual reductions of a project, a baseline case has to be assumed that states how much GHG would have been emitted additionally if the CDM project had not been implemented (therefore, this problem is referred to as 'additionality of emission reductions'). A baseline scenario is inherently subject to uncertainty. Second, the CDM regulations demand that the investments for CDM projects would not have been made without the incentive of a CER. Addressing this problem is negotiated under the label 'additionality of investments'. Third, 'financial additionality' implies that CDM investments should not crowd out development aid that would have been issued to developing countries anyways. Again, the problem is to calculate a baseline scenario of what would have happened in absence of CDM.[92] Fourth, the CDM may create a negative incentive for firms in developed countries for reducing their own emissions and for develping low-emission technologies. Fifth, it is difficult to operationalize the term sustainable development. Finally, for biosequestration (or CCGS) projects that are implemented via CDM there should be some penalty in case the CO_2 leaks out of the sink again (this issue is not addressed in the current CDM design). [Schwarze 2000; IEA GHG 2002; Hopkin 2004]

Joint Implementation

The Joint implementation mechanism allows Annex I countries to conduct GHG reduction activities in other Annex I nations. Emission reductions achieved by JI projects are awarded Emission Reduction Units (ERU), which are issued under supervision of some authority (e.g., the UNFCCC Secretariat). In order to trade an ERU from a host country to the country

[91] The host country because there are no negative consequences if it does so (CERs are not subtracted from its own national inventory), and the developed country because it wants to achieve emission reductions at a low price. [Schwarze 2000, 106]

[92] For an overview of the baseline/ additionality problem, see Schwarze [2000, 169-183].

conducting a project, the host country has to (a) account for the ERU in its emission inventory, and (b) note the transmission of the ERU to the partner country (in order to avoid double accounting for ERUs).

Within Joint Implementation, Track 1 and Track 2 activities are distinguished. Track 1 activities can be conducted by Annex I parties that meet a number of eligibility criteria, among them being calculation of Assigned Amount Units, institution of a national registry, and reporting of GHG inventories. Countries performing JI under Track 1 are free to set their own national guidelines for JI. [IEA GHG 2002, 43]

If countries do not comply with Track 1, Joint Implementation can be carried out via Track 2. Such projects are basically regulated analogous to CDM activities, apart from some issues involving crediting and supervision by the UNFCCC secretariat. Track 2 JI is eligible only in the commitment period from 2008 to 2012. No regulation is in place concerning the crediting period, and there are no obligations with regard to consultation of local stakeholders. [IEA GHG 2002, 43]

If the permanence of a JI acitivity is put into question, the ERU is 'frozen' but may still be traded until final decision on the viability of that credit by the responsible authority. [Schwarze 2000, 102-103]

JI activities should create additional GHG reductions compared to a baseline. The same general problems that are related to 'additionality' in CDM do apply.

To conclude, the Kyoto Protocol ecourages the use of (biological) carbon sequestration technologies in the flexibility mechanisms JI and CDM in general terms, but without specific reference to CCGS. It may be difficult to address the problem of leakage within JI or CDM.

The seventh Conference of Parties of the UNFCCC at Marrakesh 2001 introduced regulation for accounting for biosequestration projects. These state that if Annex I countries achieve emission reductions through biosequestration activities, these are awarded with ‚removal units' (RMU). RMUs are fungible units in the international market, but cannot be carried over to the next commitment period. This means they can only be used in the period they were created. Depending on the length of the commitment period, there effectively is a built-in depreciation of the RMU. [Bode and Jung 2004, 11-12; see also IEA 2004b]

CDM projects have to demonstrate that their implementation will have sustainable benefits for the host countries. While this may apply for EOR or ECBM operations, it appears very difficult to show what ancillary sustainability benefit a CCGS project would imply. [IEA GHG 2002, 43-44]

Verification and accounting

Emission inventories of Annex I countries comprise information on the annual amounts of GHG emissions. The IPCC has issued guidelines for inventory reporting that states have to comply with. [IPCC 1996] Emissions are commonly calculated by computing the carbon content of energy inputs into certain sectors, which allows for calculation of CO_2 emissions via constant conversion factors. [Schwarze 2000]

Accounting refers to quantifying emission reductions achieved by the flexibility mechanisms CDM and JI. Some regulatory body confirms (accounts for) the amount of CO_2 avoided by such an activity, and a corresponding amount of certificates (CER or ERU) is issued.

Verification means that a regulatory body states that a certain amount of GHG emissions has been emitted to the atmosphere. This implies a statement about emissions not released to the atmosphere (these are not listed as atmospheric emissions). Therefore, in CCGS operations CO_2 that results from burning fossil fuel primary energy carriers and which is injected underground for storage purposes has to be quantified. This amount is then subtracted from the amount of emissions computed for a respective sector based on the primary energy inputs. The process of assuring that CO_2 is not emitted to the atmosphere but stored in an underground reservoir is labelled verification.[93]

Overall, it is worth noting that under the UNFCCC there are four kinds of emission permit certificates. Within an emission permit trading scheme, Assigned Amount Units (AAU) will be used. For CDM activities, Certified Emission Reductions (CER) are issued. Joint Implementation efforts generate Emission Reduction Units (ERU). Since the COP 7 at Marrakesh, Removal Units (RMU) can be issued under the UNFCCC for activities enhancing CO_2 sinks, that is, biosequestration activities.

The IPCC is currently working on revised guidelines for national greenhouse gas inventories, and parts of the IPCC special report on CCS will address the issue of accounting for CCGS within UNFCCC. [IPCC 2002]

5.2.2 The European Union Greenhouse Gas Emissions Trading Scheme (ETS)

In January 2005 the European Union (EU) will commence its Emissions Trading Scheme (ETS) that introduces a CO_2 cap and trade regime for high emission industries (e.g., power generation facilities, mineral mining applications, cement and paper factories). The first commitment period of the EU ETS stretches from 2005 to 2007. The second period extends from 2008 to 2012 (Kyoto).

The EU ETS constitutes a regional 'bubble' trading scheme. Each EU member country has set up a national allocation plan which allocates the total amount of emissions permits available to a country to individual facilities (~12,000 installations overall EU-wide). These permits can then be traded on a EU-wide market. A central electronic registry keeps track of the actual emissions and permits held by industrial facilities. If emissions exceed the amount of permits held by an installation, a fine of € 40 per ton CO_2 is incurred (€ 100 per ton after 2008). [EU 2004; Hopkin 2004; Senior et al. 2004]

One problem of the EU ETS may be that only certain sectors are included, while others (e.g., transportation, housing) are left out but still contribute to rising emissions. Therefore only ~50% of total EU emissions are covered by the EU ETS. [Hopkin 2004, 270]

Neither the EU ETS nor the (so far only virtual) US Chicago Climate Exchange does address CCGS in any form. [IEA 2004b, 23]

---

[93] The issue of reservoir leakage and record keeping on CCGS could be addressed by introducing a new category for geologically stored CO_2 into national emission inventories. Also, leaked CO_2 should be represented in the national inventories. [IEA 2004b, 19-20] Both fugitive emissions and leakage from CCGS operations (atmospheric emissions resulting from energy requirements of compression, transportation and injection, and atmospheric leakage during these process steps; see 2.1.4) should also be quantified and integrated to make sure national emission inventories do reflect the actual net amount of CO_2 avoided by CCGS. [IEA 2004b, 4-5]

5.3 Designing a regulatory framework for CO_2 capture and storage

Many regulations have evolved incrementally from existing regulatory structures without comprehensive analysis and consequently without anticipation of the later consequences of the regulation framework implemented. Without adequate scientific analysis and debate, regulators may have to act abruptly and uninformed. Today, only one proposal for an integrated regulatory framework of CCGS is available and has been put forward by Edenhofer et al. [2004a].[94]

In subchapter 5.1 the regulatory requirements for CCGS arising from the associated risks, costs and opportunities have been outlined and categorized. In subchapter 5.2 the international social conditions for regulating CCGS have been addressed. This subchapter will first discuss which rationale of regulation may be appropriate for regulating CCGS (5.3.1). Then, the concept of Carbon Sequestration Bonds (CSB) by Edenhofer et al. [2004a] is outlined and discussed along with an alternative emission trade based scheme (5.3.2). Because regulation of CCGS will be inherently related to that for renewable energies, Green Energy Certificates as a means for fostering the development of renewables will finally be introduced in (5.3.3).

5.3.1 Rationale of regulation

There is an ongoing discussion concerning the basic rationale and design of regulatory frameworks in which two approaches are being contrasted: performance-based and procedural practices, both concepts having different implications.

Performance-based vs. procedural regulation

In a *performance-based* framework key performance goals are defined by the regulator, leaving the operator free about how to meet these goals. It is the operator, and not the regulator, who is responsible for achieving these goals, and the operator has to convince the regulator that his means (management and technology system) to do so are adequate. The advantage of this approach is seen in its efficiency which is allowed by its inherent flexibility allowing the operator to adapt to changing social and technological conditions; it also implies incentives for operators to develop efficient (regarding costs, performance) technologies and methods in order to meet the required standards. While this approach works well in areas that allow for relatively easy monitoring or spot-checking of the key parameters (e.g., SO_2 emissions), it has its main drawbacks where such parameters can not be so easily observed. The latter applies for important aspects of CCGS: leakage rates from reservoirs can not be measured directly but have to to be inferred from complex monitoring schemes and simulation models. As model parameters and methods imply heavy uncertainties and model results can not be interpreted without ambiguities, the use of models makes it very difficult for the regulator (and the operator himself) to assess whether the operator really complies with the standards. [Wilson et al. 2004a, 3] Therefore, implementing a performance-based approach which may be desirable both from the point of view of

[94] For treatment of Carbon Sequestration Bonds see also Edenhofer [2003], Edenhofer et al. [2004b], Fischedick et al. [2004, 34], and Edenhofer et al. [2005b].

efficiency and safety may be difficult for some aspects of CCGS, e.g. leakage to the atmosphere or adjacent formations. However, if these problems can be overcome (e.g., by improvements in monitoring technology), this approach appears preferable for regulating crucial aspects of CCGS such as leakage.

In a *procedural* approach instead of specifying a performance goal the regulator specifies detailed procedures that must be followed by the operator. These procedures must be designed in a way that make sure the risks involved in the process are adequately taken care of. The responsibility for ensuring that the mandated procedures lead to the desired outcome rests with the regulator. In effect, procedural standards therefore usually also imply performance goals. The operators' responsibility is simply to follow the prescribed procedures. [Wilson et al. 2004a, 3] A procedural approach could be interesting for CCGS where monitoring and verification procedures have to be regulated, and might complement a performance approach by specifying the parameters and methods for evaluation of operational performance. Also, some requirements for CO_2 pipeline construction could be regulated on a procedural basis (e.g., mandated use of specific materials).

Therefore, Wilson et al. [2004a, 3] propose to combine both approaches for a CCGS framework. Aspects which allow for definite goal attainment control could be designed performance-based, while aspects where data is uncertain should be regulated in a procedural way. Public debate would likely foster around the specification of performance goals, especially leakage rates and ultimate storage retention time. [Wilson et al. 2004a, 3; Wilson et al. 2003, 3482]

Institutional aspects

The rationale of regulation aiming at maximizing safety of CCGS operations should create a strong incentive for firms to actually focus on providing and improving safety of CCGS operations, and not merely focus on enhancing the public acceptance of CCGS. Radkau [1983, 470] notes that in the 1970s in the United States a total of US$ 100 million were spent on reactor safety studies. Of these, 90 millions were spent on proving that the existing systems were safe, and only 10 million were spent on research actually improving safety.

Another important question of the basic outline of regulation are timescales for institutional control of geological storage sites. Analogous experience from final storage schemes for radioactive waste indicates that in this area regulatory agencies assume timescales of 0 to 300 years of control. [Stenhouse et al. 2004, 5] There has been no debate on this issue with respect to CCGS, yet. Considering the timescales envisaged for storage and the character of risks (e.g., earthqakes leading to leakage may occur after hundreds of years), it seems desirable to establish long-term institutional control over CO_2 reservoirs. More specifically, future generations should at least know where CO_2 has been injected. Taking into account the possibility of social change and disturbances over centuries, an institution controlling CCGS should be unpolitical.

Hawkings [2002] suggests that it could be important to hold a single authority responsible for the assessment of the global CCGS system. Such an authority would have to compile site-specific leakage rates as well as the average global CCGS system leakage rate.

5.3.2 Carbon Sequestration Bonds

Edenhofer et al. [2004a, b] principally assume that before specific instruments for CCGS are implemented, some kind of emission regulation is already in place. This is because without such regulation, be it an emission cap and trade system or a CO_2-tax, there is no incentive for profit-oriented companies and investors to conduct CCGS as the emission of CO_2 to the atmosphere does not constitute a restrictive cost factor for private firms.

Assuming existence of emission regulation Edenhofer et al. [2004a, b] make two proposals. The first is based on the idea of environmental performance bonds and is termed 'Carbon Sequestration Bonds' CSB. The second involves a direct integration of CCGS into an emission cap and trade regime. Both approaches will be discussed after having outlined the principal concept of environmental performance bonds in the following section.

Environmental performance bonds

Perrings [1989] proposed environmental performance bonds that are based on the economical theory of uncertainty in social action. The basic idea of environmental performance bonds is to address the decision-making problem of an environmental authority that is faced with innovative private economic activities that involve uncertain future environmental effects. That is, the problem is to achieve internalization of uncertain externalities of innovative activities of (profit-oriented) private firms.

The extent of uncertainty correlates negatively with historical experience on a particular innovative activity, that is, the less experience is available, the larger the problem of uncertainty surrounding possible future damages. Also, even if some activity has already been conducted in an innovative field, there has usually been no incentive for private firms to systematically research all socially relevant aspects (e.g., risks) in such early projects. Therefore, according to Perrings the problem of an environmental authority is to consider

> "whether there exists an incentive to research that will ensure that all socially relevant questions are asked about the future external effects of activities with no or few historical precedents." [Perrings 1989, 96]

Perrings argues that this can be achieved if the environmental authority forces the innovating company to buy a bond representing (a) the social costs (risks) of an economic activity (social insurance aspect) and comprising (b) a premium that represents the uncertainties related to an assessment of social costs of that activity (uncertainty aspect). Both factors have to be quantified by the environmental authority. The amount of the latter premium will depend on the degree of uncertainty averseness of the environmental authority, that is, whether the focus of attention of the environmental authority (and ultimately, society) is put on the more or the less appalling aspects (gains or losses, opportunities or risks) of an innovating activity. In other words, the authority can choose in its evaluation process whether it will rather focus on the largest (catastrophies) or the lowest possible risks of the activity.

The company receives an interest rate on the bond and is free to sell it on a market to offset its costs. It can be expected that uncertainties related to the activity will be reduced and knowledge on risks will increase with experience gained. In fact, there is an explicit incentive for firms to reduce this uncertainty, as research activities can lower the price of the bond by reducing uncertainties, particularly those surrounding the largest risks.[95] Both uncertainty and risk premium can be re-assessed by the environmental authority in periodical intervals. Introduction of a discount rate allows to calculate the present net value of the bond.[96] [Perrings 1989]

Hence a systematic incentive is created for private firms to reduce (a) the uncertainties and (b) risks related to an innovative activity. If firms do fail to reduce uncertainties, an environmental authority may periodically devalue a bond. If firms succeed in making risks more calculable, this may be awarded by increasing returns from the bond (e.g., partially paying it back). If an accident actually occurs, the bond can be devalued accordingly. [Perrings 1989]

The revenues of the environmental authority that are generated from issuing the bond may be used for various tasks. They could, for example, be directed to public research reducing uncertainties related to the activity. While other usages are possible, Shogren et al. [1993, 114] remark that using resources from the bond payments for other research does imply that these funds can not be returned to the firm, that is, partial failure of firms is implicitly anticipated. [Perrings 1989] Another option for using the bond revenues may be to keep them for remediation measures in case of accidents.

Perrings [1989] defines the function of environmental performance bonds as follows:

> "[the environmental bond would, C.F.] (1) (...) register the value placed by the environmental authority on allowing an innovative activity to proceed without further research; (2) it would provide an incentive to innovative firms to research the future effects of their own activities; (3) since the bond would yield interest income it would generate public research funds in direct proportion to the public concern about future effects of innovative activities; (4) it would determine the timing of an innovative activity; (5) it would encourage sufficient advanced experimental research to eliminate, so far as possible in an uncertain world, catastrophic but unsurprising conjectured outcomes; and (6) it would insure society against the irreducible residuum of conjectured but unsurprising losses." [Perrings 1989, 101-102]

Finally, Perrings highlights two properties of environmental performance bonds. First, by implicitly weighing the worst case costs of an innovative activity a society (via the environmental authority) can signal to private actors the value of research that can reduce

[95] However, as firms have an incentive to conduct research that, as its result, leads to a reduction of the bond price, there is a strong incentive to conduct research which downplays risks and uncertainties. Therefore, related basic research will be a controversial issue because considerable monetary interests are at stake (moral hazard), and privately funded research without alternatives (concurring research, e.g., publicly funded) is likely to be insufficient. [see Shogren et al. 1993, 112-113]

[96] In the terminology of economic theory on decision-making under ignorance the present value of social costs in situations of heavy uncertainty can be defined as follows:
"[The present net value of the social costs, C.F.] therefore depends on four factors: (1) the (subjective) probability of each of an exhaustive list of outcomes of choice-options with respect to those constituent actions with historical precedents; (2) the potential surprise associated with each of an incomplete list of outcomes of choice-options with respect to those constituent actions without historical precedents; (3) the utility or profit function that explains the power of each option to command the attention of the decision-maker; and (4) the rate of discount. None of these factors is independent of time." [Perrings 1989, 100] These properties render the practical problem of periodically calculating the social costs of CCGS accessible to Bayesian analysis.

uncertainties about worst case scenarios. Second, the environmental authority can steer the amount of the innovative activity via the bond price. [Perrings 1989]

Bonds have encountered limited use only which Shogren et al. [1993] attribute to three disadvantages: moral hazard, liquidity contraints, and legal restrictions on contracts. The moral hazard problem can take two forms. First, the regulator may have an incentive to capture the bond as this could increase the power and revenues of the agency (e.g., the firm could be labelled a cheater, or conditions could be changed to make it more difficult for firms to comply with regulatory standards; this might apply especially in countries where there is an insufficient legal and/or juridical system). Second, if the firm realizes that actual environmental damages exceed the bond value, it has an incentive to eliminate pollution control and the bond is no longer an effective threat to increase precaution. [Shogren et al. 1993, 114-115]

In case of high bond prices liquidity constraints may hinder firms with low liquidity to enter the market. This is because even if capital is borrowed and bonds traded and risk of the devaluation of bonds is pooled in an insurance scheme, considerable amounts of capital are still required for the backup regime. [Shogren et al. 1993, 114-118]

Legal constraints refer to the possibility that firms may legally contend confiscation of a bond in case of environmental damages pledging that this constitutes an unfair penalty. This would undermine the incentives of the bond, ultimately rendering it an ineffective means for regulation. [Shogren et al. 1993, 118-119]

Proposal A: Carbon Sequestration Bonds

For CCGS to be conducted and Carbon Sequestration Bonds being issued at a socially optimal rate Edenhofer et al. principally assume that CSBs have to be combined with an emission regulation scheme, be it a CO_2 tax or an emission cap and trade scheme. This is formally shown by Edenhofer et al. [2004a, b] within a generic model. Also, Edenhofer et al. demonstrate that Carbon Sequestration Bonds are fully equivalent to a tax solution for implementation of CCGS.

An environmental authority calculates the best account of the largest potential future environmental damage of a specific CCGS project.[97] The calculated amount reflects the external costs of CCGS under uncertainty and constitutes the price of the bond. A private firm that wants to conduct CCGS has to buy such a bond in order to attain project permission by the authority. CCGS becomes economically viable for a firm if the emission certificate price exceeds the combined discounted costs of the technological process of CCGS and the (discounted) price of the bond. An incentive is created for the firm to choose the safest formations known because for these, the highest expected risks are lower, and hence the bond will be cheaper.

If an environmental damage actually occurs, the bond is devalued accordingly by the authority and the firm has to purchase the corresponding amount of emission permits which

[97] Edenhofer at al. assume that catastrophic simultaneous outgassing of CO_2 from all existing CO_2 reservoirs will not occur.

leads to an increase of the permit price.[98] The money that is effectively transferred to the authority due to the devaluation of the bond could then be spent on RD&D on renewables. If no damage occurs, the bond bears an interest rate in an escrow account.[99] In addition to devaluation in case of accidents, the bond is automatically devalued in periodical intervals (for example every three years) except if the owner of a bond can prove beyond doubt that all CO_2 has remained within the reservoir. CSBs can be sold on a market if other actors are willing to bear the risk of devaluation.[100]

Within a generic model Edenhofer et al. [2004a, b] are able to show that a CSB regulation of CCGS is equivalent to a CCGS Pigou-tax or price regulation.

Although this issue remains unclear in the argumentation of Edenhofer et al., it can be shown that the CSB bond scheme takes into account both local and global environmental risks of CCGS. The variable E environmental pressure used by Edenhofer et al. [2004a, b] is determined by two other variables, A the amount of CO_2 in the atmosphere and D the amount of CO_2 in geological formations. As CCGS can have an impact on A in case of leakage from geological reservoirs (reservoir leakage rate b multiplied with amount of CO_2 in reservoir D), it can be argued that b D represents the global (climate change) risk of CCGS, and D the local environmental risks of CCGS. Edenhofer et al. [2004a, b] find that a social planner will conduct CCGS if the impact of the atmospheric CO_2 concentration A on the environmental pressure E is high (this represents the climate sensitivity), if the reservoir leakage rate b is low, and if the local environmental risks of CCGS D are low. A CCGS tax has to represent both the global (b D) and local (D) environmental impacts of CCGS. Because it is shown that a CCGS tax (in a world without uncertainty and perfect capital markets) is equivalent to the concept of Carbon Sequestration Bonds, it can be argued that the CSB concept by Edenhofer et al. [2004a, b] implicitly takes into account the local and global environmental risks of CCGS, although the explicit argumentation focuses on global environmental risks, only.

---

98 If the obligation to purchase a permit in case of leakage were the only regulation in place for CCGS, this would create a strong incentive for mismanagement of operations for two reasons: (a) the management could hope for decreasing permit prices, and (b) the management could simply assume that it will not be affected by the problems that a future management may have with leakage rates (that is, there are no incentives for taking care of safety in case the time horizon of management is shorter that timescale for leakage, and risk affinity is high). This problem can be avoided by introducing a bond. [Edenhofer et al. 2004a, b]

99 The interest rate could be equal to that of very long-term governmental bonds if the income from the bond payments could be freely used by the authority. In this case, if the interest rate paid out on the bond by the authority were higher than the usual interest rate in order to promote CCGS activities, the difference between the interest rate of a common long-term obligation and the interest rate on the CSB would represent a subsidy for CCGS.
However, it is unlikely that the authority can freely make use of the money payed for the bond because eventually it may have to pay it back to the CCGS firm (if safety is high). Therefore, the interest rate on the CSB can in part be interpreted as a subsidy for CCGS (if it is financed by tax income). Via the height of the interest rate, the authority can influence the economic attractiveness of risky CCGS projects.

100 A buyer would carry responsibility for proving that the reservoir is safe (this creates a long-term incentive to minimize the risk for reservoir leakage). CCGS firms might increase (and finance) the interest rate on the bond in order to make it more attractive for buyers.

It is worth noting that if an environmental authority is to practically calculate the price of a CSB, it has to calculate both the risks and costs of the local and global implications of CCGS under uncertainty. It therefore requires a classification of local and global environmental risks of CCGS. [Edenhofer et al. 2004b, 28] Such a classification is provided with chapter 2 of this thesis, for example.

The global risks of CCGS which arise from the threat of climate change due to reservoir leakage, from investments into significantly leaking CCGS operations that can be written off, and from the opportunity costs of CCGS which arise because investments into CCGS are not available for developing renewables (see 2.5), may be difficult to quantify for the environmental authority. In order to calculate the price of a CSB, all of these factors would have to be quantified in monetary terms. This is generally associated with controversial issues of its own, e.g. choosing a discount rate or quantifying ecological degradation in monetary terms. More specifically, concerning global risks it is likely to be difficult to quantify (a) the contribution of leakage from CCGS operations to climate change, and (b) to specify the amount of damages resulting from climate change which can be attributed to CCGS operations. Also, calculating the opportunity costs of CCGS with respect to renewables is problematic, especially under considerable uncertainties concerning learning rates of renewables, learning rates of CCGS, and reservoir leakage rates.

Proposal B: certificate based regulation

Pre-requisite to proposal B is the implementation of an emission cap and trade regime (in contrast to proposal A, an emission tax regime would be insufficient). This is because proposal B involves the idea that for CO_2 which is injected into geological formations, emission permit certificates have to be purchased by CCGS firms prior to injection. While these certificates can be sold on the market immediately, their value remains uncertain as long as it is unclear how much of the CO_2 will ultimately remain within the reservoir. They are blocked or ‘frozen’ by an environmental authority. As soon as the uncertainty regarding reservoir confinement (leakage) rates for an indivdual storage site is reduced, the environmental authority will define how much of the stored CO_2 can be considerd to be deposited safely. The amount of CO_2 that may be emitted by an owner of a frozen certificate is then established accordingly.[101] There is hence an incentive for private firms to reduce the uncertainty related to the storage safety of individual reservoirs.

In the long-run it can be expected that the uncertainty on leakage rates will decrease for individual formations. Based on this knowledge, the authority periodically decides on the amount considered to be contained safely within the reservoir and unblocks frozen certificates accordingly. If a company injects additional CO_2 into a reservoir the performance of which is well known, a certain fraction of the issued certificates may be unblocked right away.

The economic incentive to conduct CCGS within such a regulatory regime derives from the expectation of the firm that in the long run the price of the certificate will increase. Because frozen certificates can be traded, a secondary market for certificates will develop on which

[101] The implications of this proposal remind of the issues involved in a cap and trade regime if liability for emitting CO_2 without holding the corresponding amount of permits is with the buyer of traded certificates (5.2.1).

the trustworthiness of individual projects will determine the value of a frozen certificate (that is, expectations on reservoir performance will become a tradable good). [Edenhofer et al. 2004a, b]

It can be remarked that depending on the rate of reduction of uncertainty related to reservoir leakage rates, substantial amounts of certificates may become blocked; therefore, large volumes of uncertain CCGS projects may increase the general emission permit certificate price on the market.

In contrast to CSBs this second approach does not comprise a possibility for the regulator to subsidize CCGS (via bond price and interest rate in case of CSBs). Therefore, the economic incentive to conduct CCGS is relatively low. Also, local environmental risks of CCGS are not taken into account; the focus is on atmospheric leakage of CO_2, that is, the global environmental risk of CCGS. [Edenhofer et al. 2004a, b]

It is worth noting that storage safety may not develop monotonously and positively, that is, risks for accidents may increase with cumulated injections into individual formations, and there may be critical thresholds for injection capacities that render an operation risky[102] (this may make definition of safely contained CO_2 more difficult; the overall amount defined to be contained safely may remain very low for a long time, at least until some time after termination of injection operations).

The drawback of this approach appears to be that it exclusively focuses on atmospheric leakage of CO_2. While it may fit very well into a (global) emission permits trading scheme, there appears to be little potential for direct integration with a framework managing the local risks of CCGS.

Discussion

In the following it is attempted to systematically discuss both approaches with respect to their capability to meet the regulatory requirements for CCGS that have been identified above (5.1). Some general remarks will conclude this section.

In both proposals an incentive is created to reduce the uncertainties related to CCGS, which is due to the effect that a reduction of uncertainty concerning the risks of individual storage facilities will render CCGS more cheaply. Therefore, private firms will have an incentive to conduct research that reduces fundamental gaps of knowledge concerning the risks of CCGS.[103]

Other regulatory requirements for CCGS that are met by both concepts include creation of an incentive for a site selection and permission process which minimizes the risks of leakage and accidents both locally and globally (short-term as well as long-term, because otherwise it will be impossible to sell the bond or frozen certificate on a market), as this lies in the very self-interest of the CCGS firm (or owner of the bond/certificate). Although proposal B focuses less on local risks, it may be argued that (i) global risk of leakage always involve local risks, too, and (ii) the certificate approach could be complemented by some other type

---

[102] E.g. due to risk of induced earthquakes that can occur even several years after termination of injection operations (see 2.4.6).

[103] As noted above citing Shogren et al. [1993], it has to be taken into account that there is also a strong incentive for private firms to conduct very biased research. This may be an inherent drawback to these concepts.

of local liability regime. Also, a long-term liability for the local and global risks is indirectly established due to the bond devaluation and obligation to buy permits corresponding to the leaked amounts of CO_2, and the possibility of the authority to refrain from unblocking frozen certificates (or to re-block them), respectively.[104] An incentive is created in both proposals to ensure that remediation measures and agents are available because this will decrease the probability of devaluation resulting from severe local environmental damages in the case of bonds, and would decrease the likelihood of 're-freezing' of certificates by the regulator in proposal B. In case of devaluation of a Carbon Sequestration Bond due to an accident, the resulting revenue for the authority could be used for remediation measures, if required. This local aspect of remediation measures is not addressed by proposal B.

Verification of the amounts of injected CO_2 is pre-requisite to both proposals, and the related incentives do therefore not seem to constitute a significant problem.[105]

Installation of a monitoring regime by the CCGS firm is induced in both cases at least short- to mid-term because in each approach the owner of the asset is eager to prove that the reservoir is safe, which requires a monitoring framework. However, it is questionable if the institutional proposals can ensure monitoring and reservoir management (remediation) over several hundred years. More generally, in the very long-run (more than several hundred years, taking into account political instability) it is questionable whether these approaches will suffice to ensure reservoir safety.

In both cases there may be very strong incentives to understate leakage rates. This risk seems to be somewhat lower in case A, because danger of detection of the fraud carries the risk of devaluation of the bond; but a similar penalty could be included in scheme B.

An incentive for site operators to exchange experiences and best practice is created in both proposals because (i) it improves the capacity (knowledge) to prove high rates of containment in the reservoir is advantageous for the owner of a bond or certificate, and (ii) reducing leakage rates will benefit the site operator and increase the value of his assets in both approaches.

Both approaches create no incentives for technology transfer to developing countries. For this, a complementary mechanism (e.g., CDM) has to be introduced.

Whether compliance with regulation can be ensured by the proposals put forward is a complicated question that requires more detailed considerations that can not be addressed here.

Neither proposal A nor B can deliver a legal definition of CO_2. This will have to be addressed by local legislatory and/or jurisdictional processes. Also, both proposals fail to principally create an incentive to minimize the uncertainties associated with renewable

---

[104] Concerning long-term liability the advantage of both approaches is that in case of bankruptcy of the owner of a bond or certificate it can be transferred to another organization which is then responsible for the reservoir.

[105] Especially in case of proposal B, where verification is crucial for the amount of certificates issued. While due to this there may actually some incentive for overrating injection amounts in proposal B, for CSBs there may be an incentive to underrate the amounts of CO_2 injected in order to reduce the amount of bonds that have to be purchased. On the other hand, the danger of revelation and the associated risk of devaluation of the bond/certificate may outbalance both effects (depending on the institutional arrangements for ensuring compliance with regulation).

energies and related to this, the global economic risks of CCGS. While approach A comprises the scheme that the income of the environmental authority generated by devaluation of bonds is allocated to RD&D on renewables, no incentive to conduct research on renewables in case of a success of CCGS is implied. Also, transfers from devaluation may occur only several decades after commencement of CCGS operations; it may then be too late to start investing into renewable energies. Therefore, Edenhofer et al. [2005] argue that CSB type solutions have to be complemented by green energy certificates, which will be discussed in the following subchapter 5.3.

Two remarks will be made prior to some concluding considerations. First, an interesting question may be who has the right to legally contend the reports of bond/certificate owners to the environmental authority. If nobody except the regulator and the firm has this right there is the danger of strategic compliance of regulator and firm on understating risks and accidents in CCGS operations. Also, if (a heterogenous group of) holders of CSBs have to prove reservoir integrity, they will likely mandate a third party to do so (e.g., Technischer Überwachungsverein TÜV in Germany). The environmental authority may have to cross-check the results of these investigations. In order to ensure compliance with regulation, a right to file action may be included in the regulation that allows to contend the validity of such third party reports (e.g., by issuing counter reports) at a court of law.[106]

Second, it is an open question whether the environmental authority should be national (local), transnational (e.g. European Union) or truly global (analogical to, e.g., the World Bank or IMF). This has some important implications for the scope of the regulation associated with CSBs, because if they were implemented on a more local scale, local regulations would have to make sure that they are ultimately compatible with UNFCCC regulations on global emissions (e.g., through best practice guidelines); in case of a global environmental authority this may be no issue. Characterization of local risks may be more problematic in a global scheme. In general, if global performance standards would be implemented but, e.g., the methodologies for calculating bonds would vary significantly, this may pose a significant problem for integrating CCGS into the UNFCCC framework. From this point of view, a global environmental authority implementing global standards may be preferable. Again, this aspect deserves more in-depth analyses.

Edenhofer et al. [2004b] remark that proposal B stresses the need for climate protection because the emission cap scheme is emphasized. If uncertainties regarding leakages cannot be reduced, the costs of certificates and hence climate change mitigation will increase. In contrast to this proposal A does require purchase of certificates only in case leakage has actually occurred. Therefore, more CCGS may be implemented than under regime B. Proposal A puts more emphasis on the economic risks of CCGS because it is possible for the environmental authority to subsidize CCGS while scheme B focuses on the issue of climate change. Edenhofer et al. propose to combine the two approaches temporally, that is, CSBs may be appropriate to foster early engagement of firms in CCGS, while the certificate scheme may be more promising in case of a large-scale long-term implementation of CCGS.

---

[106] I would like to thank Nico Bauer for this remark.

Apart from implying the potential to be extended to local risks of CCGS, CSBs have the advantage that they make it necessary to reveal the true environmental costs and risks of CCGS, thus enabling a more informed public debate. [Shogren et al. 1993, 112]

5.3.3 Green energy certificates

A regulatory framework focusing exclusively on the introduction of an emission cap and trade system and the market introduction of CCGS would constitute an insufficient regulatory strategy for an energy system sustainability transition because in the long run, all energy scenarios project the requirement of a considerable share of renewable energies if dangerous anthropogenic climate change is to be avoided. However, while introducing a price for the emission of CO_2 and CSBs for enhancing the development of CO_2 capture and storage may be one important aspect of long-term energy policy, it is insufficient to foster the development of renewable energies.

This is because the energy sector is subject to market imperfections that arise both from lock-in effects within the fossil fuel sector (long power plant life-cycles) and increasing returns to scale in the renewable sector. The increasing returns to scale of renewables constitute a strong incentive for investors to delay their investment into renewables, because the (costly) progress made by first movers can easily be adopted by later investors (without having to bear those costs). As a result, little technical development takes place in the renewable sector. [Edenhofer et al. 2004b]

However, while the performance of renewables is currently not competitive to fossil fuel-based technologies, renewables are subject to learning effects, that is, for every doubling in installed capacity there are cost reductions per unit of energy delivered. Therefore, if incentives for investment into renewables would be implemented and the installed capacity of renewables would increase, with time they might become competitive to other energy carriers on a free market. [Edenhofer et al. 2005; Grübler 1998]

Therefore, renewables should be subsidized for a limited period of time. Current subsidy schemes, e.g. in Germany, are price based. [WBGU 2003, 159] Quantity based certificate schemes have several advantages over price mechanisms. They allow for more flexible allocation of resources to the most efficient options as well as for political definition of the desired market share of a technology (or a group of technologies).

Green energy certificates work as follows. A government decides on a specific share that renewables should have in, e.g., generation of electricity supply until a specific year; for example 10% until 2010. The operators of the electrical grid (alternatively, producers or consumers of electricity) are obliged to hold a certain quota of tradable 'green' energy certificates. Green energy certificates are only issued to producers of renewable electricity approved by an environmental authority. The operators of the grid have two possibilities for acquiring the certificates: either by physically feeding green electricity into the grid, or by purchasing the certificates on a (international) market. Grid operators who physically feed in more green electricity than required can sell certificates, while those using less renewable electricity have to purchase certificates.

Two competitions are established through this scheme. First, on the tradable certificate market, and second, in the renewable energy sector where the increased market demand for green electricity renders renewable electricity more profitable. Different renewable energy technologies (solar, biomass, wind) will compete in order to increase their market share and firms are thus forced to increase the technological efficiency of their respective approaches. [Edenhofer et al. 2005b]

Australia has recently launched the first nationwide renewable energy certificate trading system that aims at increasing the share of electricity from renewable energy sources in Australia by an additional 2% (to a total share of 11% until 2010). Grid operators are required to hold renewable energy certificates which can only be handed out by accredited renewable energy generators. These certificates can be traded on a market. The scheme comprises a A$ 40 per MWh penalty if a grid operator does not hold sufficient certificates. It is estimated that the scheme will trigger some A$ 6 billion additional investments into renewables, although it is difficult to quantify how much of this will actually be due to the certificate scheme (problem of additionality, see 5.2.1). [Rossiter and Wass 2003]

6. Conclusion

Carbon dioxide capture and storage technologies come with the prospect of contributing to mitigating the modernization risk of global climate change that results from anthropogenic GHG emissions. Because CCGS allows for the continued use of fossil fuels without emitting CO_2 into the atmosphere, it involves the opportunity of buying time for the transition of the global energy systems towards a more sustainable reliance on renewable energies. Integrated assessment studies suggest that CCGS could lower the cost of the required energy system transformation. [Bauer et al. 2004; Bauer 2005] The principal technological viability of CCGS has been established at some commercial and demonstration projects. Also, experience is available from analogical processes (natural CO_2 recovery, acid gas injection, liquid waste injection, natural gas storage).

However, there are several problems associated with CCGS. First, implementation of CCGS at a scale that would significantly reduce anthropogenic CO_2 emissions would involve considerable upscaling of existing CCGS processes, which could lead to problems on a technical level. Second, CCGS implies several risks. On a local scale these include human safety[107] and ecological (plants, animals) risks due to migration and/or surface leakage of CO_2 and other substances. On a global scale, surface leakage of CO_2 from geological storage sites could render CCGS useless as a climate change mitigation option if critical overall leakage rates are exceeded. Also, economic risks arise because the large-scale investments required for a significant contribution of CCGS to global climate change mitigation would reduce the amount of resources that are available for allocation to renewable energy technologies. If CCGS becomes implemented but leakage rates are high, the investments have to be written off and had better been allocated to renewables in the first place. A major problem with all of the risks arising from CCGS (probably most importantly, leakage rates) is that their likelihood and scale is impossible to assess today because very little experience is available from CCGS operations. In order to reduce these uncertainties, carefully conducted pilot projects are required.[108]

While there is a wide range of technological issues that have to be resolved in order to render CCGS a feasible climate change mitigation option, including reduction of the costs of technical processes, overcoming the technical problems of CCGS is only necessary condition for the viability of its large-scale application. Meeting favourable social conditions is the commensurate condition for the viability of CCGS. This is first because without some kind of GHG emission regulation (tax, emission cap and trade regime) CCGS will not be economically attractive at all. Second, associated opportunities and risks touch interests of many stakeholders involved, e.g. those of local (NIMBY syndromes) and global publics, renewable energy industries, and environmental NGOs. Dedicated opposition to CCGS from one or many of such groups could render implementation of this technological option impossible. Studies of the public perceptions of CCGS show that public attitudes are

[107] It therefore appears recommendable to set up CCGS operations in unpopulated areas only. Also, the local conditions should allow for quick dispersion of leaking CO_2.
[108] Still, preliminary small-scale pilot projects can not resolve the issue of upscaling. Ultimately, only large-scale applications running for longer periods of time can achieve this.

ambivalent, and tending to be in the negative. Also, other climate change mitigation options are usually favoured over CCGS. While CCGS is currently hardly known to the public, and processes of broader societal communication and opinion formation about it remain to take place, these initial results indicate that public support is not overwhelming. It should therefore not be difficult to promote and diffuse a very negative image of CCGS by any group that is interested in doing so.

Controverse discussions about CCGS will focus on opportunities, risks, and regulatory conditions that would integrate CCGS into the fabric of social institutions. Crucial regulatory issues – which could turn into particular "battlegrounds" for conflicts about CCGS[109] – are likely to include legal definition of CO_2 and CCGS as a whole, site selection, acquisition and permission, definition of an acceptable reservoir leakage rate, monitoring, leakage and verification/accounting, short- and long-term liability, the relations between CCGS, renewables and incentives for climate change mitigation technologies, and the adoption of CCGS in developing countries and countries in transition. Competing proposals for regulating CCGS will have to address these and related issues and will involve certain evaluations of the risks and opportunities of CCGS and alternative climate change mitigation technologies. It can be expected that the regulatory proposals put forward by different stakeholders will reflect their respective interests.

Drawing on the approach of Dewey, the (social) sciences should play an active role in formulating and proposing regulatory schemes that enable to direct societal debates about controversial technologies towards discussion of their risks and opportunities. Regulatory instruments like Carbon Sequestration Bonds require explication of inherent risks and uncertainties of technological systems, thereby rendering public debates more transparent. In a modernized social world that systematically produces risks through the application of scientific and engineering knowledge, the sciences have to take the consequences of their action into account and must (a) engage in designing institutional frameworks that minimize modernization risks and (b) institutionalize intercommunication with lay cultures in order to take into account plural evaluations of risky technologies (e.g., perception of publics affected by risks). While CSBs are a first proposal to deal with the global risks of CCGS, proposals are required that address the local risks of CCGS, which in fact may ultimately prove decisive for the overall adoption of CCGS. No regulatory scheme for management of local risks of carbon capture and geological storage is available today.

A sociology of technology could address a wide range of research tasks in the case of carbon dioxide capture and storage. Concerning the conceptual tools that could be applied in such analyses, the concept of modernization risks and reflexive modernization put forward by Beck [1986] allows for a principal framing of the issue of global climate change. Also, principal characteristics of related research in terms of competing scientific approaches to and political proposals for the shape of the future global energy system and regulation are addressed by Beck. The political philosophy approach of John Dewey could be applied for conceptualizing political and social processes of communication that allow for a successful

[109] And possibly about the future of the whole fossil fuel industry in general. In this case, it is likely that the adverse environmental and human safety impacts of fossil fuel extraction, transport and use would be part of a portfolio of arguments against the fossil fuel industries.

treatment of modernization risks. However, in order to enable meaningful empirical analyses, more refinement of Dewey's approach is required with respect to the processes by which a public (Great Community) can organize itself, and for setting up particular processes of inquiry under the conditions of the Great Society. Conflict sociology as represented by Randall Collins [1975; 1990] enables empirical analyses of the implications that interests (e.g., of or within organizations) have within such processes of inquiry. However, it appears necessary to extend the scope of conflict sociology in order to enable description of cooperative action of groups and individuals. Combining conflict sociology's focus on particular interests and power with theories of normative (e.g., Parsons) and value (e.g., Taylor) oriented action and intersubjective approaches (e.g., Joas and Mead) that emphasize the role of communication in the establishment of shared norms, values and interests seems very desirable in order to be able to properly account for the empirical social processes surrounding CCGS.[110] Finally, all of these approaches should be integrated with a more developed[111] sociological theory of technological change in modern industrial capitalism.

Concerning the analysis of social aspects of CCGS, pursuing the following research tasks could increase the understanding of the impact of critical social factors on the viability of CCGS. As little experience is available from CCGS operations, critical and comprehensive reports comprising analyses of problematic incidents at analogical facilities with a focus on socially conflictual issues would be desirable.[112] Based on the principal scheme of social determinants of the viability of CCGS that has been developed in this thesis, the costs of each factor could be determined in economic terms. Concerning the impact of regulation on economic costs, particular regulatory schemes could be analyzed with respect to their economical implications (e.g., the costs of different long-term monitoring schemes; impact of varying liability frameworks; the relation between costs of long-term monitoring and costs of liability; the regulatory implications of a CO_2 stream containing toxic substances). Concerning transaction costs, an empirical study of the positions and interests of relevant stakeholders – based on expert interviews – could facilitate an assessment of the transaction costs that will be incurred by, e.g., processes of political negotiation, legislation (analyses of law with respect to CCGS on regional, national and international level) or open (medially stage-managed) conflict.[113] In addition, particular proposals (and dialogue with relevant stakeholders) for regulating CCGS are required in order to avoid the implementation of regulatory schemes that turn out to induce unwanted consequences in the long-run. While Carbon Sequestration Bonds are a first proposal for addressing the global risks of CCGS and for fostering social processes of inquiry and conflict that revolve around the risks of CCGS, more proposals are required especially for managing local risks. Comparative analyses should be conducted in order to reveal evaluations that are – unavoidably – implicitly

[110] It would be interesting, for example, to analyze the role and the relation of values and interests in the action of environmental NGOs (and individuals therein). Also, empirical research on the role of negotiations (communication) for establishing consensus between parties with initially conflicting interests might be fruitful.

[111] In terms of explanatory power, and not merely capacity to be able adequately describe such processes.

[112] A first report has been produced by Benson et al. [2002].

[113] More particularly, it would be interesting to identify the circumstances under which stakeholders are willing to cooperate. Methodically this could include conducting stakeholder dialogues.

contained in such proposals. Practical questions concerning the implementation of these schemes have to be addressed, e.g. mechanisms that ensure compliance with regulation. Also, the compatibility with global emission regulation schemes (Kyoto, ETS, future schemes) has to be investigated.

To conclude, CCGS involves both the opportunity of becoming part of a climate change mitigation technology portfolio[114] and many risks that relate to human and ecological safety as well as global climate change and economics. All of these aspects need to be addressed in processes of public inquiry involving intercommunication of lay and expert cultures as well as proposals for regulatiory schemes put forward by scientists. Also, dealing with risks and opportunities of climate change mitigation technologies and ultimately deciding upon their societal implementation requires normative evaluations. This thesis has attempted to contribute to the effort of putting such evaluations on a more informed basis.

[114] CCGS as the only climate change mitigation approach does not seem to be a socially viable option with respect to the interests of publics, environmental NGOs, and the renewable energy industries.

Literature

Abelson, P.H. (2000): Limiting Atmospheric CO_2. *Science*, Volume 289, Issue 5483, p.1293

AETF Australasian Emissions Trading Forum (2004): Regulating Geosequestration. Draft Guiding Regulatory Framework. *AETF Review*, October/November 2004.
Internet: http://aetf.emcc.net.au/ContentStore/pdf/ReviewOctNov2004.pdf

Allison, M. (2001): The Hutchinson Gas Explosions: Unraveling a Geologic Mystery. Kansas Bar Association, 26th Annual KBA/KIOGA Oil and Gas Law Conference.
Internet: http://www.kgs.ukans.edu/Hydro/Hutch/Refs/Hutch_KBA_final.pdf

Anderson, S., and R. Newell (2003): Prospects for Carbon Capture and Storage Technologies. Resources for the Future Discussion Paper 02-68, January 2003.
Internet: http://www.rff.org/~newell/

Anderson, J. (Climate Action Network Europe) (2003): Environmental NGOs' views on CO_2 capture and storage/ sequestration/ disposal/ dumping. Presentation held at Climate Technologies Assessment Workshop in Brussels, September 23rd 2003.
Internet: www.climnet.org/CTAP/workshop2003/presentations.htm

Arts, R., A. Chadwick, and O. Eiken (2004): Recent time-lapse seismic data show no indication of leakage at the Sleipner CO_2-injection site. In: E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.): Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Volume 1: Peer-reviewed Papers and Plenary Presentations. Cheltenham, UK: IEA Greenhouse Gas Programme

Audus, H. (2000): Leading options for the capture of CO_2 at power stations. In: Proceedings of the 5th International Conference on Greenhouse Gas Control Technologies. Collingwood (Australia): CSIRO Publishing

Bachu, S., W.D. Gunter, and E.H. Perkins (1994): Aquifer disposal of CO_2: Hydrodynamic and mineral trapping. *Energy Conversion and Management*, Volume 35, Issue 4, p.269-279, April 1994

Bachu, S., and D.W. Gunter (2004): Overview of acid-gas injection operations in Western Canada. In: E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.): Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Volume 1: Peer-reviewed Papers and Plenary Presentations. Cheltenham, UK: IEA Greenhouse Gas Programme

Barrie, J., K. Brown, P.R. Hatcher, and H.U. Schellhase (2004): Carbon Dioxide Pipelines. A Preliminary review of design and risks. In: E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.): Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Volume 1: Peer-reviewed Papers and Plenary Presentations. Cheltenham, UK: IEA Greenhouse Gas Programme

Bauer, N. (2005): Carbon Capturing and Sequestration. An Option to buy time. Doctoral Thesis University of Potsdam, Faculty of Economics and Social Sciences. Forthcoming.

Berger, P.L., T. Luckmann (2004): Die gesellschaftliche Konstruktion der Wirklichkeit. Eine Theorie der Wissenssoziologie. Frankfurt am Main: Fischer-Taschenbuch

Beck, U. (1986): Risikogesellschaft. Auf dem Weg in eine andere Moderne. Frankfurt am Main: Suhrkamp Verlag

Beck, U.. (ed.) (1998): Perspektiven der Weltgesellschaft. Frankfurt am Main: Suhrkamp Verlag

Bengal, L. (2004): Regulatory Framework for geologic CO_2 Sequestration. Interstate Oil and Compact Commission Presentation at US Regional Carbon Sequestration Partnership Annual Program Review Meeting, November 16-17th 2004.
Internet: http://www.netl.doe.gov/publications/proceedings/04/RCSP/rcsp04.html#Papers

Bennaceur, K. (2004): Risk Management and Mitigation for CO_2 Storage. Presentation at IEA (International Energy Agency) and CSLF (Carbon Sequestration Leadership Forum) Joint Workshop on Legal Aspects of Storing Carbon Dioxide. Paris, 12-13 July 2004. Internet: see IEA [2004]

Benson, S., R. Hepple, J. Apps, C.F. Tsang and M. Lippmann (2002): Lessons Learned from Natural and Industrial Analogues for Storage of Carbon Dioxide in Deep Geologic Formations. LBNL #51170, technical report for BP-DOE CRADA under contract DE-AC03-76F00098
Internet: http://repositories.cdlib.org/lbnl/LBNL-51170/

Benson, S., and L. Myer (2002): Monitoring to ensure safe and effective geologic sequestration of carbon dioxide. In: IPCC (Intergovernmental Panel on Climate Change) (2002): Workshop on Carbon Dioxide Capture and Storage Proceedings. Regina, Canada, 18-21 November 2002, p.137-151. Published by ECN.
Internet: http://arch.rivm.nl/env/int/ipcc/pages_media/ccs-report.html

Berger, B., O. Kaarstad, and H.A. Haugen (2004): Creating a large-scale CO_2 infrastructure for Enhanced Oil Recovery. In: E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.): Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Volume 1: Peer-reviewed Papers and Plenary Presentations. Cheltenham, UK: IEA Greenhouse Gas Programme

Berliner Zeitung (2004a): 30 Meter hohe Stichflamme aus dem Gaslager. 24.04.2004, p.21

Berliner Zeitung (2004b): Bauarbeitern geht es nach Gas-Unfall besser. 08.05.2004, p.24

Berliner Zeitung (2004c): Chemikalie löste Gasexplosion aus. 03.08.2004, p.28

Bode, S., and M. Jung (2004): On the Integration of Carbon Capture and Storage into the International Climate Regime. HWWA Discussion paper 303. Hamburg Institute of International Economics.
Internet: http://www.hwwa.de/Publikationen/Discussion_Paper/2004/303.pdf

Brown, L.M. (1996): Uptake of carbon dioxide from flue gas by microalgae. *Energy Conversion and Management*, Volume 37, p.1363-1367, 1996

Bruant, R.G., A. Guswa, M.A. Celia, and C.A. Peters (2002) : Safe Storage of CO_2 in Deep Saline Aquifers. *Environmental Science & Technology*, Volume 36, Issue 11, p.240-245

Buen, J. (2002): CDM investment: market actors' perceptions. In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Amsterdam: Pergamon Press

Burns, T. and T. Dietz (1992): Cultural evolution: social rule systems, selection and human agency. International Sociology, Volume 7, Number 3, pp.259-283

Celia, M.A., and S. Bachu (2003): Is leakage unavoidable and acceptable? In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Amsterdam: Pergamon Press

Clarke, T. (2001): Taming Africa's killer lake. *Nature*, Volume 409, 554-555

Collins, R. (1975): Conflict Sociology: toward an explanatory science. With a Contribution by Joan Annett. New York: Academic Press

Collins, R. (1986): Weberian Sociological Theory. Cambridge, New York: Cambridge University Press

Collins, R. (1990): Conflict Theory and the Advance of Macro Historical Sociology. In: Ritzer, G. (ed.): Frontiers of Social Theory. The New Syntheses. New York, Oxford: Columbia University Press

Coninck, H. de (2004): Geological Storage of CO_2 in the emission trading market. Presentation held at the VIIIth EU Clean Fossil Technology Industry Forum, organised by SESEMCFT. Brussels, June 8th.
Internet: http://www.climatepolicy.info/technologies/docs/brussel-hdc.pdf

CO2SINK (2004): Project homepage.
Internet: http://www.gfz-potsdam.de/pb5/pb51/projects/project-CO2SINK/content.html

CRUST Legal Task Force (2001): Legal Aspects of CO_2 Underground Buffer Storage. A legal analysis of legislation and regulations relating to the CRUST project. Translation of:: 'Juridische aspecten van ondergrondse CO_2-bufferopslag'.
Internet: http://www.co2-reductie.nl

Curry, T., D.M. Reiner, S. Ansolabehere, and H.J. Herzog (2004): How aware is the public of carbon capture and storage? In: E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.): Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Volume 1: Peer-reviewed Papers and Plenary Presentations. Cheltenham, UK: IEA Greenhouse Gas Programme

Cypser, D. (2004): Induced Earthquake Bibliography.
Internet: http://www.nyx.net/~dcypser/induceq/.bib.html

Damen, K., A. Faaij, and W. Turkenburg (2003): Health, safety and environmental risks of underground CO_2 sequestration. Overview of mechanisms and current knowledge. Commissioned by RMNO (Advisory Council for Research on Spatial Planning, Nature and Environment of the Netherlands). Copernicus Institute, Department of Science, Technology and Society, Utrecht University. NWS-E-2003-30.
Internet: http://www.chem.uu.nl/nws/www/publica/e2003-30.pdf

Desideri, U., and A. Paolucci, (1999): Performance Modelling of a Carbon Dioxide Removal System for Power Plants. *Energy Conversion and Management*, Volume 40, Number 18, pp. 1899-1915

Dewey, John (2001): Die Öffentlichkeit und ihre Probleme. Herausgegeben und mit einem Nachwort versehen von Hans-Peter Krüger. Berlin, Wien: Philo

de Figueiredo, M.A., D.M. Reiner, and H.J. Herzog (2002): Ocean carbon sequestration: a case study in public and institutional perceptions. In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Amsterdam: Pergamon Press

de Figueiredo, M.A. (2003) : The Hawaii Carbon Dioxide Ocean Sequestration Field Experiment: A Case Study in Public Perceptions and Institutional Effectiveness. MIT Master Thesis.
Internet: http://sequestration.mit.edu/bibliography/policy.html

de Figueiredo, M.A., H.J. Herzog, and D.M. Reiner (2003): Framing the Long-Term Liability Issue for Geologic Carbon Storage in the United States. Accepted by Mitigation and Adaptation Strategies for Global Change.
Internet: http://sequestration.mit.edu/bibliography/policy.html

Doctor, R.D., J.C. Molburg, and P.R. Thimmapuram (1997): Oxygen-Blown Gasification Combind Cycle. Carbon Dioxide Recovery, Transport, and Disposal. *Energy Conversion and Management*, Volume 38, (Supplement), p.575-580

DOE Department of Energy (2004): Carbon Sequestration Program Environmental Impact Statement. Public Scoping Report. October 5th, 2004. DOE/EIS-0366.
Internet: http://www.netl.doe.gov/coal/Carbon%20Sequestration/eis/scoping_report.html

Dooley, J.J., and M.A. Wise (2002): Why injecting CO_2 into various geologic formations is not the same as climate change mitigation: the issue of leakage. In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Amsterdam: Pergamon Press

DNV (2003): Risk of Long Term Leakage from CO_2 Geological Storage: Options, Considerations and Challenges. Presentation.
Internet: http://www.mi.uib.no/CO2/Presentations/todd_flach.pdf

DTI Department of Trade and Industry (2002): Carbon Dioxide Capture and Storage. Report of DTI International Technology Service Mission to the USA and Canada from 27th October to 7th November 2002. Internet: http://www.dti.gov.uk/energy/coal/cfft/co2capture/

DTI Department of Trade and Industry (2003): Review of the feasibility of Carbon Dioxide Capture and Storage in the UK. Internet: http://www.dti.gov.uk/energy/coal/cfft/co2capture/

Edenhofer, O. (1996): Das Management Globaler Allmenden. In: Jaeger, C.C., and A. Diekmann (eds.): Umweltsoziologie. *Kölner Zeitschrift für Soziologie und Sozialpsychologie*, Sonderheft 36/1996, p.390-419

Edenhofer, O. (2003): Wege zu einer nachhaltigen Klima- und Energiepolitik. *Aus Politik und Zeitgeschichte*, 30. Juni 2003, p.18-26

Edenhofer, O., H. Held, and N. Bauer (2004a): A Regulatory Framework for Carbon Capturing and Sequestration within the Post-Kyoto Process. In: E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.): Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Volume 1: Peer-reviewed Papers and Plenary Presentations. Cheltenham, UK: IEA Greenhouse Gas Programme

Edenhofer, O., H. Held, and N. Bauer (2004b): Wege zu einem nachhaltigen Energiesystem: Ein ordnungspolitischer Rahmen für Emissionsminderung und Kohlenstoffdeponierung. In: Johnke, B., J. Scheffran, and K. Soyez (eds.): Abfall, Energie und Klima. Wege und Konzepte für eine integrierte Ressourcennutzung. Mit einem Vorwort von Ernst Ulrich von Weizsäcker. Berlin: Erich Schmidt Verlag

Edenhofer, O., N. Bauer, and E. Kriegler (2005a): The Impact of Technological Change on Climate Protection and Welfare: Insights from the Model MIND. *Ecological Economics*, in press.

Edenhofer, O., K. Lessmann, and N. Bauer (2005b): Klimaschutz! – Eine neue Energiekrise? Forthcoming.

Ennis-King, J., and L. Paterson (2003): Rate of dissolution due to convective mixing in the underground storage of carbon dioxide. In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. p.365-370.. Amsterdam: Pergamon Press

Ennis-King, J., J. Bradshaw, C. Gibson-Poole, A. Hennig, S. Lang, L. Paterson, R. Root, J. Sayers, L. Spencer, J. Streit, and J. Undershultz: Long-term numerical simulation of a portfolio of possible sites for geological storage of carbon dioxide in Australia. In: E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.): Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Volume 1: Peer-reviewed Papers and Plenary Presentations. Cheltenham, UK: IEA Greenhouse Gas Programme

Enquete-Kommission des Deutschen Bundestages (2002): Abschlussbericht der Bundestags Enquete-Kommission zur Nachhaltigen Energieversorgung unter den Bedingungen der Globalisierung und Liberalisierung. Berlin: Bundesdrucksache

EU European Union (2004): Internet Homepage on Greenhouse Gas Emission Trading Scheme.
Internet: http://europa.eu.int/comm/environment/climat/emission.htm

Farrar, C., M. Sorey, W. Evans, J. Howlw, B. Kerr, B. Kennedy, C.-Y. King, and J. Southon (1995): Forest-killing diffuse CO_2 emission at Mammoth Mountain as a sign of magmatic unrest. *Nature*, Volume 376, p.675-678

Fischedick, M., D. Schüwer, A. Esken, N. Supersberger, J. Nitsch, P. Viebahn, A. Bandi, and O. Edenhofer (2004): Ökologische Einordnung und strukturell-ökonomischer Vergleich regenerativer Energietechnologien mit anderen Optionen zum Klimaschutz, speziell der Rückhaltung und Speicherung von Kohlendioxid bei der Nutzung fossiler Primärenergien. 1. Zwischenbericht. Forschungsvorhaben im Auftrag des Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit.

Forbes, Sarah M. (2002): Regulatory Barriers for Carbon Capture, Storage and Sequestration. National Energy Technology Laboratory. Internet: http://www.netl.doe.gov

Fredrickson, J.K., and T.C. Onstott (1996): Microbes Deep inside the Earth. *Scientific American*, October 1996, p.42-47

Friberg, L. (2004): CCS – necessary or evil plot? Presentation held at CEPS Brussels, October 22nd, 2004. Internet: www.ceps.be/files/TF/CAN_Europe.ppt

Gale, J. (2003): Geological Storage of CO_2: What's known, where are the gaps and what more needs to be done. In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Amsterdam: Pergamon Press

Gale, J., and J. Davison (2003): Transmission of CO_2 – safety and economic considerations. In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Amsterdam: Pergamon Press

Gale, J., and T. Read (2004): Rules and standards for CO_2 capture and storage: considering the options. In: E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.): Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Non peer-reviewed article. Cheltenham, UK: IEA Greenhouse Gas Programme

Geertz, C. (1973): The Interpretation of Cultures. Selected Essays. New York: Basic Books

Germanwatch (2004): 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. Authors: Druckat, R., M. Treiber, C. Bals, and G. Kier. Internet: http://www.germanwatch.org/rio/ccs04.htm

Giddens, Anthony (1995a): Konsequenzen der Moderne. Frankfurt am Main: Suhrkamp

Giddens, Anthony (1995b): Die Konstitution der Gesellschaft: Grundzüge einer Theorie der Strukturierung. Frankfurt am Main, New York: Campus Verlag

Godec, M. (2003): Geologic Sequestration of CO_2: Policy and Regulatory Issues. Presentation. Internet: www.coal-seq.com

Greenpeace (2004a): Kohlendioxid in den Untergrund? Hokus Pokus CO_2-Verpressung. Author: G. von Goerne.

Greenpeace (2004b): CO_2-Speicherung ist das Letzte. Author: G. von Goerne. Internet: http://www.greenpeace.org/deutschland/?page=/deutschland/news/klima/co2-speicherung-ist-das-letzte

Grübler, A. (1998): Technology and Global Change. Cambridge, New York, Melbourne: Cambridge University Press

Ha-Duong, M., and D.W. Keith (2003): Carbon storage: the economic efficiency of storing CO_2 in leaky reservoirs. *Clean Technologies and Environmental Policy*, Volume 5, p.181-189

Hanisch, C. (1998): The Pros and Cons of Carbon Dioxide Dumping. *Environmental Science & Technology*, Volume 32, Issue 1, p.20-24

Hanisch, C. (1999): Exploring Options for CO_2 Capture and Management. *Environmental Science & Technology*, Volume 33, Issue 3, p.66-70

Hawkins, D. (2001): Stick it where? – Public Attitudes toward Carbon Storage. Presented at First National Conference on Carbon Sequestration, Washington, D.C., May 14-17, 2001. Internet:
http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/carbon_seq01.html

Hawkings, D. (2003): Passing Gas: Policy Implications of Leakage from Geologic Carbon Storage Sites. In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Amsterdam: Pergamon Press

Hawkings, D. (2004a): Policies to promote carbon-less energy systems. In: E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.): Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Non peer-reviewed article. Cheltenham, UK: IEA Greenhouse Gas Programme

Hawkins, D. (2004b): No exit: thinking about leakage from geologic carbon storage sites. *Energy*, Volume 29, p.1571-1578

Heddle, G.A. (2003): Sociopolitical Challenges to Siting Facilities with Perceived Environmental Risks. Master Thesis, Massachusatts Institute of Technology (MIT).
Internet: http://lfee.mit.edu/publications/PDF/LFEE_2003-005_TH.pdf

Heinrich, J., Herzog, H.J., and D.M. Reiner (2003): Environmental Assessment of Geologic Storage of CO_2. Internet: http://sequestration.mit.edu/bibliography/policy.html

Hepple, R.P., and S.M. Benson (2002): Implications of surface seepage on the effectiveness of geologic storage of carbon dioxide as a climate change mitigation strategy. In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Amsterdam: Pergamon Press

Hepple, R.P., and S.M. Benson (2003): Performance Requirements for Geological Storage of CO_2. Climate Variability and Carbon Management Program, Earth Sciences Division Lawrence Berkeley Lab. Research Summaries 2002-2003. Internet:
http://www.csuchico.edu/~cp55/Info%204%20Sp%2004/performance_requirements_for_geo.htm

Herzog, H.J., E.M. Drake, and E.E. Adams (1997): CO_2 Capture, Reuse and Storage Technologies for Mitigating Climate Change – A White Paper. DOE Order No. DE-AF22-96PC01257.
Internet: http://sequestration.mit.edu/bibliography/index.html

Herzog, H.J., B. Eliasson and O. Kaarstad: Capturing Greenhouse Gases. *Scientific American*, Ferbruary 2000, p.54-61

Herzog, H.J., K. Caldeira and J. Reilly (2003): An issue of permanence: assessing the effectiveness of temporary carbon storage. *Climatic Change*, Volume 59, p.293-310

Holloway, S., C.A. Rochelle, K. Bateman, J.M. Pearce, H.E. Bailey, R. Metcalfe, I. Czernichowski-Lauriol, B. Sanjuan, J. Barbier, H. Fabriol, I.R. Summerfield, E. Lindeberg, T. Schwarzkopf, J. Putter, M. Krumbeck, H. Moller, K.A. Gaida, O. Kaarstad, B. Berger, J.P. Heederik, L.G.H. van der Meer, R. van der Straaten, E. Elewaut, D. Koelewijn, H. Cox,

R. Harrison, and P. Doherty (1996): The Underground Disposal of Carbon Dioxide. Final Report of Joule II Project No. CT92-0031

Holloway, S. (1996): An overview of the Joule II Project 'The Underground Disposal of Carbon Dioxide'. *Energy Conversion and Management*, Volume 37, p.1149-1154

Holloway, S. (1997a): An overview of the underground disposal of carbon dioxide. *Energy Conversion and Management*, Volume 38 (Supplement), p.193-198

Holloway, S. (1997b): Safety of the underground disposal of carbon dioxide. *Energy Conversion and Management*, Volume 38 (Supplement), p.241-245

Honneth, A. (1999): Die zerrissene Welt des Sozialen. Sozialphilosophische Aufsätze. Frankfurt am Main: Suhrkamp

Hopkin, A. (2004): The Carbon Game. *Nature*, Volume 432, p.268-270

Houlder, V. (2004): The case for carbon capture and storage. *Financial Times*, 23.01.04. Internet: http://www.scientific-alliance.org/news_archives/climate/thecasefor.htm

Hoversten, G.H., R. Gritto, T.M. Daley, E.L. Majer, and L.R. Myer (2003): Crosswell Seismic and Electromagnetic Monitoring of CO_2 Sequestration. In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Amsterdam: Pergamon Press

Huijts, N. (2003): Public Perception of Carbon Dioxide Storage. The role of trust and affect in attitude formation. Master Thesis, Eindhoven University of Technology.
Internet: http://www.climatepolicy.info/technologies/

IEA International Energy Agency (2003): Policy Issues Linked to Carbon Sequestration. Note by the Secretariat. Authors: R. Dickel, J. Pershing, and C. Philibert. IEA/SLT(2003)26

IEA International Energy Agency (2004a): World Energy Outlook 2004. Paris: IEA Publications

IEA International Energy Agency (2004b): Carbon Dioxide Capture and Storage Issues – Accounting and Baselines under the United Nations Framework Convention on Climate Change (UNFCCC). IEA Information Paper. Authors: S. Haefeli, M. Bosi, and C. Philibert.
Internet: http://www.iea.org/dbtw-wpd/textbase/papers/2004/css.pdf

IEA GHG International Energy Agency Greenhouse Gas R&D Programme (2002): Opportunities for early application of CO_2 sequestration technology. Report Number PH4/10, September 2002. Internet:
http://www.copernicus.uu.nl/uce-uu/downloads/Presentaties/Ph4_10_Early_Opportunities.pdf

IEA GHG International Energy Agency Greenhouse Gas R&D Programme (2003): Acid Gas Injection: A study of existing operations. Phase I: Final Report. Report Number PH4/18.
Internet: http://www.em.gov.bc.ca./dl/oilgas/carbon/iea_acid_gas_apr03.pdf

IEA (International Energy Agency) and CSLF (Carbon Sequestration Leadership Forum) Joint Workshop on Legal Aspects of Storing Carbon Dioxide. Paris, 12-13 July 2004. Internet: http://www.iea.org/dbtw-wpd/textbase/work/workshopdetail.asp?id=183

Itaoka, K., A. Saito, and M. Akai (2004): Public acceptance of CO_2 capture and storage technology: a survey of public opinion to explore influential factors. In: E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.): Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Volume 1: Peer-reviewed Papers and Plenary Presentations. Cheltenham, UK: IEA Greenhouse Gas Programme

IPCC Intergovernmental Panel on Climate Change (1996): Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.
Internet: http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm

IPCC Intergovernmental Panel on Climate Change (2001): IPPC Third Assessment Report – Climate Change. Internet: http://www.ipcc.ch/

IPCC Intergovernmental Panel on Climate Change (2002): Workshop on Carbon Dioxide Capture and Storage Proceedings. Regina, Canada, 18-21 November 2002. Published by ECN. Internet: http://arch.rivm.nl/env/int/ipcc/pages_media/ccs-report.html

Jaeger, C.C., and B. Kasemir (1999): Climatic risks and rational actors. *Global Environmental Change*, Volume 6, Number 1, p.23-36

Joas, H. (1992): Die Kreativität des Handelns. Frankfurt am Main: Suhrkamp Verlag

Joas, H. (1997): Die Entstehung der Werte. Frankfurt am Main: Suhrkamp Verlag

Johnson, J., and J. Nitao (2003): Reactive transport modelling of geologic CO_2 sequestration at Sleipner. In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Vol. 1, p. 323-327. Amsterdam: Pergamon Press

Johnston, P., D. Santillo, R. Stringer, R. Parmentier, B. Hare, and M. Krüger (1999): Ocean Disposal/Sequestration of Carbon Dioxide from Fossil Fuel Production and Use: An Overview of Rationale, Techniques and Implications. Greenpeace Research Laboratories. Technical Note 01/99, March 4th 1999. Internet: http://www.greenpeace.to/pdfs/co2dump.pdf

Johnston, P., and D. Santillo (2002): Carbon Capture and Sequestration: Potential Environmental Impacts. In: IPCC [2002]

Jimenez, J., and Chalaturnyk, R. (2003): Are disused oil and gas reservoirs safe for the geological storage of CO_2? In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Vol. 1, p. 471-476. Amsterdam: Pergamon Press

Kallbekken, S., and A. Torvanger (2004): Can geological carbon storage be competitive? CICERO Working Paper 2004:5.
Internet: http://www.cicero.uio.no/publications/cicerolop.asp?lang=en#RPRTWP

Kaufmann, F.X. (1992): Der Ruf nach Verantwortung. Risiko und Ethik in einer unüberschaubaren Welt. Freiburg, Basel, Wien: Herder

Keith, D.W., and G. Morgan (2000): Industrial Carbon Management: Crosscutting Scientific, Technical and Policy Implications. Chair's Essay at Elements of Change 2000 Conference, Aspen Global Change Institute.
Internet: http://www.agci.org/publications/eoc00/Session1/pdf/EOC00_1chair.pdf

Kennedy, P. (1989): The rise and fall of the great powers: economic change and military conflict from 1500 to 2000. New York: Random House

Kinder Morgan CO2 Company (2004): Homepage.
Internet: http://www.kindermorgan.com/business/co2/

Klusmann, R. (2003): Evaluation of leakage potential from a carbon dioxide EOR/sequestration project. *Energy Conversion and Management*, Volume 44, Number 12, p.1921-1940

Kosugi, T., W. Zhou, and K. Tokimatsu (2002): Potential evaluation of CO_2 emissions reduction by CDM projects – project design to bring benefit for both developed and developing countries. In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Amsterdam: Pergamon Press

Krug, A. (2003): Der Emissionsrechtehandel als Instrument der Europäischen Umweltpolitik. Theoretische Ausgestaltung des Instruments und praktische Umsetzung. Diplomarbeit Freie Universität Berlin.

Krüger, H.-P. (2000): Prozesse der öffentlichen Untersuchung. Zum Potential einer zweiten Modernisierung in John Deweys „Logic. The Theory of Inquiry". In: Joas, H. (ed.): Philosophie der Demokratie. Beiträge zum Werk von John Dewey. Frankfurt am Main: Suhrkamp Verlag

Kruse, H., and M. Tekiela (1996): Calculating the consequences of a CO_2-pipeline rupture. *Energy Conversion and Management*, Volume 37, p.1013-1018

LeGuern, F., and G.E. Sigvaldason (eds.) (1989): The Lake Nyos event and natural CO_2 degassing. *Special Issue of Journal of Volcanology and Geothermal Research*, Volume 39, Issues 2-3, p.97-275

Lee, A. (2004): CO_2 Capture Project's Policies & Incentives Study. Presentation at IEA (International Energy Agency) and CSLF (Carbon Sequestration Leadership Forum) Joint Workshop on Legal Aspects of Storing Carbon Dioxide. Paris, 12-13 July 2004. Internet: see IEA [2004b]

Lenstra, W.J. and B.C.W van Engelenburg (2002): Legal and policy aspects: impact on the development of CO_2 storage. In: IPCC [2002]

Lindeberg, E., and P. Bergmo (2003): The long-term fate of CO_2 injected into an aquifer. In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Vol. 1, p. 489-494. Amsterdam: Pergamon Press

Lippmann, M.J., and S.M. Benson (2002): Relevance of underground natural gas storage to geologic sequestration of carbon dioxide. Lawrence Berkeley National Laboratory. Paper LBNL-51294. Internet: http://repositories.cdlib.org/lbnl/lbnl-51294

Maldal, T., and I.M. Tappel (2003): CO_2 Undergournd storage for Snøhvit gas field development. In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Amsterdam: Pergamon Press

Marchetti, C. (1977): On Geoengineering and the CO_2 Problem. *Climatic Change*, Volume 1, p.59-68. Available as preprint RM-76-1, International Institute for Applied Systems Analysis, Laxenburg, Austria.
Internet: http://www.cge.uevora.pt/energia/marchetti/marchetti-024.pdf

Marland, G., K. Fruit and R. Sedjo (2001): Accounting for sequestered carbon: the question of permanence. *Environmental Science & Policy*, Volume 4, p.259-268

May, F., J.P. Gerling, and P. Krull (2002): Underground Storage of CO_2. Bundesanstalt für Geowisenschaften und Rohstoffe (BGR).
Internet: http://www.bgr.de/b123/at_co2_storage/co2_storage.pdf

May, F., S. Brune, P. Gerling, and P. Krull (2003): Möglichkeiten zur untertägigen Speicherung von CO_2 in Deutschland – eine Bestandsaufnahme. *Geotechnik*, Volume 26, Number 3, p.162-172

Mead, G.H. (1987): Gesammelte Aufsätze. Bd. 1+2. Herausgegeben von Hans Joas. Frankfurt am Main: Suhrkamp

Moberg, R., D.B. Stewart, and D. Stachniak (2003): The IEA Weyburn Monitoring and Storage Project. In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Amsterdam: Pergamon Press

Oberthür, S., and H.E. Ott (2000): Das Kyoto-Protokoll. Internationale Klimapolitik für das 21. Jahrhundert. Mit einem Vorwort von Ernst Ulrich von Weizsäcker. Opladen: Leske + Budrich

Okamoto, I., X. Li, and T. Ohsumi (2003): Effects of supercritical CO_2 on the integrity of cap rock. In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Amsterdam: Pergamon Press

Pacala, S.W. (2003): Global Constraints on Reservoir Leakage. In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Amsterdam: Pergamon Press

Palmgren, C., M. Granger Morgan, W. Bruine de Bruin, and D.W. Keith (2004): Initial public perceptions of deep geological and oceanic disposal of CO_2. *Environmental Science and Technology*, Volume 38, Issue 24, p.6441-6450

Parson, E.A., and D.W. Keith (1998): Fossil Fuels Without CO_2 Emissions. *Science*, Volume 282, Issue 5391, p.1053-1054

Perrings, C. (1989): Environmental Bonds and Environmental Research in Innovative Activities. *Ecological Economics*, Volume 1, p.95-110

Perrow, Charles (1992): Normale Katastrophen. Die unvermeidbaren Risiken der Großtechnik. Frankfurt am Main, New York: Campus Verlag

Pipes and Pipelines International (1988): Gas Pipeline Incidents – A report of European gas pipeline incident group, July-August 1988. Cited in Holloway et al. [1996, 161]

Radgen, P., C. Cramer, P. Gerling, F. May, and S. Knopf (2004): Bewertung von Verfahren zur CO_2-Abscheidung und –Deponierung. 2. Zwischenbericht an das Umweltbundesamt Berlin. F+E Vorhaben Nr. 203 41 110

Radkau, J. (1983): Aufstieg und Krise der deutschen Atomwirtschaft 1945-1975. Verdrängte Alternativen in der Kerntechnik und der Ursprung der nuklearen Kontroverse. Reinbek: Rowohlt Taschenbuch Verlag GmbH

Reiner, D.M., and H.J. Herzog (2004): Developing a Set of Regulatory Analogs for Carbon Sequestration. *Energy*, in press.
Internet: http://sequestration.mit.edu/bibliography/policy.html

Reusswig, F. (2001): Umwelt. In: Joas, H. (ed.): Lehrbuch der Soziologie. p.557-575. Frankfurt am Main: Campus Verlag

Riahi, K., L. Barreto, S. Rao, and E.S. Rubin (2004): Towards fossil fuel-based electricity systems with integrated CO_2 capture: implications of an illustrative long-term technology policy. In: E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.): Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Volume 1: Peer-reviewed Papers and Plenary Presentations. Cheltenham, UK: IEA Greenhouse Gas Programme

Riddiford, F., A. Tourqui, C. Bishop, B. Taylor, and M. Smith (2003): A Cleaner Development. The In Salah Gas Project, Algeria. In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Amsterdam: Pergamon Press

Rogner, H.H. (1997): An Assessment of World Hydrocarbon Resources. *Annual Review of Energy and Environment*, Volume 22, p.217–262

Rosa, H. (1998): Identität und kulturelle Praxis: politische Philosophie nach Charles Taylor. Frankfurt am Main: Campus Verlag

Rossiter, D., and K. Wass (2003): Australia's renewable energy certificate system. In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Amsterdam: Pergamon Press

Rost, Sophia (2003): John Deweys Logik der Untersuchung für die Entdeckung des Politischen in modernen Gesellschaften. Münster: LIT Verlag

Rothberg, P., and H.D. Hassan (2002): Pipeline Safety: Federal Program and Reauthorization Issues. National Council for Science and the Environment Report for Congress RS20640. Internet: http://www.ncseonline.org/NLE/CRSreports/energy/

Ruttan, V.W. (2001): Technology, Growth, and Development. An Induced Innovation Perspective. New York, Oxford: Oxford University Press

SACS – Saline Aquifer CO_2 Storage Project (2003): Best Practice Manual.

Schneider, S.H. (2001): Earth systems engineering and management. *Nature*, Volume 409, p.417-421

Schönwiese, C.D. (1994): Klimatologie. Stuttgart: Ulmer (UTB für Wissenschaft)

Schubert, H.J. (2002): Demokratie in der Kleinstadt. Eine empirische Studie zur Motivation lokalpolitischen Handelns. Wiesbaden: Westdeutscher Verlag

Schwarze, R. (2000): Internationale Klimapolitik. Marburg: Metropolis Verlag

Sedlacek, R. (2003): Untertage-Erdgasspeicherung in Deutschland. In: *Erdöl, Erdgas, Kohle*, 119. Jg. 2003, Heft 11, p.392-402

Senior, B., J. Adams, T. Espie, and I. Wright (2004): Investigation of how capture and storage could evolve as a large scale CO_2 mitigation option. In: E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.): Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Volume 1: Peer-reviewed Papers and Plenary Presentations. Cheltenham, UK: IEA Greenhouse Gas Programme

Shackley, S., C. McLachlan, and C. Gough (2004): The Public Perceptions of Carbon Capture and Storage. Tyndall Centre for Climate Change Research, January 2004, Working Paper 44. Internet: http://www.tyndall.ac.uk/publications/working_papers/wp44.pdf

Shogren, J.F., J.A. Herriges, R. Godvindasamy (1993): Limits to environmental bonds. *Ecological Economics*, Volume 8, p. 109-133

Smith, A. (2004): Regulatory Issues Controlling Carbon Capture and Storage. Master Thesis, Massachusetts Institute of Technology (MIT).
Internet: http://sequestration.mit.edu/bibliography/policy.html

SRES (2000): Database.
Internet: http://sres.ciesin.org/data/Version1.1/table/A1_MARIA/A1_MARIA_World.xls .

SRU Der Rat von Sachverständigen für Umweltfragen (2004): Umweltgutachten 2004. Umweltpolitische Handlungsfähigkeit sichern.
Internet: http://www.umweltrat.de/02gutach/umwelt.htm

Stenhouse, M., M. Wilson, H.J. Herzog, B. Cassidy, M. Kozak, W. Zhou, and J. Gale (2004): Regulatory issues associated with deep (geological) CO_2 storage. In: E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.): Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Volume 1: Peer-reviewed Papers and Plenary Presentations. Cheltenham, UK: IEA Greenhouse Gas Programme

Stevens, S.H., J.M. Pearce, and A.J. Rigg (2001): Natural Analogs for Geologic Storage of CO_2: An Integrated Global Research Program. Presented at First National Conference on Carbon Sequestration, May 15-17, 2001, Washington D.C.
Internet: http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/6a1.pdf

Stroink, L. (2003): Ökonomische und Ökologische Perspektiven der unterirdischen CO_2-Deponierung. 1. EFUC-Kongress in Sudergurg b. Uelzen, Juni 2003

Taylor, C. (1992): Negative Freiheit? Zur Kritik des neuzeitlichen Individualismus. Frankfurt am Main: Suhrkamp

Taylor, C. (1999): Quellen des Selbst: die Entstehung der neuzeitlichen Identität. Frankfurt am Main: Suhrkamp

Torp, T., and J. Gale (2003): Demonstrating storage of CO_2 in geological reservoirs: the Sleipner and SACS projects. In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Amsterdam: Pergamon Press

Torvanger, A., S. Kallbekken, and K. Rypdal (2004): Prerequisites for Geological Carbon Storage as a Climate Policy Option. CICERO Report 2004:4.
Internet: http://www.cicero.uio.no/publications/cicerolop.asp?lang=en#RPRTWP

Tsang, C., S. Benson, B. Kobelski and R. Smith (2002): Scientific considerations related to regulation development for CO_2 sequestration in brine formations. *Environmental Geology*, Volume 42, p.275-281

UNFCCC (1992): United Nations Framework Convention on Climate Change. Internet:
http://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf

UNFCCC (2001a): Decision 5/CP.7, Implementation of Article 4, paragraphs 8 and 9, of the Convention (decision 3/CP.3 and Article 2, paragraph 3, and Article 3, paragraph 14, of the Kyoto Protocol), FCCC/CP/2001/13/Add.1

UNFCCC (2001b): Matters relating to Article 3, paragraph 14 of the Kyoto Protocol (FCCC/CP/2001/13/Add.1: Draft decision -/CMP.1, art.7).

UNFCCC (2004): Homepage. Internet: http://unfccc.int/2860.php

Union of Concerned Scientists (2002): Policy Context of Geological Carbon Sequestration. Internet: http://www.ucsusa.org/documents/geo_carbon_seq_for_web.pdf

Veawab, A., A. Aroonwilas, A. Chakma, and P. Tontiwachwuthikul (2001): Solvent Formulation for CO_2 Separation from Flue Gas Streams. Presented at First National Conference on Carbon Sequestration, Washington, D.C., May 14-17, 2001. Internet:
http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/carbon_seq01.html

Vine, E. (2004): Regulatory Constraints to Carbon Sequestration in Terrestrial Ecosystems and Geologic Formations: a California Perspective. *Mitigation and Adaptation Strategies for Global Change*, Volume 9, p.77-95

Wall, C., C. Bernstone, M.L. Olvstam (2004): International and European Legal Aspects of Underground Geological Storage of CO_2. In: E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.): Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Volume 1: Peer-reviewed Papers and Plenary Presentations. Cheltenham, UK: IEA Greenhouse Gas Programme

Watanabe, Y., and D.O. Hall (1996): Photosynthetic CO_2 conversion technologies using a photobioreactor incorporating microalgae – energy and material balances. *Energy Conversion and Management*, Volume 37, p.1321-1326

WBGU Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen (2003): Welt im Wandel: Energiewende zur Nachhaltigkeit. Berlin, Heidelberg: Springer Verlag

Westbrook, R. (1991): John Dewey and American Democracy. Ithaca, London: Cornell University Press

Wildenborg, A.F.B., and L.G.H. van der Meer (2002): The use of oil, gas and coal fields as CO_2 sinks. In: IPCC [2002]

Wilson, E., and D.W. Keith (2003): Geologic Carbon Storage: Understanding the Rules of the Underground. In: Gale, J., and Y. Kaya (eds.): Proceedings of 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan. Amsterdam: Pergamon Press

Wilson, E., T. Johnson and D. Keith (2003): Regulating the Ultimate Sink: Managing the Risks of Geologic CO_2 Storage. *Environmental Science & Technology*, Volume 37, Number 16, p.3476-3483

Wilson, E., D. Keith and M. Wilson (2004a): Considerations for a Regulatory Framework for Large-Scale Geological Sequestration of Carbon Dioxide: a North American Perspective. In: E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.): Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Volume 1: Peer-reviewed Papers and Plenary Presentations. Cheltenham, UK: IEA Greenhouse Gas Programme

Wilson, M., P. Tontiwachwuthikul, A. Chakma, R. Idem, A. Veawab, A. Aroonwilas, D. Gelowitz, and R. Stobbs (2004b): Evaluation of the CO_2 Capture Performance of the University of Regina CO_2 Technology Development Plant and the Boundary Dam CO_2 Demonstration Plant. In: E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.): Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Volume 1: Peer-reviewed Papers and Plenary Presentations. Cheltenham, UK: IEA Greenhouse Gas Programme

WWF (unknown): Position Paper Carbon Capture and Storage from Fossil Fuels.
Internet: http://ld.panda.org/downloads/climate_change/wwfpositionstorage.doc.

Zhang, Y. (1996): Dynamics of CO_2-driven lake eruptions. *Nature*, Volume 379, Issue 4, p.57-59

Zhou, W., M. Stenhouse, S. Whittaker, D.H.S. Law, R. Chalaturnyk, and W. Jazrawi (2004): The IEA Weyburn CO_2 Monitoring and Storage Project – Modeling of the Long-term Migration of CO_2 from Weyburn. In: E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.): Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Volume 1: Peer-reviewed Papers and Plenary Presentations. Cheltenham, UK: IEA Greenhouse Gas Programme

Note: all internet addresses were contacted between September and December 2004.

Appendix A – Review of analyses of existing regulatory conditions for CCGS

The following sections are based on a review of literature addressing the existing regulatory conditions for CCGS. The current legal situation and regulatory analogues (and as far as available: their history) for CCGS in the United States, Europe, the Netherlands, and Germany will be discussed. The different scope of treatment is solely due to the availability of literature, which focuses mainly on the United States.

It is worth noting that all GS projects currently underway are, from a legal point of view, part of an industrial process, that is, EOR operations or purification of natural gas in order to meet sales specifications. Mitigation of carbon dioxide emissions is a desired side effect, but not main purpose of these storage activities (the reason for this is, of course, that in absence of a price for CO_2 emissions CCS projects as exclusive climate change mitigation efforts are not economically viable). Therefore, the legal situation of these projects cannot simply be transferred to future CCS projects with the exclusive aim of mitigating CO_2 emissions. This is due to the fact that the use of carbon dioxide in industrial processes is regulated under existing legal conditions which do not require a permission for CO_2 injection. Genuine CO_2 storage projects, however, will require distinct regulation. [Wall et al. 2004, 1]

Lee [2004] states that some countries are currently moving towards regulation for CCGS. These are Netherlands, Norway, Canada, United Kingdom, and the USA. Lee does not specify the aims and scope of these regulation efforts.

A.1 United States

This subchapter aims at providing an overview of US regulations that (could) principally relate to CCGS.

A.1.1 History of underground injection regulation in the US

The first kind of underground injection activity in the USA started in the 1930s with injection of wastewater by the oil and gas industry. Prior to that, the large quantities of brine water that come up with oil were disposed of in ditches on the surface to evaporate. It turned out, however, that this practice contaminated shallow aquifers and caused health problems. [Wilson and Keith 2003, 2; Smith 2004, 25-26] Due to tighter surface water pollution regulation the producers started to reinject the brines into depleted reservoirs. [Wilson and Keith 2003, 2; Smith 2004, 25-26] Industrial injection wells were first mentioned in an article describing Dow Chemical's problems with a well disposing of industrial brines in 1939. [Wilson and Keith, 2003, 2; Tsang et al. 2002] Other states began to regulate the underground injection of fluids in the late 1960s (Ohio, Michigan, West Virginia, New York, Colorado), with Missouri and North Carolina principally banning underground waste disposal in the early 1970s. [Smith 2004, 26]

Due to disposal well failures in the 1960s, the Federal Water Quality Administration (FWQA) introduced a federal policy in October 1970 stating that waste injection was to be considered only as a temporary alternative until better alternatives were developed. The operator of an underground waste disposal scheme had to demonstrate that water supplies would not get contaminated and no environmental damages be induced, and strict controls were to be applied. [Tsang et al. 2002; Wilson and Keith 2003, 2; Smith 2004, 26] In December 1970, the FWQA was merged into the newly formed EPA. [Smith 2004, 26]

The EPA tried to regulate underground injection in 1973 under the 1972 Clean Water Act (CWA) but ran into legal problems with EXXON, as the CWA only allowed for the regulation of the "navigable waters of the US", preventing regulation of underground injection through the CWA. [Wilson and Keith 2003, 3; Smith 2004, 26] By passing the Safe Water Drinking Act (SWDA) in 1974, Congress extended EPA's authority to regulate underground injection by establishing the Underground Injection Control (UIC) program, a mixed Federal-State system. [Wilson and Keith 2003, 3] The rules for this program were implemented in 1980, and according to Smith [2004, 27] the program still applies today.

However, Benson et al. [2002, 6] report that due to many well failures and drinking water contaminations regulations were updated in 1988 in order to overcome their shortcomings. Well failures were mainly attributed to (i) poor characterization of the confining units, (ii) improper well completion technology, (iii) use of unsuited well construction materials that corroded when exposed to the waste stream, (iv) inconsistent or inadequate monitoring, and (v) leakage through abandoned wells. According to Benson et al. [2002, 6] no incidents of drinking water contamination have been reported since the update of regulations in 1988.

A.1.2 UIC regulation today

Aims, general issues and institutional structure

The explicit aim of the UIC program is to regulate the injection of any substances into the subsurface in order to protect current and potential underground sources of drinking water (USDW). Exempted from regulation is natural gas storage in geologic reservoirs, which is due to the assumption that natural gas storage does not harm groundwater and that federal regulation would have inhibited the expansion of gas storage operations in the 1980s. [Wilson et al. 2003, 3478] The EPA defines an underground source of drinking water as an aquifer that supplies a public water system (PWS) or contains enough water to supply a PWS, currently supplies drinking water for human consumption, or contains water with less than 10,000 mg/liter of total dissolved solids. [Smith 2004, 27]

The rules for Class I-III mandate a *zero* contamination policy of USDWs: if 'movement of any contaminant into the underground source of drinking water' is detected, corrective actions have to be taken 'as are necessary to prevent such movement' (40 CFR 144.12 (b)). [cited after Wilson et al. 2004, 5] The regulations also prohibit movement between USDWs with different TDS concentrations (i.e. a 9,000 TDS USDW must not flow into a 3,0000 TDS USDW), but this provision isn't widely enforced in many Class II programs. [Wilson et al. 2004, 5]

Although detailed requirements for siting, constructing, and monitoring injection well operations are in place, federal regulation does not require monitoring of the actual movement of fluids within the injection zone. There are no requirements for monitoring in overlying zones to detect leakage, with the exception of specific Class I hazardous wells, where this monitoring can be specifically mandated, although it rarely is. [Wilson et al. 2004, 5]

Wilson and Keith [2003, 3] state that since the 1980 regulations were adopted, four cases of wastewater migration from injection wells and no case of USDW contamination from a Class I hazardous well has been reported.

As the UIC is a federal-state system defining minimum standards, states can apply to run their own UIC programs if they meet basic proficiency criteria. On the federal side, GHG issues are generally purviewed by the EPA's Office of Air and Radiation, while issues associated with surface risks are usually mitigated by Occupational Safety and Health Administration (OSHA) standards. [Forbes 2002, 3] On the side of the states, 34 states currently run their own program, 6 share responsibility with the EPA, and 10 are administered directly by the regional EPA office. [Smith 2004, 27]. The states can apply more stringent rules for underground injection, specify the permitting process, and they can ban certain or all types of underground injection. Smith [2004, 61] argues that states which combine an own UIC program and an active climate change policy may be of special interest for CCGS projects, as these states would likely (a) have the required bureaucratic capacities (and experience) to regulate a CCGS project and (b) may offer subsidies to CCGS projects as climate change mitigation measures.

The injection program in the USA does not address the implications of long-term liability. [Wilson et al. 2004, 6]

Classification and regulation of injection wells

Underground injection is divided into five major classes. The location of the injection site, the level of potential health and environmental harm, and its disposal location determine what class an injection will fall under. [Tsang et al. 2002]

Class I - Class I wells inject hazardous industrial and non-hazardous industrial and municipal wastes below the lowermost underground sources of drinking water. Injection occurs into deep, isolated rock formations that are separated from the lowermost USDWs by layers of impermeable clay and rock. Typical injection depths range from 1,700 to 12,000 feet. [Smith 2004, 29-31]

Injection of lightly treated sewage into porous underground formations involves features similar to CO_2 injection, as the sewage is less dense than the surrounding fluids and has an upwards bouncy driven flow. CO_2 is less dense at these depths and has an even stronger tendency to rise than sewage. [Smith 2004, 29-31]

Class I wells require the most stringent regulation. Pre-injection testing is required to ensure sufficient size, porosity and permeability of the injection zone. At least one relatively impermeable cap rock is required. Project developers must show that the formation is homogenous, without faults and separated from drinking water by submitting geologic and hydrologic data. They must prove that there are no abandoned, unplugged wells in the so-called area of review (AoR), which is a minimum ¼ mile radius for non-hazardous and 2 miles for hazardous wells (states often increase that radius in their own legislation). Also, it is required that the applicant demonstrates that the injection region is not seismically active. For hazardous wells it must be demonstrated, using modeling, that the injected waste will not leave the injection zone for 10,000 years. However, these modeling results have not been systematically compared in detail with actual injectate behavior in the past. [Wilson and Keith 2003, 4] Wells are required to have an inner and an outer casing to prevent the hole from caving in. All materials must be corrosion resistant. Injection pressure, flow rate and volume must be continuously monitored. If acceptable pressures are exceeded, automatic shutoff switches must enable the termination of the injection process. USDWs within the AoR have to be monitored. Mechanical integrity tests of the wells are required every year for hazardous, and every 5 years for non hazardous wells.[115] [Tsang et al. 2002; Smith 2004, 29-31]

The wells must be designed so that in case of system failure the fluid remains in the intended subsurface layer. Permitting a hazardous class I well can cost up to US$ 2 million, involving 11,000 hours of work. [Smith 2004, 29-31]

In the USA there currently are 473 Class I wells in operation. 123 of these inject hazardous, and 350 non-hazardous or municipal wastes. 70% of all Class I wells are sited in Texas, Louisiana, Florida (which has all of US municipal injection wells, amounting to 84 wells) and Kansas. [Wilson et al. 2003, 3478; Smith 2004, 29-31]

Benson et al. [2002, 6] report that in 1987 the cost of liquid hazardous waste disposal ranged from US$ 49 to US$ 207 per ton.

Class II - Class II wells are wells that are associated with energy production. Gas and oil production wells and wells that reinject fluids (brines) from oil and gas production (about 10 barrels of brine for every barrel of oil on average) fall under this class. Enhanced oil recovery (EOR) projects also fall under Class II. [Smith 2004, 32] There currently are ~9,000 injection wells active in EOR operations using CO_2 in the USA.[116] [Wilson et al. 2004, 4] Two billion barrels of brine are injected daily in Class II wells. [Smith 2004, 32]

Class II wells follow the same construction requirements as Class I non-hazardous wells, the permitting requirements being less stringent than Class I wells, making them less expensive. [Smith 2004, 29-31]

Class III - Class III wells inject super-heated steam, water or other fluids into geological formations in order to extract minerals. The injected fluids are pumped to the surface and the minerals in the solution are extracted. In general, the fluid is treated and reinjected into the same formation. Class III wells should not be relevant for CCGS. [Smith 2004, 29-31]

Class IV - Class IV wells dispose off hazardous wastes into or above underground sources of drinking water. They also dispose off radioactive wastes. Class IV wells are principally banned because they directly threaten public health. [Smith 2004, 29-31]

Class V - Class V wells are the “catch-all” class of the UIC program, regulating all injection wells that are not included in the other classes. These are generally shallow and depend upon gravity to drain or “inject” liquid waste into the ground above or into underground sources of drinking water. To be classified as a Class V well, the waste material must not be a

[115] For an overview of specific monitoring tasks at class I well operations, see Tsang et al. [2002].
[116] Forbes [2002, 2] notes that both EOR and ECBM have been encouraged through tax incentives, as tax credits for both processes are offered under section 29 of the Federal Windfalls Profits Act.

hazardous waste as defined under the Resource Conservation and Recovery Act. Experimental UIC projects also receive Class V status. [Smith 2004, 29-31]

The EPA estimates that there are 686,000 Class V wells in the US. The two largest of the overall 23 Class V categories are storm water drain wells (approximately 248,000) and large septic systems (approximately 353,000). [Smith 2004, 29-31]

Regulations vary widely between states. They at least comprise the requirement of compliance with technical specifications, the respective authory's right to issue site-specific permits, make inspections and take enforcement action if necessary. [Smith 2004, 29-31, citing EPA 1999]

A.1.3 Pipelines

CO_2 Pipelines are covered under the 2001 Code of Federal Regulations, Parts 190-199. They are classified as High Volatile/Low Hazard and Low Risk. The body responsible for implementation of regulations is the Office of Pipeline Safety of the United States Department of Transportation. Regulation follows a best practice approach.

Setting up pipelines is achieved by establishing a right of way (ROW). A ROW concerns the piece of land over (pipelines are usually buried) and around the pipeline (typically 25 feet on both sides of the pipe), and establishing a ROW involves the property owner granting some legal rights to the pipeline company. These rights involve access to the pipeline for operation, testing, inspecting, repairing, maintaining, replacing and protecting the pipeline [Smith 2004, 58-59]. The company proposes a route for a pipeline to the Federal Energy Regulatory Commission (FERC). It has to choose the route with the least environmental impacts. Pipeline routes along existing pipelines are therefore preferred. ROWs for transmission lines, roads and railroads have to be purchased. FERC has the authority to force a land owner to sell the property required for a pipeline under the powers of eminent domain if it has approved the pipeline and the owner refuses to sell his land to the company. [Smith 204, 59] Some federal land can be used for pipelines. The Bureau of Land Management is authorized (through the Federal Land Policy and Management Act) to issue ROWs for electricity transmission and distribution lines, communication towers, highways, railroads, pipelines (except oil and gas pipelines) and other facilities or systems which are in the public interest. CO_2 pipelines fall under this classification. [Smith 2004, 59]

A.1.4 Protected Areas

In the US, ownership and regulation determine what land can be used for. Both the building of CO_2 pipelines and setting up geological storage sites will be restricted at varying degrees at national parks,[117] areas falling under the Roadless Area Conservation Rule,[118] and specific

[117] Regulations vary from park to park. There are some pipelines through national parks, for example a natural gas pipeline runs through the Great Smoky National Park. [Smith 2004, 60]

[118] The Bush administration has weakened this rule that protects 58.8 million acres of US Forest service land from forest and road building by exempting the Alaska's Tongass Rainforest. [Smith 2004, 53]

protected areas. [119] Private land unrestricted for development will very likely be most attractive for CCGS projects. Smith [2004, 50-51] assumes that – as CCGS is likely to be considered as a matter of national interest – public land should also be available for CCGS projects (both for pipelines and storage sites) and could be very well suited, as it is usually largely uninhabited and intended to host some industrial activity. [Smith 2004, 39-60]

A.1.5 Implications for potential US regulation of CCGS

The most important difference between existing regulatory analogues and CCGS may be the time-frame of such projects. With a few exceptions regarding hazardous waste injection in the USA, existing underground injection regulation does not specify any explicit storage time or does require long-term monitoring activities after injection has been finished. CO_2 storage will exceed several hundred, and possibly thousands of years. [Stenhouse et al. 2004, 1; Wilson et al. 2004, 2]

Another difference are the risks imposed by CO_2 injection (e.g., due to buoayncy: leakage to surface, migration to USDWs), which make necessary a much stronger focus on trapping mechanisms than in existing operations.

Today it is unclear how injection of CO_2 for long-term storage will be regulated in the USA. However, many authors assume that it will be regulated under the framework of the UIC program. [Forbes 2002, 3; Stenhouse et al. 2004, 7; Wilson et al. 2004, 7; Smith 2004, 34].

Regulators at EPA held a stakeholder meeting in February 2004 with researchers, EPA regulators, DOE, and state agencies, in order to clarify what regulatory regime would be appropriate for CCGS. [Smith 2004, 35] NETL is organizing the Regional Carbon Sequestration Partnership Program which coordinates these activities in the US. In January 2005 a final report will be published that will include recommendations for regulating CCGS. [Godec 2003; Bengal 2004]

Many possibilities for regulating CCGS are currently being discussed in the US. One open question is whether the states or the federal EPA should be responsible for CCGS. Some of the states champion a solution where the states will be responsible for designing and implementing the UIC regulation for CCGS. [Smith 2004, 35]

Another issue relates to the question under which well class CO_2 injection projects for long-term storage would fall. Principally, it is clear that CO_2 injection would never occur above USDWs [Forbes 2002, 5]. CO_2 injection into deep brine aquifers might, on these grounds, be regulated as Class I operations. Smith [2004, 36] cites an unpublished paper by Apps (2004) which claims that the requirements of Class I hazardous wells for retaining the injected fluid for 10,000 years are appropriate for CCS. According to Apps it has also to be taken into account, however, that CO_2 is less dense than its surrounding and is thus always tending to migrate upwards. Tsang et al. [2002] also claim that Class I is the most relevant regulation for CCS. They argue that CO_2 will be stored at depths greater than 800 meters because there

[119] For example National Wildlife refuges, Globally Important Bird Areas, National Monuments, National Battlefields; for a comprehensive list see Smith 2004, 46-48. Smith also remarks that a buffer area around protected sites should be taken into account, as siting a CCS project next to a protected area will spark public concerns about migrating CO_2. [Smith 2004, 49]

it reaches supercritical state and is easier to store. Most drinking water aquifers are shallower than 800 meters, so Class I scheme – regulating storage beneath USDWs – would apply.

Class I projects are often controlled by a states' environmental or national resource office. According to Forbes [2002, 3], critics of this approach argue that the costs of up to US$ 2 million for permitting a Class I hazardous well (including geological characterization and modeling) will lower the attractiveness of CCGS for private investors.

Concerning the question of the definition of CO_2 as hazardous or toxic, Benson et al. [2002, 3] remark that CO_2 is not regulated, studied, or suspected as toxic substance by the following federal agencies or regulations: Clean Air Act 1970, 1990, Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) 1972, Resource Conservation and Recovery Act (RCRA) 1976, Comprehensive Environmental Response, Compensation, and Liabililty Act (CERCLA or Superfund) 1980, Superfund Amendments and Reauthorization Act (SARA) 1986, National Toxocology Program, Agency for Toxic Substances and Disease Registry or the National Institute of Environmental Health Science in the National Institutes of Health, and the National Center for Toxicological Research (NTCR) in the FDA. Contrary to that, the following institutions treat carbon dioxide as a hazardous substance to the extent that any concentrated, pressurized or cryogenic gas poses a danger: inventory list for the Toxic Substances Control Act (TSCA) 1976, NIOSH confined space hazard classification system, FEMA hazardous materials guide. [Benson et al. 2002, 3]

EOR applications with the intention of CCGS projects are likely to be regulated under Class II rules. Class II wells are usually controlled by a states' hydrocarbon agency. [Smith 2004, 35] As the permitting costs for Class II wells are lower than those for Class I hazardous waste wells (as the regulation requirements are less strict), some argue for adding CCGS to this class in order to make it economically more attractive for firms. [Forbes 2002, 3; Godec 2003]

Alternatively, federal EPA regulators could decide that CCGS will become a special category in Class V[120]. An experiment to store CO_2 in a saline aquifer in Texas carried out by the Texas Bureau of Economic Geology received a Class V permit from Texas regulators, as Class I (small volume of CO_2) and II (no liquid hydrocarbons involved) were ruled out as inappropriate. [Smith 2004, 36-37] Wilson et al. [2004, 7] suggest that regulating CCGS within the Class V regime may be appropriate, as this regime allows for upward migration of the injected fluid as long as it doesn't harm public drinking water standards (see also Wilson et al. [2004, 7] for possible institutional procedures of introducing CCGS in the US regulatory body).

Finally, Smith [2004] proposes that a sixth UIC class could be designed especially for CO_2 storage, containing several categories depending on which kind of injection scheme is applies (EOR, brine aquifers, unminable coal seams). The design of the CCGS category could be performance-based (e.g. defining an acceptable leakage rate), and specific well-construction and geological siting standards for CCGS could be taken into account.

[120] or in Class I.

Benson et al. [2002, 6] remark that as surface handling of CO_2 will fall under different jurisdiction than the injection process, costly regulatory divergences may arise that should be avoided through early attention and integration of regulation.

Whichever classification CCGS will receive and whoever will carry responsibility, with regard to a global CCGS framework including comprehensive CO_2 emission accounting and verification[121] it will be necessary that a nationally consistent set of CO_2 reporting and monitoring standards for CCS will be implemented to ensure compatibility of CCGS with that more global scheme. The local regulation scheme for CCGS will therefore be very likely designed in a way making it compatible with the emission inventory accounting system. [Smith 2004, 37]

Vine [2004] sketches relevant issues for a potential permit process for CCGS projects in California (he does not take into account environmental regulations and monitoring requirements after the project start). He argues that a permit process too complicated could be very expensive and ultimately hinder the implementation of CCGS.

Concerning local regulations, it also not clear whether CCGS project developers will have to demonstrate that their CCGS project does entail the risk of surface leakage of CO_2 (stemming both from the pre-injection handling of CO_2 and the possibility of leakage to the atmosphere from the underground) only to the agency responsible for the UIC program, to the state health and environment agency, or both. [Smith 2004, 38]

Liability

Four levels of liability can be identified in the USA: federal (national) government, state (sub-national) government, industry, and individual corporations. The four levels are non-exclusive and liability issues are likely to be tackled on several levels. [Stenhouse et al. 2004, 3; de Figueiredo et al. 2003, 1]

> "Legal standards of liability are typically assessed in the terms of *negligence* and *strict liability*. Excluding specific statutory authority governing liability, most of modern accident law in the USA is addressed through negligence claims. Negligence is the failure of a person (or corporation) to exercise reaonable care. Lawsuits often hinge on the interpretation of "reasonable care". Firms that conduct activities associated with CO_2 storage would be considered professionals. Under negligence law, professionals must exercise the skill and knowledge normally possessed by member of the profession, otherwise they may be found negligent. In an effort to internalise costs with the entity most able to control risk, the concept of "strict liability" was established. Under strict liability in the USA, a person (or corporation) is held liable for the harm that his or her (or corporation's) activity caused, regardless of whether reasonable care was used. Although the ultimate finding of strict liability is made in court, application of strict liability can be imposed by either the courts or the legislature. Strict liability and negligence / duty of care also apply in European countries. […] The critical question [in liability, C.F.] is how the judiciary, legislature, and regulatory authorities will treat geologic storage […]. Whether liability for geologic CO_2 storage will be treated more like the historic treatment of natural gas which has imposed relatively low costs on operators, or more like hazardous waste management which has been much more demanding (financially) to ensure protection of the environment, is currently uncertain. The answer will depend in part on

[121] the EPA is currently tasked with keeping the US CO_2 emission inventory. [Smith 2004, 37]

a number of factors, *viz.* (i) the results of current research assessing the risks of this technology; (ii) the first projects that attempt to store CO_2 on a large scale explicitly for the purposes of reducing emissions of CO_2 to the atmosphere; (iii) the reaction of the public and interest groups to those risks and efforts; and (iv) acturial and financial analyses of liability. It is still too early to have a definitive answer in terms of these factors." [Stenhouse et al. 2004, 2-3]

A.2 Europe

Transnational regulation of CCGS in Europe could be important for three reasons: first, climate change due to anthropogenic CO_2 emissions is a global issue and the EU member states are already cooperating closely on it. Second, because the geological formations suitable for CCGS usually extend over large areas across nation-state boundaries in Europe, the risks associated with a CCGS project in Europe might not only concern the nation where it is carried out. And third, European directives (e.g., on waste) aim at approximating regulations in Member States to the aims formulated in the EU directives already today.

There is no comprehensive legal European framework that deals with CCGS today. Legal rules that are or might be applicable to CCGS are fragmentary. [Wall et al. 2004, 1-2] European legal rules that might apply to or affect CCGS regulation in Europe as identified by Wall et al. [2004] and CRUST [2001] will be discussed in the subsequent sections.

A.2.1 IPPC-Directive: Council Directive 96/61/EC concerning integrated pollution prevention and control

The EU IPPC-directive provides a list of large industrial installations that have to undergo an authorization procedure. Although this list does not include storage sites for CO_2, the directive indicates the general position within the Union, that is, large industrial installations (traditionally point sources of pollution) are subject to permit procedures that can include investigation of environmental and other impacts of the facility. Included in the list of facilites requiring authorization are landfills receiving more than 10 tons of waste per day or with a total capacity exceeding 25,000 tons, excluding inert waste, and combustion facilities with a rated thermal input exceeding 50 MW. [Wall et al. 2004, 2]

Two more specific conclusions can be drawn for CCGS. First, as CO_2 is not traditionally regarded as a pollutant, it is difficult to predict whether the IPPC-directive will apply for CCGS. Second, geological storage of carbon dioxide would probably not be considered as a part of the power plant generating the carbon dioxide. Due to this aspect the IPPC-directive is therefore not likely to come into effect for CCGS.

However, while these directions have no bearings on GS, they indicate the general approach of EU towards large scale industrial installations. That is, facilities involving potential impact on environment or humans require authorization within EU. [Wall et al. 2004, 2]

A.2.2 Water Framework Directive

The purpose of the European Water Framework Directive is to protect inland surface waters, transitional waters, coastal waters and groundwater within the EU. Aims include ensuring the supply of quality surface and groundwater for sustainable use, reducing existing pollutions of groundwater, and protecting marine and territorial waters. Groundwater should not be polluted at all; a precautionary approach is in place that prohibits direct discharges to groundwater, and requires monitoring in injection activities in order to detect changes in the water composition. A river basin approach is applied, that is, member states must set up appropriate governance structures, if necessary transnational. [Wall et al. 2004, 2]

It is in general unclear how the water framework directive will concern CCGS in detail. However, it is very likely that as goundwater must principally not be polluted, leakage of CO_2 into groundwater changing groundwater quality (e.g. a decrease in groundwater pH) – even if such migration would not involve toxic chemicals – would be restricted and forbidden. In addition, a GS project would likely have to conduct monitoring of adjacent groundwater aquifers. [Wall et al. 2004, 2]

A.2.3 Waste

Whether a substance is defined as waste, hazardous waste or no waste at all makes a significant difference in European law, especially with respect to strictness of regulation. [Wall et al. 2004, 2]

The EU waste directive

If a substance is defined as a waste by the EU waste directive, the Member States have to take the necessary measures to ensure recovery or disposal of the waste without endangering human health, without using processes or methods which could harm the environment, and more particularly, for example, without risk to water, air, soil, plants and animals. This implies increased documentation about the waste, and acquisition of permits for transporting and handling wastes. The permission procedure between an authority and a project operator has to cover the following aspects: type and quantities of waste, technical requirements, security precautions, disposal site, treatment methods, and record keeping on quantity, nature, and origin (and where relevant: destination, frequency of collection, and mode of transport). [Wall et al. 2004, 2-3]

With regards to CCGS, the most important question apparently is, whether liquefied CO_2 from fossil fuel power plants that is to be injected into geological formations is defined as a waste, hazardous waste or no waste. There is currently no such explicit definition. [Wall et al. 2004, 3] Instead, general definitions of waste and hazardous waste from different regulative contexts have to be applied to CO_2 in CCGS.

The EU framework directive on waste defines (in Art. 1) waste as (i) any substance or object set out in Annex 1, or (ii) which the holder discards or intends or is required to discard. Concerning (i), Annex 1 offers a list of categories of wastes, where the last category includes any materials, substances or products which are not defined in the previous list. Concerning (ii), these are, for example, substances that no longer perform satisfactorily, residues of industrial processes, residues from raw material extraction and processing, and products for which the holder has no further use. [Wall et al. 2004, 3] Apparently these definitions are very broad, and anything meeting the definition of Article 1 is waste. Article 2 specifies some exceptions, such as gaseous effluents emitted into the atmosphere, but as CO_2 for

CCGS is liquefied and stored and the point is to not let it get into the atmosphere, this exception doesn't apply. CO_2 from power plants would also likely be deemed analogous to actual waste disposal activities in practice, which are defined in Annex II A and B. Such activities include, for example, injection of pumpable discards into wells, salt domes, or naturally occurring repositories. [Wall et al. 2004, 3]

CRUST [2001, 17] quotes the following EU definition of "disposing of wastes":

> "In this act and the stipulations arising out of it, disposing of wastes is taken among other things to mean:
> a. the useful application or removal of wastes within the organization in which they were created;
> b. taking wastes from an organization to an organization located elsewhere that belongs to the same natural or
> legal person for the purposes of useful application or removal;
> c. temporarily handing over wastes for useful application (article I A, subsection 2)."

On these combined grounds Wall et al. [2004, 3] and [CRUST 2001, 17] conclude that under the EU waste directive, geological storage of CO_2 would be defined as waste disposal according to European Law.

Concerning the question whether CO_2 in CCGS might be classified as hazardous waste, hazardous wastes are defined in the European waste catalogue, which takes into account the origin (e.g., power stations and other combustion plants) and composition of waste and, where necessary, limit values of concentration. Flue gases are not included in this definition. This is due to the fact that flue gases are usually emitted into the atmosphere and thus not defined as wastes. As there is no category for flue gases so far, captured CO_2 could fall under category non-hazardous "wastes not otherwise specified".

According to Wall et al. [2004, 3] and CRUST [2001, 17] there is no indication that a pure stream of CO_2 would be classified as hazardous waste.

However, if the CO_2 stream – depending on the capture technology – will contain other substances classified as hazardous (e.g., sulphur containing components like SO_2, H_2S, COS and nitrogen containing components like N_2, NO, NO_2, and O_2, Ar, H_2, CO, hydrocarbons, metals and particulates), this would be different, depending on the level of concentration of these substances. There is, so far, no definition of what a "high concentration" of such substances would be. [Wall et al. 2004, 4]

Wall et al. [2004, 3] remark that not enough attention has been spend on the issue of hazardous components in the CO_2 stream which could lead to classification of CCGS projects as hazardous waste disposal, in this case involving considerable regulation requirements (thus costs).

A.2.4 EU legislation on the transport of waste

EU-Regulation on the transport of wastes does exist and should pose principal no problem for pipeline transportation of CO_2. [Wall et al. 2004, 4]

A.2.5 EU directive on landfill of waste

The EU Directive on landfill of waste offers a definition of underground storage as a permanent waste storage facility in a deep geological cavity such as a salt or potassium mine. While CO_2 would not be stored in such formations, EU has defined criteria and procedures for the acceptance of wastes for underground storage activities in general terms. These criteria include: a site-specific safety assessment has to be carried out, with special emphasis put on a geological barrier and the final aim of preventing leakage of the waste to the biosphere. Identification of risks, receptors, pathways of possible leakages to the biosphere and impact assessment if the substance comes into contact with the biosphere are required. If the result of the safety assessment indicates adverse impacts, waste disposal may not be allowed. [Wall et al. 2004, 4]

All wastes that may undergo undesired physical, chemical or biological transformation after they have been deposited must not be disposed of in underground storage. Therefore, among others all liquid wastes have been excluded from underground storage. [Wall et al. 2004, 4]

Under this current regulation (or, concerning the following aspect (i), at least the 'spirit' of it), (i) it is clear that although CO_2 storage in e.g. an aquifer is not explicitly considered, strict regulation would apply for such operations. (ii) Maybe more importantly, as CO_2 is injected in supercritical phase, that is, as a fluid, its underground disposal would be – from this point of view – forbidden as it would constitute a liquid waste. The decisive question yet to resolve here is: is a liquid defined to be a liquid under atmospheric pressure and temperature, or in the state where it is actually stored? [Wall et al. 2004, 4]

A.2.6 Implications for potential EU regulation of CCGS

Current European Law and Regulation does not explicitly cover CCGS. Under current legislation, CCGS is faced with legal incertidudes regarding its status as waste material, and CCGS projects with the explicit aim of mitigating greenhouse gases that exceed the status of R&D efforts would likely require negotiation of legal and safety issues at a court. It is only relatively clear that some authorizsation would be required for CCGS projects. However, regulation requirements of CCGS concern more than some authorization, e.g. selection criteria for storage sites, requirements for monitoring, standards for abandoning wells, regulation on the question of long-term liability for the injected CO_2, and the issue of liability if CO_2 migrating from adjacent projects should merge. [Wall et al. 2004, 6]

The question is therefore if EU will adopt a EU-wide regulation scheme for CCGS through new legislation, which comes along with the question if EU wants to principally endorse CCGS or not. By establishing a framework two general possibilities are thinkable: (i) an effective ban of CCGS, (ii) regulation that invites some CCGS by making available legal security for investors. Both decisions, especially (ii), would likely be an issue of society-wide debate, including many stakeholders (e.g., environmental NGOs).

There may be three reasons for a uniform EU-wide solution: first, climate change due to anthropogenic CO_2 emissions is a global issue and the EU member states are already cooperating closely on it. Second, because the geological formations suitable for GS usually extend over large areasa across nation-state boundaries in Europe, the risks associated with a

CCGS project in Europe might not only concern the nation where it is carried out. Third, uniform accounting procedures for leakages with respect to the ETS are desirable.

Comprehensive considerations concerning future regulation of CCS should also take into account the current liberalization process on European electricity markets.

A.3 The Netherlands

A legal analysis for GS on national level for the Netherlands has been carried out within the Dutch CRUST project. This analysis, however, does only deal with GS as a temporary measure, as CRUST did imply that the CO_2 would be stored only temporarily, and not long-term. [CRUST 2001, 4] Therefore, treatment of the potentially most problematic aspect of regulating CCGS – the long timescale – has been evaded.

The report also assumes that pure CO_2 will be available for storage, that is, the CO_2 stream will not contain any substances classified hazardous. [CRUST 2001, 6] Natural gas storage activities are considered to be the closest regulatory analogue to CCGS. [CRUST 2001, 4]

Two aspect are legally relevant for CCGS: first, mining legislation which overs the mining activities associated with scout studies, exploration and storage. Second, environmental legislation. [CRUST 2001, 4]

A.3.1 Mining legislation and regulation

A new mining legislation was due to be implemented in 2003 when the CRUST report was written in 2001. The report relies on this new legislation. [CRUST 2001, 4-5]

Mining legislation does only cover underground activities. Surface activities such as capture, transport and surface facilities for storage are not covered. Most surface safety aspects would likely be part of the Working Conditions Act.

Scouting

Scouting is the search for suitable storage sites using geological maps, seismic data, and measurements from existing wells. To obtain a more detailed picture of the subsurface, additional seismic analysis is usually carried out. No licence for carrying out a scouting study is required in the Netherlands (potentially except EOR). [CRUST 2001, 7] However, a scouting company would have to negotiate conditions with a landowner. Also, local by-regulation might apply. [CRUST 2001, 8]

Exploration

In contrast to scouting, exploration involves drilling a borehole to examine geological conditions. Under mining legislation (which regulates exploration as a means to search for information and/or existence of minerals) a licence is required for exploration activities concerning minerals, regulating spacial scope and the time period of exploration. However, CCGS does not involve minerals and therefore this legislation does not apply.

Exceptions are possible, though, and environmental law (see below) would likely make acquisition of a licence pre-requisite for exploration activities. [CRUST 2001, 8-9]

Storage

Mining law regulates storage of substances which are not minerals, and would thus likely apply to GS. Underground storage is defined as placing or keeping substances more than 100m under surface. [CRUST 2001, 9]

A licence is definitely required for underground storage. It is obtained from the Ministry of Economic affairs. There can be only one storage licence for a single reservoir. „The grounds for refusing to grant a storage licence are referred to in article 28 of the Mining Act. These include such matters as the capacities and the qualities of the applicant and issues in the interests of safety, national defence and the systematic management of accumulations of minerals or geothermal energy. The licence lays down who the licensee is for which substances, for how long the licence is valid, for which area and whether it relates to permanent or temporary storage (article 29 of the Mining Act). Other restrictions and regulations in the licence may only be based on the three interests referred to above (article 30 of the Mining Act). A number of stipulations in the Mining Act in relation to the storage licence have also been declared to be applicable (article 33 of the Mining Act)." [CRUST 2001, 10]

A landowner can be forced to allow underground storage (>100m depth) on his territory if the licence is given from the Ministry of Economic affairs. [CRUST 2001, 10]

Ownership of the stored substance remains with the owner of that substance before its injection or with the legal successor of that owner. [CRUST 2001, 10]

The owner has duty of care in order to avoid environmental impacts, soil movement, safety harms, and harm of the possibility of systematic retrieval of minerals and geothermal energy. A storage plan has to be submitted and must contain: the start and duration of the storage, the storage method and the activities associated with it, the annual quantity that is assumed, the annual costs of the storage, the movement of soil as a result of the storage (measures have to be taken on this until 5 years after completed injection) and the measures to prevent damage. [CRUST 2001, 11-12; 13]

An environmental impact assessment is required prior to storage. [CRUST 2001, 12-13]

Strict liability for damages associated with underground storage (e.g., soil movement) is with the operator. The Ministry of Economic Affairs, however, can provide financial guarantees for the case of damage. [CRUST 2001, 13] A technical soil movement committee has been set up in the Netherlands to identify causal links between soil movement and extraction/storage activities. It reports to the Ministry of Economic Affairs, the harmed party and company and makes definite recommendations. [CRUST 2001, 13-14]

Mining legislation is enforced and supervised by the Dutch State Supervision of Mines. [CRUST 2001, 14]

A.3.2 Environmental legislation

From the point of view of environmental regulation, there are three main apects relevant for CCGS: Definition of CO_2 as a substance (non-hazardous/hazardous); environmental impact assessment for GS; and soil protection.

Defining CO_2 (wastes)

The CRUST Legal Taskforce [CRUST 2001, 15] states that there is a close link between European and national legislation when it comes to the definition of substances as wastes. As it is currently unclear in EU-legislation whether CO_2 to be stored would defined as waste, the CRUST Task Force analyzed the criteria for defining substances (among them being: origin, the opinion of society, the question of whether another use is possible, the composition of the substance, whether or not it is necessary to take supplementary, special precautions, the application possibilities, and the question of whether the substance has the same characteristics as a primary raw material) in order to assess whether CO_2 would likely be defined as being a waste.

The answer of CRUST is in the positive, that is, CO_2 is likely to be defined as a waste under EU legislation. CO_2 is not likely to be defined as hazardous waste. [CRUST 2001, 17]

The Ministry of Economic Affairs is the authority in charge of waste disposal regulation in the Netherlands. However, a waste disposal activity can only be carried out if the Ministry of Housing, spatial planning and the Environment has stated a declaration of no objections. This does apply for disposal non-hazardous wastes as well as for hazardous wastes. [CRUST 2001, 18-19]

Environmental Impact Assessment (EIA)

For EIA, European Directives are decisive, too. [CRUST 2001, 20] Both setting up an installation for underground waste disposal and deep injection of wastes requires an EIA which has to be appraised by some authority if more than 500,000m^3 of waste are being disposed of. Due to the likely definition of CO_2 as a waste, this would apply to CCGS. [CRUST 2001, 20-21]

The Ministry of Economic Affairs is the authority concerned with EIA for waste disposal and has to take into account the National Waste management plan for its decisions. [CRUST 2001, 21]

Whether or not an EIA is carried out for an underground waste disposal project must be published in several daily (national and local) newspapers, and always in the Netherlands Government Gazette.

Soil protection

Soil protection is handled under duty of care (for this see A.1.5). The respective Dutch legislation is as follows:

> "Everyone carrying out activities on or in the soil as referred to in articles 6 to 11 and who knows or could reasonably have been expected to suspect that these activities can contaminate or harm the soil is obliged to take all measures that can reasonably be required of him in order to prevent this contamination or harm or, if this contamination or harm occurs, to decontaminate the soil or to limit or undo the harm and the immediate consequences as much as possible. If the contamination or harm is the result of an unusual event, the measures are taken immediately." [CRUST 2001, 25]

A distinction is made with respect to responsibility for preventive or curative obligations. The preventive obligation means that activities that pose a threat to the soil are prevented or that soil protective measures are taken and provisions are made. The curative obligation means that any soil contamination that is caused despite the preventive obligation is cleaned up. In this regard the quality of the soil must be completely restored. [CRUST 2001, 25]

A.3 Germany

There is hardly any literature available on regulatory issues of CCGS in Germany. May et al. [2003] state that in Germany underground storage of natural gas is treated in the Bundesberggesetz (§2, Abs. 2.2; §4, Abs.9; §126). CCGS involves the concept of disposal of a substance and could therefore also relate to the Kreislaufwirtschafts- und Abfallgesetz which, however, explicitly excludes gaseous substances contained in sealed tank systems. Also, with respect to aquifer storage and potential leakage into groundwater the federal Wasserhaushaltsgesetz and the states' Landeswassergesetze have to be taken into account. Contamination of groundwater is prohibited. If CCGS as a whole would be regared as a disposal operation, it may be regulated as a disposal facility. Another possibility would be to subsume CCGS under the Bundesimmissionsgesetz, which involves protection of both the atmosphere and groundwater. These juridical and regulatory aspect are all completely unresolved today. It is worth noting though that at Ketzin near Berlin an experimental GS pilot project lead by GFZ Potsdam and funded by EU is to start in 2005. [CO2SINK 2004]

A.3.1 An analogue: natural gas storage

Currently there are 43 natural gas underground storage facilities in Germany. [Sedlacek 2003, 395-398] Their (working) volume is 18,8 billion m^3 on average (V_m). It differs depending on temperature. [Sedlacek 2003, 400] Half of this volume is sited at 4 storage facilities (Rehden, Dötlingen, Epe and Bierwang). [Sedlacek 2003, 400] There is plenty of more potential for underground storage of natural gas in Germany; development of these strucutures mainly depends on developments on the german natural gas market (overall demand, seasonal and daily demand variations, gas prices, optimization of gas purchase). [Sedlacek 2003, 402]

Sedlacek states that Germany is internationally leading in natural gas storage technology. [Sedlacek 2003, 402] Natural gas is stored in empty oil and gas caverns and in aquifers. [Sedlacek 2003, 402] In world-wide comparison, the USA have the most natural gas storage volumes (2/3 of total world capacity), followed by Russia, Ukrainia, and Germany. [Sedlacek 2003, 401]

Sedlacek [2003, 392] states that the processing of relevant data stemming from natural gas/ oil exploration and production, injection of mining process fluids and underground storage of natural gas is regulated by the 'Bundesberggesetz' and the 'Lagerstättengesetz'. According to this legislation, industry is required to report all of its data (seismological-, wellbore-, petrophysical data, studies etc.) to the 'Bergbehörde' or the 'Geologischer Dienst' of the relevant state ('Länder'), which organizes all relevant data in comprehensive geographical and geological data archives in cooperation with the respective authorities of the other german states. [Sedlacek 2003, 394]

A ‘Betriebsplan’ is required for setting up a natural gas storage facility, which has to be delivered to the relevant authority (‘Bergbehörde’ or comparable institution). The ‘Bergbehörden’ decide whether an expertise on mining safety of the storage site is required from the geological services (Geologischen Dienste). [Sedlacek 2003, 394]