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Inducing the International Diffusion of Carbon Capture and Storage Technologies in the Power Sector

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"This report is a revised version of a master thesis submitted to the Department of Environment, Technology and Social Studies at Roskilde University (Denmark) in April 2006."

Abstract:

Although CO_2 capture and storage (CCS) technologies are heatedly debated, many politicians and energy producers consider them to be a possible technical option to mitigate carbon dioxide from large-point sources. Hence, both national and international decision-makers devote a growing amount of capacities and financial resources to CCS in order to develop and demonstrate the technology and enable its broad diffusion.

The presented report concentrates on the influence of policy incentives on CCS diffusion and examines the following research question: *Which policy strategy is needed to stimulate the international diffusion of carbon capture and storage technologies in the power sector?* Based on the analysis of innovation-specific (e.g. CCS competitiveness and compatibility), market-related (e.g. national CO_2 discharges and storage capacities) and institutional determinants (e.g. existing national and international policy frameworks) of CCS diffusion, the paper discusses the suitability of various national and international policy instruments to induce the international deployment of CCS. Afterwards, three CCS diffusion paths are derived from fundamentally different carbon stabilisation scenarios which include climate policy measures to stimulate the adoption of CO_2 mitigation technologies.

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List of Abbreviations

AEP	American Electric Power
Approx.	Approximately
ARC	Australian Research Council
AZEP	Advanced Zero Emissions Power Plant
BBergG	German Bundesberggesetz
BGR	German Federal Institute for Geosciences and Natural Resources
BP	British Petroleum
CAN	Climate Action Network
CARNOT	European Multiannual Programme of Technological Actions Promoting the Clean and Efficient Use of Solid Fuels
CASTOR	CO_2 from Capture to Storage
CATO	CO_2 Capture, Transport and Storage in the Netherlands
CBM	Coalbed Methane
CCCSTN	Canadian CO_2 Capture and Storage Technology Network
CCGT	Combined Cycle Gas Turbine
CCL	British Climate Change Levy
CCP	Carbon Capture Project
CCS	CO_2 Capture and Storage
CDM	Clean Development Mechanism
CDU	Christlich Demokratische Union (Germany)
CENS	CO_2 for Enhanced Oil Recovery in the North Sea
CER	Certified Emission Reductions
CES	Clean Energy System
CETC	CANMET Energy Technology Centre
CFB	Circulating Fluidised Bed
CFT	Clean Fossil Technologies
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2-CRC	Australian Cooperative Research Centre for Greenhouse Gas Technologies
COP	Conference of Parties
CRUST	CO_2 Reduction and Underground Storage

CSLF	Carbon Sequestration Leadership Forum
CUCBM	China United Coalbed Methane Corporation Ltd.
DMT	Deutsche Montan Technologie GmbH
EC	European Commission
ECBM	Enhanced Coalbed Methane Recovery
EGR	Enhanced Gas Recovery
EJ	Exajoules (10^8 Joules)
EnBW	Energie Baden-Württemberg AG
ENCAP	Enhanced Capture of CO_2
EOR	Enhanced Oil Recovery
E&P	Exploration and Production
ETC	EU-Russia Energy Technology Centre
ETS	Emission Trading System
EU	European Union
FDP	Freie Demokratische Partei Deutschlands (Germany)
FGD	Flue Gas Desulphurisation
FY	Fiscal Year
G8	Group of 8
GDP	Gross Domestic Product
GEODISC	Geological Disposal of Carbon Dioxide
GESTCO	Assessing the European Potential for Geological Storage of CO_2 from Fossil Fuel Combustion
GHG	Greenhouse Gas
GNP	Gross National Product
GPN	Gas de France Production Netherlands B.V.
Gt	Gigatonne
GtC	Gigatonne of Carbon
$GtCO_2$	Gigatonne of Carbon Dioxide
GW	Gigawatt
GWh	Gigawatt Hour
H_2	Hydrogen
ICBM	Investigation into the Basic Scientific Phenomena of CO_2 Injection and Retention in Coal for CO_2 Storage and ECBM
IEA	International Energy Agency

IGCC	Integrated Gasification Combined Cycle
IPCC	International Panel on Climate Change
JI	Joint Implementation
JL Group	Jurists and Linguists Group of the OSPAR
Krw/AbfG	German Kreislaufwirtschafts- und Abfallgesetz
LNG	Liquified Natural Gas
LULUCF	Land-Use, Land-Use Change and Forestry
m^3	Cubic Meter
MAC	Marginal Abatement Costs
MCMPR	Australian Ministerial Council on Mineral and Petroleum Resources
MEA	Monoethanolamine
MESSAGE	Model of Energy Supply Strategy Alternatives and their General Environmental Impact
MOFCOM	Chinese Ministry of Commerce
MOP	Conference of the Parties to the United Nations Framework Convention on Climate Change serving as the Meeting of the Parties to the Kyoto Protocol
MOST	Chinese Ministry of Science and Technology
Mt	Millions of Tonnes
MW	Megawatt
MWh	Megawatt Hour
MW_{el}	Megawatt Electric
MW_{th}	Megawatt Thermal
N_2	Nitrogen
NASCENT	Natural Analogues by the Geological Storage of CO_2
NDRC	Chinese National Development and Reform Commission
NGCAS	The Development of Next Generation Technology for the Capture and Geological Storage of Carbon Dioxide from Combustion Processes
NGCC	Natural Gas Combined Cycle
NGO	Non-Governmental Organisation
NGS	Natural Gas Storage
NO_x	Oxides of Nitrogen
NSPS	U.S. New Source Performance Standards
NZEC	European-Chinese ‘Near Zero Emissions Coal’ project

O_2	Oxygen
OECD	Organisation for Economic Cooperation and Development
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
PC	Pulverised Coal
PDS	Partei des Demokratischen Sozialismus (Germany)
PICOR	Pléage du CO_2 dans les Reservoirs
ppmv	Parts Per Million by Volume (10^{12})
PPP	Purchasing Power Parity
RECOPOL	Reduction of CO_2 Emissions by Means of CO_2 Storage in Coal Seams in the Silesian Coal Basin of Poland
R&D	Research and Development
RD&D	Research, Development and Demonstration
RGGI	Regional Greenhouse Gas Initiative
RWE	Rheinisch-Westfälische Elektrizitätswerke
SEPCA	Sotacarbo Project on Hydrogen and Energy Production from Sulcis Coal
SO_2	Sulphur Dioxide
SPD	Sozialdemokratische Partei Deutschlands (Germany)
SRES	Special Report on Emission Scenarios
TAR	Third Assessment Report of the IPCC
Tcf	Trillion Cubic Feet
t/d	Tonnes per Day
TPES	Total Primary Energy Supply
TWh	Terawatt Hour
UBA	German Federal Environmental Agency
UIC	United States Federal Underground Injection Control Programme
UK	United Kingdom
UK DTI	United Kingdom Department of Trade and Industry
UN	United Nations
UNCLOS	United Nations Convention in the Law of the Sea
UNFCC	United Nations Framework Convention on Climate Change
U.S.	United States
U.S. DOE	United States Department of Energy

U.S. EIA	United States Energy Information Administration
U.S. EPA	United States Environmental Protection Agency
U.S. NDRC	United States National Resources Defense Council
VGB	Verband der Großkessel-Besitzer e.V.
VTI	All Russian Thermal Engineering Institute
WBGU	Wissenschaftlicher Beirat der Bundesregierung für Globale Umweltveränderungen (Germany)
ZEPP	Zero Emission Power Plants
ZJ	Zetajoule (10^{21} Joules)

1 Introduction

A new technological option for carbon mitigation is gaining public attention: CO_2 capture and storage (CCS). CCS includes the removal of carbon dioxide from large-point CO_2 sources, its transfer to a storage site and disposal into geological formations. Advocates consider the technology as a bridge towards a sustainable energy system. However, CCS is highly controversial as it merely removes CO_2 instead of avoiding it. The technology prolongs the dominance of fossil fuels and risks concerning the environmental impacts and permanence of underground CO_2 storage are still unclear. Therefore, a large number of researchers doubt that CCS may actually become a large-scale carbon mitigation option.

Despite high technical, environmental and economic uncertainties, policymakers around the world devote a growing amount of capacities and financial resources to carbon capture and storage technologies. At the national level, CCS technologies have become a prominent element of several climate strategies. At the international level, political, industrial and academic representatives have formed technology platforms, such as the Carbon Sequestration Leadership Forum (CSLF), which develop detailed technology roadmaps. The broad variety of activities demonstrates that political and economic forces take concerted actions to stimulate the diffusion of CCS.

International CCS diffusion is the subject of interest of this paper. Since most ongoing related activities concentrate on technology research, development and demonstration (RD&D), this report focuses on the political incentives required for a broad deployment of carbon capture and storage technologies. The study seeks to answer the following problem formulation: *Which policy strategy is needed to stimulate the international diffusion of carbon capture and storage technologies in the power sector?* The power generation industry has been selected as a focal point since it is the single largest source of emissions and, thus, a prime candidate for CO_2 removal.

Addressing the planning dimension of CCS diffusion, the study develops policy recommendations for national and international political decision-makers (chapter 4). Their impacts are analysed in three divergent CCS diffusion paths (chapter 5). Both sections are founded on a detailed investigation of current conditions for the dissemination of carbon capture and storage technologies (chapter 3). Recognising that technology diffusion processes are influenced by technical and non-technical determinants, the chapter considers the following parameters of CCS diffusion: techno-economic parameters of different carbon capture and storage methods (chapter 3.1), specific parameters of possible national CCS lead markets (chapter 3.2) and institutional parameters, such as national and international CCS-related regulations, policies and technology initiatives (chapter 3.3).

Each parameter comprises a group of sub-determinants which have been identified in chapter 2. Chapter 2 includes an introduction to the overall concept of technological change and develops an analytical framework which functions as the investigation's conceptual basis.

2 Theoretical Determinants of the Successful Diffusion of Carbon Capture and Storage Technologies

This chapter aims to build an analytical framework for the analysis of the problem formulation. It discusses crucial definitions (chapter 2.1), the concept of technological change (chapter 2.2) and determinants of technology diffusion processes (chapter 2.3). Chapter 2.4 gives a brief introduction to the rationale of carbon stabilisation scenarios.

2.1 Technology Definitions

Dealing with the diffusion of carbon capture and sequestration technologies, this project report implies a technology-specific perspective. Today, technologies are widely recognised as an important means of progress in industrialised countries. They both consist of software, such as knowledge, and hardware, such as physical items, and may be defined as “the knowledge, experience, know-how, and physical equipment or facilities which can create certain products or produce new types of products and services” (Frankel 1990: 5).

With regard to their field of research, students of environmental studies apply a more environmentally-specific explanation of the term technology. Environmental technologies are defined as “each technique, process or product which conserves or restores environmental qualities” (Kemp 1997: 11). Among different types of environmental technologies[1], carbon capture and storage technologies have to be grouped into the category of end-of-pipe technologies which “prevent the direct release of emissions in the air, surface waters or oil” (op. cit.). They are also known as abatement or add-on technologies since they do not avoid or alleviate the production of hazardous emissions during industrial procedures. Carbon capture and storage processes are added to processes such as power production in order to separate and sequester generated CO_2 emissions.

[1] Kemp distinguishes six categories of environmental technologies (Kemp 1997: 11): End-of-pipe-technologies (see above), waste management (handling, treatment and disposal of waste), clean technologies (process-integrated reduction of pollutants), clean products (imply a cleaner technology life cycle), clean-up technology (include remediation technologies such as air purifiers) and recycling (re-usage of materials from waste streams).

2.2 The Concept of Technological Change

As end-of-pipe solutions aim at improving existing technologies, they may serve as an example of technological change. Technologies have a dynamic nature and are object of permanent progress since researchers, developers and companies are seeking to optimise existing designs or to create new ideas. The phenomenon is widely considered as an important driver for economic growth and can be described as a gradual, cumulative, interactive and non-linear process. Experts commonly distinguish among four stages of change:

Invention: "The discovery of a new product, process, material, service or method" (Frankel 1990: 69/70) resulting from research and development (R&D) activities or chance discovery.

Innovation: "The development of an idea, invention or discovery towards commercial exploitation by improving its ability to serve market demands (op. cit.: 5). Innovations may be completely new technologies which lead to radical industrial changes (radical innovations) or optimisations of existing technologies, including minor and major improvements (incremental innovations) (Strahl 1991: 31).

Niche Market Commercialisation: A phase in which innovations are tried out and tested on a limited scale (Christiansen 2001: 8), such as private or public demonstration projects. Niche markets lead to learning-by-doing effects about a technology's use and may result in so-called feedback effects which modify and enhance the original innovation (Hall 2005: 460).

Diffusion: "The process by which individuals and firms in a society/economy adopt a new technology, or replace an older technology with a newer" (op. cit.). Diffusion processes are intertwined with the innovation stage and do as well show the phenomenon of feedback mechanisms. This report focuses on the stage of technology diffusion and will investigate parameters of this process with regard to CCS technologies.

2.3 Determinants of Technology Diffusion Processes

In the following sections, three technology diffusion processes - the cases of combined cycle gas turbine technology, flue gas desulphurisation technology and natural gas storage – will exemplify what kind of parameters do affect a technology's market spread. Afterwards, the identified parameters are used to build a framework for the analysis of CCS diffusion.

2.3.1 Three Diffusion Case Studies

2.3.1.1 The Diffusion of Combined Cycle Gas Turbine Technology

The market spread of combined cycle gas turbine technologies (CCGT) is an excellent example for the successful diffusion of large-scale energy technologies[2]. At the end of 2001, 360 Gigawatts (GW) of CCGT capacity were in operation or under construction worldwide (Watson 2004: 1069). How did the diffusion of CCGT proceed and what were the main determinants of the process?

CCGT power generating technology was developed in the 1950s and commercialised at a niche market level of certain base power stations and certain semi-base power stations in the early 1970s (Islas 1997: 58). In the following years, resulting from several technical improvements and a complex set of determinants, CCGT diffusion gradually accelerated.

Individual technical features were the main drivers of the process. Over the years, CCGT improved its *competitiveness* towards conventional fossil-fired steam plants as the technology has excellent starting-up capabilities and is less capital-intensive than most other generating options. Furthermore, CCGT designs have a comparatively good *environmental performance* due to their high efficiency. By the end of the 1980s, steady gains in efficiency outweighed concerns about reliability and maturity (Watson 2001: 14). Both factors were continuously improved as the technology's rate of adoption increased in the following years. Today, CCGT technologies are well-proven and operate at efficiencies (approx. 58%) which supersede those of conventional plants by about 10% (UBA 2003: 28).

Besides being competitive, the application of gas turbines in aircrafts and power plants indicates a high "interpretative flexibility" and *technical compatibility* (op. cit.: 17). The development and deployment of CCGT significantly benefited from rapid technical improvements and highly funded R&D programmes in the aircraft sector during the 1970s which provided continuous *learning-by-doing* effects and increasing *practical experiences* with gas turbines and CCGT processes (Islas 1997: 62).

During the 1960s and 1970s, the interest in CCGT grew as a consequence of sudden ***external events***. Because of power blackouts in the UK and North America, utilities installed emergency gas turbines to restore electricity supply. The increasing demand encouraged equipment manufacturers to improve their designs, which eventually led to the emergence of the CCGT technology (Watson 2001: 10). Hence, a *technology's availability* at the time of decisive external developments has a high influence on its progress and deployment.

2 The technical principle of CCGT is simple: Natural gas is burned in a gas turbine to generate electricity and waste heat. In a heat recovery boiler, the latter is transformed into steam which is then used to drive a small steam turbine and produce some more electricity.

Institutional factors, both at the *international* and *national level*, fostered the popularisation of CCGT devices. As CCGT plants are more environmentally benign than conventional fossil-fired plants, the growing prominence of global climate policy encouraged their diffusion. At the national level, related policies – for instance the liberalisation of national energy sectors – stimulated CCGT adoption due to their technical and economic advantages.

In addition to government support, diffusion was fostered by ***actor- and market-related factors***, such as the *high competence* and *capacities* of major equipment manufacturers like Siemens or General Electric and the existence of cross-industrial *knowledge networks* among the aircraft and electricity industries.

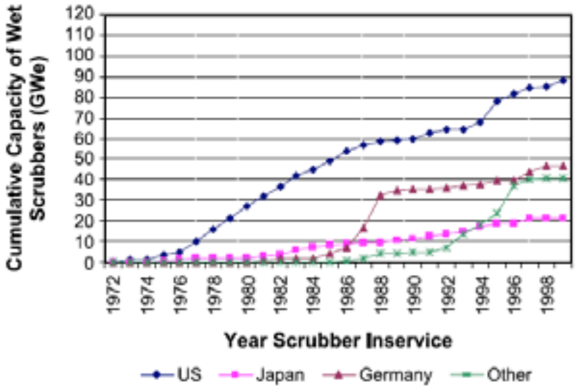
2.3.1.2 The Diffusion of Flue Gas Desulphurisation Technology

The deployment process of Flue Gas Desulphurisation (FGD) technologies is relevant for CCS diffusion as both technologies have an end-of-pipe-character. Since the mid-1990s, post-combustion FGD is well established and currently being applied in 27 countries[3]. In 1926, FGD devices were firstly applied in the Battersea, Bankside and Fulham power stations in London but paused at a niche market stage due the technology's high costs, insufficient reliability and maturity and a lack of political incentives (Taylor et al 2005: 355). In the U.S., the issue of air pollution control gained political relevance during the 1950s and 1960s, but efforts to reduce SO_2 emissions concentrated on pre-combustion reduction of sulphur from fuels and the construction of tall gas stacks. At the beginning of the 1970s, the focus shifted to post-combustion FGD technologies and the U.S. became the main driver of FGD diffusion.

FGD diffusion was decisively stimulated by ***national institutional framework conditions*** which usually implied a *command-and-control character*. The 1970 and 1977 U.S. Clean Air Act Amendments established strict SO_2 emission limits and performance standards. In 1979, the New Source Performance Standards (NSPS) required a 70 to 90% reduction of potential SO_2 emissions for new plants built after 1978. These air pollution control regulations created a national market for FGD technologies and stimulated intense research, development and demonstration activities (Taylor et al 2003: 4530). In other countries, similar regulatory approaches were adopted at the same time (e.g. Japan) or a few years later (e.g. Germany) (Popp 2004: 9/10). From the mid-1980s, ***international institutional framework conditions,*** especially the new prominence of international environmental policy, and an ***external event*** like the increasing awareness of acid rain improved the overall climate for FGD deployment.

[3] FGD technologies, otherwise known as post-combustion control technologies, contact a post-combustion gas stream with a base reagent in an absorber in order to remove SO_2. Depending on the moisture level of the waste material and the flue gas leaving the absorber, FGD technologies can be classified as 'wet' or 'dry' systems (Taylor et al 2005: 355).

Figure 2-1 Cumulative Installed Capacity of Wet Lime or Limestone Scrubbers



Source: Riahi et al 2004: 542

The growing interest in post-combustion FGD technologies was accompanied by RD&D efforts aiming to gain *experiences* and optimise FGD's technical and economic ***innovation features***. The U.S. government and private companies set up research, training, technical assistance and demonstration projects which provided *learning-by-doing effects* and considerable improvements in the *costs*, *reliability*, *maturity*, *efficiency* and *environmental performance* of FGD technologies. Whereas early designs of the 1970s removed, in average, less than 80% of the SO_2 produced in U.S. power plants, devices developed in the mid-1990s removed about 90%. At the same time, capital costs decreased by a factor of two (op. cit.). Today, FGD systems are routinely designed for SO_2 removal efficiencies in the range of 95 to 98% or more. Reliability has not been an issue for over a decade (Taylor et al 2003: 4532).

The described effects of air pollution policies and technology initiatives show that, within the range of ***actors*** involved in FGD diffusion, national governments played a key role. At the firm's side, FGD manufacturers and power companies were the most important forces. Unlike CCGT deployment, FGD diffusion was dominated by *competent* and *prosperous* but rather *domestic companies* which responded to stricter national environmental standards (Popp 2004: 23) and formed a well connected FGD 'community' (op. cit.: 4533).

2.3.1.3 The Diffusion of Underground Natural Gas Storage

The international deployment of underground natural gas storage is highly relevant for the analysis of CCS diffusion as the utilised technologies and storage types are largely identical with CO_2 injection and storage processes[4]. The first underground gas storage was operated in North America in 1915 (Sedlacek 2002: 499). In the following years, NGS experienced rapid deployment in the United States and, in the late 1940s, the

4 Generally, natural gas may be stored in three types of underground reservoirs: Depleted reservoir storage, aquifer storage and salt cavern storage. Depleted gas fields constitute the most favourable option, both in economic and geological terms.

development spilled-over to Europe. In 1949, the first European underground gas storage was put into operation in Gifhorn, Germany. Along with the gradual emergence of national gas markets, the diffusion of NGS proceeded. At the time being, more than 630 natural gas storages are in operation at a global level (op. cit.: 503).

Institutional aspects and public authorities did not have a strong influence on NGS deployment (Interview H. Øbro, 1.12.2005: 24). Instead, diffusion was decisively stimulated by firms due to favourable ***economic and technical innovation features***. Firstly, natural gas storages indicate a high *competitiveness* towards alternative storage options, such as gas tanks, since many storage sites (e.g. depleted gas fields) entail comparatively low costs for drilling and operation and are capable of storing much higher amounts of gas than tanks (op.cit.: 22). Furthermore, NGS outweighs gaps among steady gas transmission through pipeline systems on the one hand and unstable gas demand on the other hand. Consequently, the technology is particularly useful on gas markets which are characterised by long distances among centres of gas production and consumption or a high share of gas imports (***market-related factors***). Another relevant market-specific aspect is the availability of suitable geological formations which decisively affects the amount of stored natural gas.

Besides economic and market-related factors, the deployment of natural gas injection procedures was fostered by a *high compatibility* with existing technologies. At most storage sites, the same devices which are applied in natural gas exploration and production processes may be utilised for the injection of gas into geological formations. Consequently, NGS processes include technologies which are *mature* and *reliable*. Several **actors** involved in early natural gas storage projects already had significant *experiences* with the applied technologies and, hence, did not face significant technical barriers.

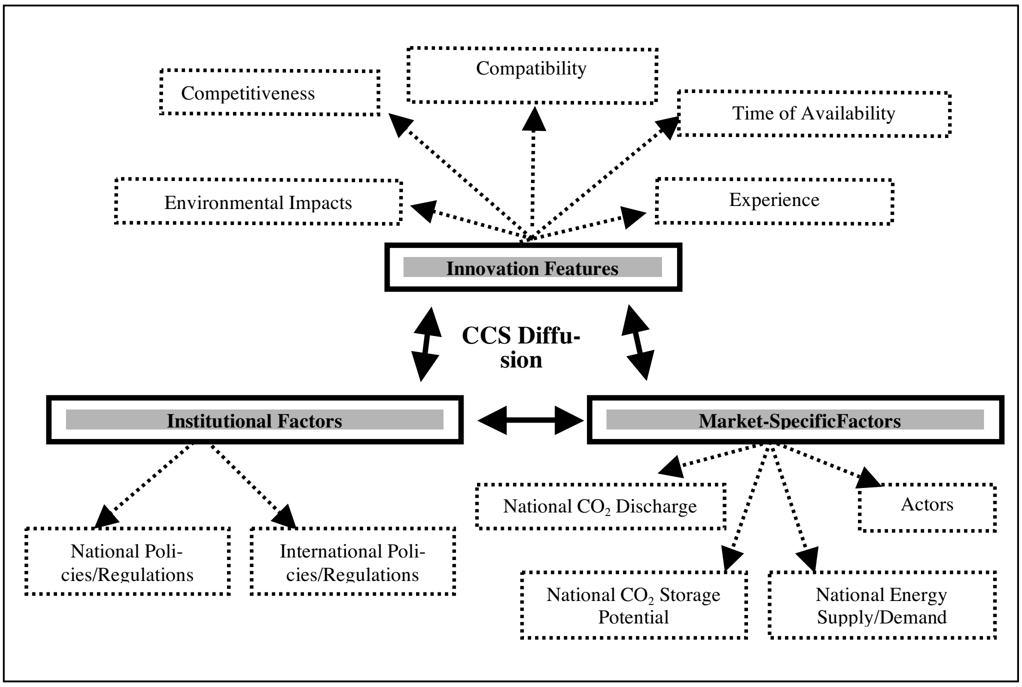
Contrary, the *environmental impacts* of natural gas storage projects continuously arouse concerns of residents and influence the acceptance of NGS (Interview R. Sedlacek, 5.12.2005: 28/29). However, public protests did not decisively hamper NGS deployment which is partly attributable to its temporary character and intensive efforts of storage operators to inform the public about possible impacts and risks (Interview N. Tegethoff, 12.12.2005: 56). With respect to CO_2 storage, it may be recognised that informational measures can considerably alleviate public concerns.

2.3.2 Determinants of CCS Diffusion: Building an Analytical Framework

The presented cases of technology diffusion indicate that the deployment of energy technologies is determined by an innovation's individual features, institutional aspects, involved actor- and market-related factors and external events. In the following paragraphs, these parameters will be used to establish a systemic and interactive analytical framework for the investigation of CCS diffusion. Besides CCGT, FGD and NGS diffusion, the framework will be conceptually based on Everett Rogers' study 'Diffusion of Innovations' and the family of innovation system approaches. However, as carbon capture and storage technologies imply some very specific issues, it is adapted to the individual characteristics of CCS diffusion.

Investigating CCS technologies is particularly complicated as they include two technical stages – carbon capture and carbon storage – which show divergent characteristics and include several different technical options. Nonetheless, both processes are complementary goods which are inevitably interdependent and whose deployment determinants cumulate to a common set of interrelated diffusion parameters. For example, if the costs of storing carbon dioxide in a depleted oil field are competitive but carbon capture technologies for power plants are highly uneconomic, the overall innovation features of carbon capture and storage from power plants are rather negative. Figure 3-2 illustrates the chosen analytical framework. External events are sudden historical events, such as the oil crisis or a series of power blackouts like in the case of CCGT. They may provide windows of opportunity for diffusion but can hardly be anticipated. Hence, this aspect will not be discussed in more detail.

Figure 2-2 Analytical Framework



2.3.2.1 Innovation Features

The diffusion processes of CCGT, FGD and NGS show that individual characteristics of innovations have a strong influence on their path of diffusion. As mentioned above, the innovation features of CCS are shaped by both the specific characteristics of capture and storage technologies, requiring a well thought out and detailed analysis. With respect to that fact and the presented case studies, the following innovation features are considered as relevant for CCS deployment:

Competitiveness

The courses of CCGT, FGD and NGS deployment indicate that the degree to which an innovation's technical and economic characteristics are capable of competing with incumbent technologies or other carbon mitigation options is the key to diffusion.

Because most large-scale energy technologies are very capital-intensive, economic terms – such as benefits and costs of adopting carbon capture and storage technologies – have a strong effect on their deployment. The factors maturity, efficiency and reliability are important determinants of technology popularisation. Those issues are also crucial for the adoption of carbon capture and storage technologies because most energy utilities fear economic and technical risks. A lack of maturity and reliability may result in unscheduled breakdowns or long maintenance periods of capture or storage equipment and entail high economic losses. Higher efficiency rates of capture processes are an essential prerequisite to CCS deployment as the technology causes considerable energy penalties[5].

Compatibility
The development of CCGT devices was decisively fostered by the fact that, due to their high compatibility and flexibility, both aircraft and electricity companies were involved in the development and demonstration of gas turbine technologies. Concerning CCS, the term 'compatibility' may be interpreted in a technological and a sociological sense (Rogers 1984: 15). From a technological perspective, it is important that carbon capture technologies are capable of retrofitting existing facilities and can be applied in different types of power plants (e.g. IGCC, PC and NGCC plants). From a sociological perspective, CCS may be incompatible with the values and norms of important actors like national governments in case they prefer clean energy technologies (e.g. renewable energies).

Environmental Impacts
The example of NGS deployment points out that the environmental impacts of underground storage may provoke public opposition which could delay or prevent technology projects. This shows that the environmental performance of energy technologies is a decisive determinant of diffusion. In the case of carbon capture and storage technologies, the remediation of environmental risks, like the possibility of abrupt or gradual leakage at CO_2 transportation or storage facilities, is an important condition for diffusion as CO_2 storage may otherwise not achieve a high degree of social acceptance.

Experience
The case of CCGT popularisation demonstrates that technology diffusion strongly depends on learning and feedback-effects which result from experience and contribute to an innovation's continuous adaptation to practical needs (Hall 2005: 460). Since CCS technologies are highly complex designs which are at an early stage of development, practical experiences play an essential role in reducing investment risks. Hence, successful CCS diffusion requires intensive research, development and demonstration efforts in order to provide technology-specific expertise, to reduce investment risks and optimise existing CCS devices.

[5] The term 'energy penalty' is understood as the additional amount of fossil-fuel energy needed to generate a fixed output of electricity with CCS compared to the generation without CCS.

Time of Availability

The time of availability of energy innovations functions as an important driver or barrier to diffusion as they are part of highly capital-intensive power generation facilities, which are retrofitted or replaced in long-term investment cycles. If a technology is available when an external event boosts technology demand (e.g. the installation of emergency gas turbines after a series of black-outs in the 1960s), its diffusion may accelerate. For example, if a country has to replace large shares of the installed electricity generating capacity, a window of opportunity for the broad adoption of innovative power plant equipment occurs in case the technology is ready for diffusion. Windows of opportunity refer to “the temporary existence of circumstances that allow novelty to get selected” (Zundel et al: 21/22). If a technology does not fulfil the demands of investors within such a period of enhanced opportunities, its deployment is likely to be held up.

2.3.2.2 Market-Specific Factors

More than CCGT and FGD technologies, the deployment of carbon capture and storage processes depends on market-specific factors. Market-specific factors depict the individual conditions for CCS diffusion in a country or a certain region which decisively determine the velocity and extent of the technology’s application. In combination with other CCS diffusion parameters, like technical features and institutional conditions, positive market-specific factors may strongly contribute to favourable national framework conditions for the adoption of carbon capture and storage technologies and form so-called lead markets – countries “where a globally successful innovation first took off” (Beise 2004: 998). With respect to CCS technologies, the following market-specific factors need to be considered:

National Energy Supply and Demand

It is widely accepted that countries with a fossil-centred energy supply, especially those displaying a high share of coal in electricity generation, high domestic fossil reservoirs and a growing energy demand (e.g. China), have a strong interest in developing and deploying carbon capture and storage technologies. Being compatible with centralised and fossil-centred electricity generating structures, CCS allows these countries to reform the power sector in line with incumbent path dependencies and avoids a radical transformation of the energy system. For example, the U.S. administration strongly advocates carbon removal at coal-fired power plants as it aims to continue domestic coal combustion and to maintain a large-scale electricity infrastructure despite CO_2 constraints. Another important aspect is the age and technological standard of a country’s power plant fleet which is closely related to the technical diffusion parameters ‘compatibility’ and ‘time of availability’. If the national technology mix does not indicate a sufficiently advanced level and the average age of power plants does not correspond to the availability of CCS, the application of carbon capture and storage technology may be considerably delayed.

National CO_2 Discharge
Since CCS technologies are mainly suited to large-point sources of CO_2 emissions, the technology is an important option for countries with a significant concentration of large and strongly polluting industrial facilities and power stations. Consequently, CCS is most likely to be applied in highly carbonised world regions.

National CO_2 Storage Potential
The extent and temporary dimension of CCS diffusion and application is deeply determined by a country's geological conditions, namely its carbon dioxide storage potential. Even if a nation shows significant fossil-centred path dependencies and a high number of large-point CO_2 sources, CCS deployment is restrained in case available geological formations enable only a limited injection of carbon dioxide. For example, Japan locates a high number of polluting fossil-fired power plants and is very interested in applying CCS but the prospects for deployment are rather negative due to a small number of sites suitable for geological sequestration (Dooley et al 2004: 3). In addition to the quantity of sites, the types of available storage options determine the economic viability of CCS. A country with a high potential of enhanced recovery options, such as EOR, ECBM or EGR, is likely to deploy the technology sooner than countries which need to implement costly storage methods, like CO_2 injection into saline aquifers, which do not entail economic benefits.

Actors
The deployment of FGD, CCGT and NGS technologies demonstrates that diffusion processes decisively depend on the commitment and positions of political actors (e.g. national governments), private entities (e.g. electricity utilities) and, in case of controversial processes like natural gas storage, societal actors (e.g. NGOs and the public). Political and private actors carry through innovations and are deeply involved in research, development and demonstration efforts, aiming to optimise a technology. Public units are, however, oriented towards overall societal goals, e.g. a sustainable energy system, and have the formal power of decision on some of the framework conditions that may reduce uncertainty inherent to investments in innovative technologies like CCS (Fischer et al 2005: 9). Private companies are mainly motivated by the objective of making profits and are highly relevant forces in creating demand for innovations and adapting them to market conditions.

Deployment processes are affected by the following actor-related features:

- ***Economic Competence:*** An actor's capability to generate business opportunities, to perceive new opportunities, to learn from success and failure and to take the appropriate risks (Carlsson et al 1991: 101).
- ***Capacities:*** The knowledge, financial and personnel resources and political or societal power of involved actors may decisively speed up technology optimisation and diffusion. For example, the high technical knowledge of major power equipment manufacturers in turbine designs fostered the deployment of CCGT technologies.
- ***Networks***: Interactions and communication among actors through technology-specific knowledge networks or platforms constitute an important determinant of

diffusion. This is also true with respect to the international stage, where stable communication channels are particularly meaningful.

- ***Technology Preferences***: The behaviour of actors involved in diffusion processes may imply preferences for certain technologies. For example, green parties or environmental NGOs are likely to reject CCS as a carbon mitigation option since it might inhibit the deployment of renewable technologies.

2.3.2.3 Institutional Factors

The driving forces of CCGT and FGD diffusion prove that technology deployment may be strongly fostered by an institutional framework of national and international policies. Institutions affect the rules of regulating interactions between actors and the formation of markets and, therefore, are capable of either supporting or inhibiting technology diffusion. Government intervention into technology diffusion processes occurs when market mechanisms fail to achieve the desired deployment of a technology (market failure), if existing regulations favour inefficient technologies (institutional failure) or in case there are no sufficient knowledge networks in place which deal with innovative technologies like carbon capture and storage (network failure) (Carlsson et al 1997: 307).

Analysing CCS diffusion, it may be distinguished among policies and regulations at the international and national level.

- ***International Level:*** CCS development and deployment are mainly affected by international climate policies which lay the foundation for national carbon mitigation strategies. Offshore carbon storage activities are furthermore covered by regulations on industrial waste dumping at sea (e.g. the London Convention).
- ***National Level:*** At the national level, various policy fields, for example environmental policy, energy policy, research policy or technology policy, constitute the institutional framework for CCS diffusion.

Both international and national policies apply so-called policy instruments in order to achieve their aim. Policy instruments are defined as means by which policy makers "attempt to put policies into effect" (Howlett/Ramesh 1995: 80). According to the extent of state presence, different categories of policy instruments suitable for stimulating environmentally benign technology diffusion may be distinguished (see table 2-1):

Command-and-Control-Instruments
Command-and-control instruments (direct regulations) are used to mandate certain behaviour. In the case of FGD diffusion in the United States, direct regulations were particularly useful since the technology does not entail additional economic benefits. Command-and-control instruments do, however, not necessarily promote cost-effective technology solutions and may provoke disputes among regulating and regulated actors.

Economic and Market-Based Instruments
Market-based instruments induce – rather than to mandate or command – behavioural (and technological) changes by providing financial or similar motivations. Financial incentives create demand for innovations and are expected to play an important role in

CCS deployment, as the technology implies considerable investment costs and energy penalties.

Technology Initiatives
Technology initiatives include research, development and demonstration projects and create opportunities to gain experiences of an innovation's practical applicability. As CCS is at an early stage of development, extensive demonstration and testing activities are needed to achieve technical improvements, reduce uncertainties and carry the technology to a large scale.

Informational Instruments
They address information problems related to products and processes. CCS platforms or workshops contribute to steady knowledge transfers and may increase the technology's social acceptance. Nevertheless, communication instruments are only useful as additional means, not as substitutes for regulations or market-based instruments (Kemp 1997: 321).

Table 2-1 Categories of National and International Policy Instruments for Carbon Mitigation

Category	**Instruments**		**Extent of State Presence**
	National Instruments	**International Instruments**	
Command-and-Control-Instruments	Non-tradable permit system; Technology standards; Performance standards; Product bans	Non-tradable quotas; International performance standards; International technology standards; International product bans	**High**
Market-Based Instruments	Emission or carbon taxes; Tradable permit (cap-and-trade) systems; Direct subsidies; Indirect subsidies (feed-in tariffs, tax exemptions); Deposit-refund systems	Tradable quota system; Harmonised energy or carbon taxes; Common energy or carbon tax;	**Medium**
Technology Initiatives	Technology-specific government spending and investment (R&D); State-funded demonstration projects	International technology-specific funds; CDM projects; JI projects; Other technology transfer programmes	**Medium**
Informational Instruments	Networks; Capacity-building programmes; Voluntary agreements	International technology networks or forums; International voluntary agreements; International capacity-building efforts	**Low**

Source: IPCC 2001: 404-405

2.4 The Nature and Rationale of Carbon Stabilisation Scenarios

The developed analytical framework serves as a conceptual basis for the investigation of current conditions for CCS diffusion (chapter 3) and the selection of optional policy instruments to foster the deployment process (chapter 4). Aiming to sketch divergent CCS diffusion paths, the analysis of the given parameters is supplemented by a discussion of three different carbon mitigation scenarios (chapter 5). However, the lion's share of the analysis is based on the investigation of determinants of CCS deployment which is why the concept of scenarios is only briefly introduced in the following lines.

Scenarios are defined as "internally consistent and reproducible image(s) of the future" (Schrattenholzer et al 2004: 9). They are neither a precondition nor a forecast as they do not necessarily aspire to maximise the likelihood of their occurrence (op. cit.). Instead, they assume a basic framework of driving indicators (e.g. population growth, economic development, energy demand) and perpetuate these developments up to a certain timeframe. The generation and discussion of scenarios may be conducted either in a qualitative manner through narrative models or a quantitative way, implying the development of mathematic models. Some scenarios, for example the IPCC Special Report on Emissions Scenarios (SRES), contain both narrative storylines and quantitative elements.

The discussion of possible CCS diffusion paths is founded on three families of the SRES scenarios which will be subsequently fitted with a carbon stabilisation target and, thus, function as so-called carbon stabilisation scenarios. Stabilisation scenarios aim at a pre-specified GHG reduction target which is "the concentration of CO_2 or the CO_2-equivalent concentration of a 'basket' of gases by 2100 or at some later date when atmospheric stabilisation is actually reached" (IPCC 2001: 122). The choice of the stabilisation target will be derived from the investigation of preconditions for international CCS diffusion and points out what extent of climate mitigation is assumed to be demanded for achieving the technology's broad dissemination. Embedding one stabilisation target into three divergent energy futures furthermore takes into account other deployment parameters, such as fossil-centred or sustainable path dependencies, and enables the investigation of CCS deployment under different conditions.

The scenario discussion does, however, not include detailed quantitative calculations. Instead, it presents estimations of the future diffusion of CCS technologies which have been derived from existing data about their deployment and a qualitative analysis. Thus, chapter 5 only describes a rough tendency of possible CCS diffusion paths.

3 Current Conditions for the International Diffusion of CCS

3.1 Innovation Features of Carbon Capture and Storage Technologies

Carbon dioxide capture and storage is a process consisting of separation of CO_2 from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere (IPCC 2005a: 54). Consequently, CCS may be denoted as a systemic technology consisting of three stages. Because of its limited scope, the given report concentrates on carbon capture and storage as these steps imply major techno-economic and institutional challenges to CCS diffusion. The stage of CO_2 transport[6] is not subject of this thesis.

Carbon capture and storage technologies are highly controversial due to possible negative environmental impacts and eventual constraints on the diffusion of renewable energy technologies. Contrary, CCS advocates argue that the technology may achieve a considerable reduction of carbon dioxide emissions from fossil-fuelled sources. In awareness of these controversial positions, the following chapters investigate the innovation features of carbon capture and storage technologies to describe the technical conditions for CCS diffusion.

3.1.1 Carbon Capture Technologies for Power Plants

Capturing CO_2 is best carried out at large-point sources of emissions, such as power stations, oil and gas processing plants or cement works. Worldwide, there are about 7.584 large-point sources, discharging approximately 13.375 $MtCO_2$/year (op. cit.: 81). With a share of 10.539 $MtCO_2$/year emitted by 4.942 facilities, power generation is by far the major polluter and a prime candidate for CO_2 capture. Hence, the presented investigation of carbon capture innovation features concentrates on capture technologies for power plants – although industrial processes, such as ammonia production, offer cost-effective early opportunities for post-combustion capture due to high CO_2 concentrations in the flue gas. In the following sections, it is distinguished among three CO_2 capture methods: post-combustion capture, pre-combustion capture and oxy-fuel combustion.[7]

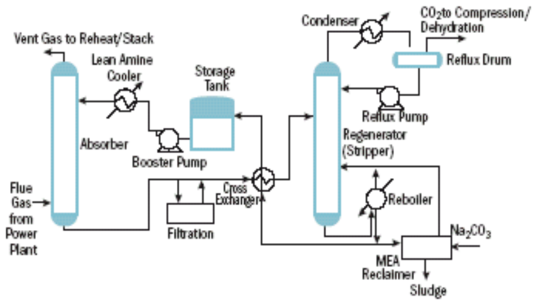
6 CO_2 transport links sources and storage sites. Long-distance movement of CO_2 in pipelines is part of current practice. The CO_2 stream ought to be dry and free of hydrogen to diminish corrosion. There is no indication that CO_2 transport is more challenging than the transfer of hydrocarbons. However, it needs to be recognised that a broad application of CCS entails an immense amount of CO_2 to be transported which requires considerable infrastructure investments. Depending on the mass flow rate, costs of CO_2 transport in offshore and onshore pipelines range from US$ 1–6 per 250 km (IPCC 2005a: 192). Liquefied CO_2 may be furthermore transported by marine tankers similar to liquefied natural gas and petroleum gases. Costs of ship transport are estimated to range from about US$ 7–28 for distances of 200–5000 km (op. cit.). Whereas technical indicators of CO_2 transport do not constitute noteworthy barriers to CCS diffusion, the formal approval, implementation and acceptance of pipeline projects could impede CCS diffusion. For detailed information, it is referred to chapter 4 of the IPCC Special Report on CCS.

7 There are several other, so-called 'novel' concepts for carbon capture which constitute long-term options. These technologies are not a subject of this study. For a brief overview, it is referred to the 2002 IEA Technology Status Report 'Solutions for the 21st Century - Zero Emissions Technologies for Fossil Fuels'.

3.1.1.1 Post-Combustion Capture Technologies

In post-combustion capture processes, CO_2 is separated from the flue gas. The CO_2 concentration in power station flue gases ranges from 4% for natural gas-fired combined cycle (NGCC) plants to about 14% for pulverised coal-fired boilers (Thambimuthu et al 2002: 32). Depending on the concentration rates and the partial pressure of CO_2, either chemical absorption in combination with heat-induced CO_2 recovery or physical absorption in combination with pressure-induced CO_2 recovery may be applied to capture carbon dioxide. Post-combustion capture is usually carried out through chemical absorption which is not sensitive to low CO_2 concentration rates (less than 10%) and partial pressures[8]. The flue gas is scrubbed with an amine solution, mostly monoethanolamine (MEA), which selectively absorbs the CO_2 and is then sent to a stripper. In the stripper, the CO_2-rich MEA solution is heated to release almost pure CO_2. Afterwards, the MEA solution is recycled to the absorber

Figure 3-1 Schematic Diagram of the Amine Separation Process



Source: IEA 2002a: 7

Competitiveness

Developed in the 1960s, chemical absorption capture systems are being utilised in several commercial industrial CO_2 capture plants, e.g. natural gas processing stations, which indicates that the technology is sufficiently mature and reliable for full-scale application. The technology is principally available for electricity plants but is only commercial in certain niche market power stations (see appendix 1). The hampered deployment of post-combustion capture equipment is attributable to economic and technical problems of chemical absorption, such as high energy intensity and costs. Due to strong bonds between the solvent and CO_2, MEA-based carbon capture covers approximately 70% of the total costs of CCS processes (Sasaki 2004: 5). Moreover, contaminants typically found in flue gases (e.g. SO_2, NO_x) must be removed prior to the capture procedure since they inhibit the solvent's effectiveness. These inefficiencies cumulate to energy penalties of about 15 to 30% for natural gas plants and 30 to 60% for coal-fired power stations (Anderson et al 2004: 117). Table 3-1 illustrates that chemical absorption leads to a significant reduction of power plant efficiency and increases in electricity generation costs and, thus, reduces the competitiveness of post-combustion capture

[8] Physical absorption requires a CO_2 concentration of more than 15% which conventional coal- and natural gas-fired power stations do not obtain. Hence, physical absorption is usually applied to pre-combustion or oxy-fuel procedures which are discussed in the following chapters.

processes. However, it needs to be pointed out that the competitiveness of MEA scrubbing processes and other carbon removal technologies depends on the economic development of regenerative technologies and is therefore uncertain.

Table 3-1 Impacts of Post-Combustion Capture on Power Plant Performance

Power Plant			**New PC**	**NGCC**	**Natural Gas Steam**
Reference Plant Size	MW_{el}		462-758	379-776	500
Net Efficiency	%	No CO_2 Capt.	41-45	55-58	42
	%	Incl. CO_2 Capt.	30-35	47-50	36,4
Electricity Generating Costs	[9] $US\$MWh^{-1}$	No CO_2 Capt.	43-52	31-50	45
	$US\$MWh^{-1}$	Incl. CO_2 Capt.	62-86	43-72	59
Costs of CO_2 Avoided (only capture)	$US\$/tCO_2$		29-51	37-74	36

Source: IPCC 2005a/Wuppertal Institute et al 2004

Compatibility

Being utilised in several industrial processes, e.g. in the chemical or oil industry, the general technical principle of post-combustion capture implies a good technical compatibility – even though some technical modifications and a specific load management are necessary to capture CO_2 from power plant flue gases. Similar to the deployment of gas turbine technologies, the application of chemical absorption in other industries may lead to a cross-industrial knowledge spill-over which eases the adaptation of post-combustion processes to the electricity sector.

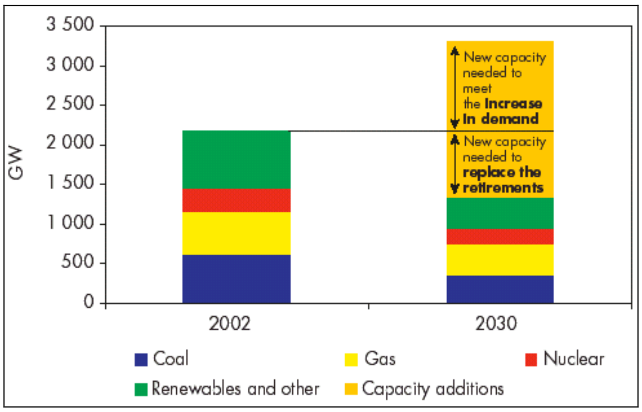
The technical compatibility of post-combustion capture processes is manifested by the fact that it is suitable for retrofits[10] of existing power plants (Wuppertal Institute et al 2004: 41). However, retrofits at exiting power plants require a lot of space for CO_2 capture and transport infrastructure and eventually demand upgrades of related plant components, such as FGD technologies. They may lead to a further decrease in efficiency and affect the plant's overall performance which is why CO_2 capture is only relevant for very efficient plants. Moreover, retrofits only come into consideration for power stations whose remaining lifespan is sufficient to amortise investments in post-combustion capture equipment (Fischedick et al 2005: 15). These aspects indicate that retrofits of post-combustion CO_2 removal technologies at existing plants are technically possible but unlikely to occur because of economic and practical barriers. Instead, it is more probable that new plants without CO_2 capture will be designed as 'capture-ready' plants which are specifically prepared for CCS retrofits.

[9] In this and all following chapters, costs originally presented in Euro (€) were converted into US Dollar (US$) at a currency exchange rate of 1,193.

[10] The term 'retrofits' means to subsequently fit a new element to an existing plant which fulfils an additional aim but does not impede the plant's overall performance (Fischedick et al 2005: 5).

Time of Availability
Due to the long lifespan of power plants and long investment cycles in the electricity sector, the diffusion of capture technologies could be accelerated if they were commercially available in periods of high demand for new generating capacity. From 2003 to 2030, OECD countries are expected to be in need of nearly 2000GW of new generating capacity. More than one third of this capacity is estimated to replace old power stations, mostly coal-fired plants[11] (IEA 2004b: 207) (see figure 3-2).

Figure 3-2 Impact of Plant Age on OECD Capacity Requirements

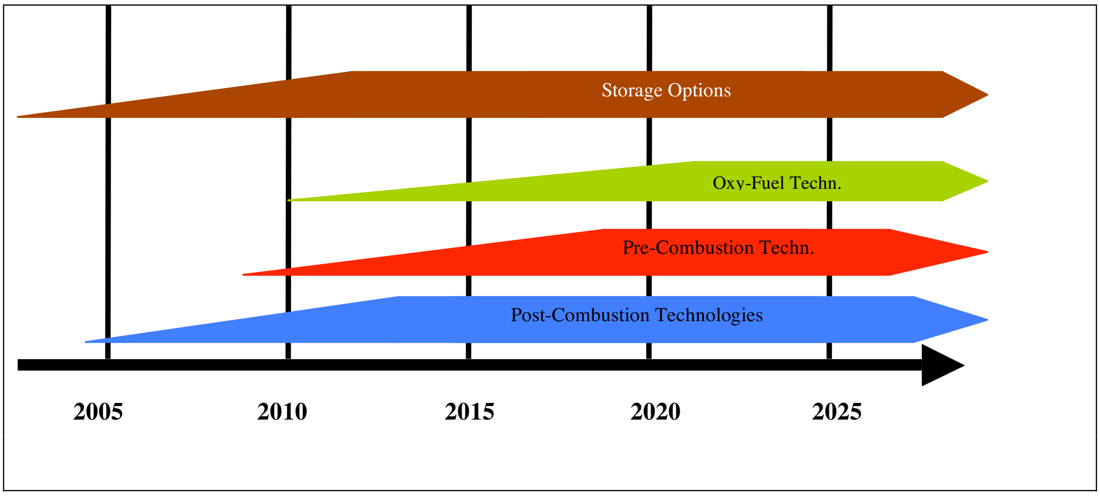


Source: IEA 2004b: 209

The high demand for new generating units could create a window of opportunity for the diffusion of CCS in the near future but post-combustion capture technologies are not likely to be diffused in near terms – even though they are generally available. Figure 3-4 illustrates the temporal availability of post-combustion capture technologies in comparison to other CO_2 removal options. The diffusion of chemical absorption procedures is hampered by economic and technical barriers, missing institutional incentives, a lack of full-scale demonstration projects and the fact that CO_2 storage reservoirs are not yet available for commercial usage. As a consequence, power plant projects in near- to mid-terms are unlikely to be equipped with post-combustion capture technologies. It is therefore an important advantage that chemical absorption procedures can be retrofitted to existing plants – if the latter have been explicitly prepared for such modifications.

[11] In Europe, approximately 30GW of coal-fired capacity are older than 20 years and approximately 80GW are older than 30 years; they need to be replaced within the next 5-15 years (Hulst 2004: 6). In North America, many coal-fuelled plants must be replaced around 2010-2020. In contrast to that, the bulk of Japanese and Chinese coal-fired generation units are under 15 years in age and unlikely to be closed down within the next couple of years (IEA 2004a: 62).

Figure 3-3 Temporal Availability of CO_2 Capture and Storage Options



Source: Wuppertal Institute 2004

Experience

Post-combustion capture technologies are currently being applied on a niche market of some industrial and few power plants which separate portions of the produced CO_2. In these cases, CO_2 capture is not primarily considered as a method to mitigate CO_2 emissions but an economic strategy since the separated CO_2 is sold to other industries (e.g. the food processing industry) which vent it back into the atmosphere (Thambimuthu et al 2002: 42). Niche market applications provide only limited experiences for large-scale CO_2 post-combustion capture and storage processes. At the current state, capture plants which remove approximately 4500tCO_2/day could be constructed without technical problems. A standard 1000MW coal-fired power plant, however, requires a capacity of 13.200tCO_2/day. The gap among the technical state-of-the-art and required removal capacities points out that demonstration projects aiming to apply post-combustion capture technologies at a large scale are an essential precondition for their application in the electricity sector. To date, numerous national and international RD&D projects are being conducted which aim to develop alternative solvents and optimise chemical absorption processes.

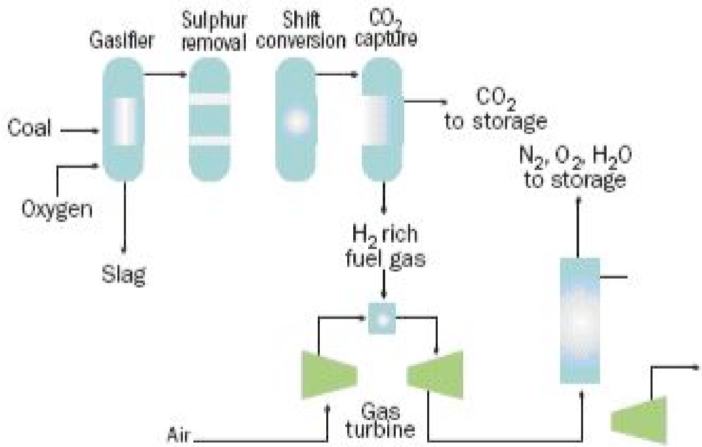
Environmental Impacts

The environmental performance of post-combustion capture technologies is mainly determined by their CO_2 recovery rate. Since they achieve a recovery rate up to 90% (Fischedick et al 2005: 7), post-combustion capture devices are capable of removing a large share of polluting power plant emissions. However, adding the additional energy demand deriving from capture processes significantly reduces net carbon mitigation rates. Furthermore, the temporal degradation of toxic amine solvents and their emission into the atmosphere may cause negative environmental impacts. Nonetheless, major environmental concerns related to CCS arise at the stage of carbon storage (see chapter 3.1.2).

3.1.1.2 Pre-Combustion Capture Technologies

Because of the high costs and energy intensity of chemical absorption procedures, two pre-combustion capture methods – a hydrogen-based and an oxygen-based approach – are gaining prominence. This chapter discusses the first option. Coal or natural gas are converted into a 'syngas', mainly consisting of hydrogen (H_2), carbon monoxide (CO) and carbon dioxide. The carbon monoxide is reacted with steam in a catalytic reactor, called a shift converter, to give CO_2 and more hydrogen. The CO_2 is separated and the hydrogen is used as a fuel in a gas turbine combined cycle plant (op. cit.: 33). To date, this option is mainly discussed with regard to coal-fired IGCC plants.

Figure 3-4 IGCC with Pre-Combustion CO_2 Capture



Source: IEA 2002a: 11

Competitiveness

Pre-combustion capture is applicable at high CO_2 concentrations (higher than 15%) and takes place at pressures, which are at least 50 times higher than in post-combustion capture processes. Physical absorption is characterised by a less strong binding among CO_2 and physical solvents[12] so that the carbon dioxide may be separated by simply reducing the pressure. This method is much less energy intensive than chemical absorption and, in IGCC plants, entails an energy penalty of only 15% (Anderson et al 2004: 118). Consequently, CO_2 capture in IGCC causes less efficiency losses than post-combustion removal in coal- or gas-fired plants.

12 Among the most important physical solvents are cold methanol (rectisol process), dimethylether of polyethylene glycol (selexol process), propylene carbonate (fluor process) and sulpholane (Thambimuthu et al 2002: 36).

Table 3-2 Pre-Combustion Capture on Power Plant Performance

Power Plant			**IGCC**	**NGCC**
Reference Plant Size	MW_{el}		401-827	500
Net Efficiency	%	No CO_2 Capt.	38-47	58
	%	Incl. CO_2 Capt.	31-40	51,5
Electricity Generating Costs	$US\$MWh^{-1}$	No CO_2 Capt.	41-61	37
	$US\$MWh^{-1}$	Incl. CO_2 Capt.	54-79	55
Costs of CO_2 Avoided (only capture)	US$/t$CO_2$		13-37	51

Source: IPCC 2005a/Wuppertal Institute et al 2004

Whereas the efficiency of coal-based steam plants with post-combustion capture decreases by about 10%points, the efficiency of IGGC facilities is reduced by approximately 7%points. Physical absorption processes therefore alleviate economic disadvantages of capture technologies. Major drawbacks of IGCC-based carbon capture systems are the high costs of and limited practical experience with the electricity generating technology itself plus problems related to power plant load management. With respect to natural gas-fired power stations, it is less clear if either post- or pre-combustion technologies are more economic since pre-combustion capture processes in NGCC units require more working steps than in coal-fuelled plants (op. cit.: 42).

Compatibility

Pre-combustion capture technologies involve a radical change of power station designs and are not suited to retrofit conventional steam plants. NGCC plants could be subsequently equipped with pre-combustion CO_2 removal technologies which would, however, be hampered by efficiency losses and practical barriers. Likewise, CO_2 removal retrofits at operating IGCC plants are generally feasible but entail costly modifications. They would, among other components, require additional space for a shift reactor, expanded coal handling facilities, larger vessels and CO_2 transportation infrastructure. Besides, CO_2 capture would necessitate a modernisation of gas turbine designs since the fuel gas fed to the gas turbine was pure hydrogen, whereas current standard turbines, like General Electric F-class turbines, only accept gases containing up to 45% H_2 (IEA 2004a: 50). Such modified turbine designs are not yet demonstrated technology (Thambimuthu et al 2002: 33). The given factors indicate that the subsequent installation of pre-combustion capture devices necessitates expensive technical adjustments which are likely to show negative effects on the economic and energetic performance of power plants. Similar to post-combustion capture technologies, retrofits demand further technical optimisation and are most likely to occur at capture-ready plants.

Experience

Pre-combustion technologies are well-proven components of other industrial processes like ammonia production which indicates that their deployment in the power sector could benefit from cross-industrial knowledge transfers. To date, they have not been commercially applied to IGCC plants because IGCC is less reliable and mature than conventional power plant designs. Being applied in about 160 power stations worldwide which do not yet have long operating times (World Coal Institute 2004: 9), it seems that IGCC designs need to be commercially established on the power market before the technology may be fitted with CO_2 removal devices. Since pre-combustion capture technologies remove CO_2 in a more efficient manner than chemical absorption processes, their development and demonstration constitute a central pillar of current CCS-related RD&D efforts. Companies and national governments are running costly programmes aiming to optimise gasification procedures and develop new processes to separate CO_2 from syngas. The 'Enhanced Capture of CO_2 (ENCAP)' project and the U.S. 'FutureGen' initiative are particularly important activities.

Time of Availability
The high demand for new power generating capacities is putting pressure on the development and demonstration of efficient carbon capture technologies. From 2015, IGCC technology is expected to deploy (IEA 2004b: 205). Until 2020, around 16.500MW_{el} of IGCC plants are planned to be constructed only in the U.S. (World Coal Institute 2004: 9). Since IGCC plants are prime candidates for pre-combustion capture technologies, the latter need to be applicable on a large scale at this time (see figure 3-3). As the cycle of planning, building and testing of a capture plant takes at least eight years, full-scale CCS pilot and demonstration projects have to be started within the next years. Hence, intensive efforts to up-scale pre-combustion technologies and to optimise their technical and economic performance should be undertaken if technological diffusion shall be obtained.

Environmental Impacts
An important advantage of pre-combustion capture technologies in IGCC plants is the generation of pure hydrogen which might serve as a bridge towards a low-carbon and hydrogen-centred energy system. Consequently, IGCC including CO_2 capture could support the transition towards a more environmentally benign energy system. In comparison to chemical amine scrubbing, physical absorption procedures are less energy intensive but imply lower CO_2 recovery rates (60-80%) (Wuppertal Institute et al 2005: 133). Hence, pre-combustion capture technologies are more compatible with a modern, environmentally friendly energy system but should be improved with respect to their CO_2 recovery rates.

3.1.1.3 Oxy-Fuel Combustion

Oxy-fuelling of either boilers or gas turbines instead of air (which contains about 78% nitrogen by volume) is another strategy for capturing CO_2. By producing oxygen in an air separation unit and using it for combustion, the concentration of CO_2 in the flue gas can be increased up to around 80%, compared to 4-14% for air-blown combustion (Thambimuthu et al 2002: 34). As a consequence, carbon capture may be carried out through simple CO_2 purification. Another portion of the CO_2-rich flue gas is recycled to the combustor in order to reduce the flame temperature onto to a level similar to a normal air-blown combustor.

Competitiveness
Oxy-fuel combustion technologies for power plants are at an early stage of development and demonstration which is why a sufficient degree of maturity and reliability has not yet been obtained. At the current state, oxy-fuelling is expensive, both in terms of capital costs and energy consumption, which is largely attributable to the energy-intensive oxygen production in air separation units. In some plant types, the electricity consumed by air separation processes amounts to about 10% of the total electricity production (IEA 2004a: 53) which entails a significant energy penalty. Since air separation processes are estimated to imply a high potential for efficiency improvements, oxy-fuel combustion is nevertheless seen as one of the most promising capture technologies – even though its application in coal-fired plants is very costly at the current state. Reliable data on the costs of oxy-fuel combustion in IGCC and NGCC plants are not yet available.

Table 3-3 Impacts of Oxy-Fuel Combustion Technologies on Power Plant Performance

Power Plant			**New PC**	**Air-Fired CFB**
Reference Plant Size	MW_{el}		677	193
Net Efficiency	%	No CO_2 Capt.	44,2	37,0
	%	Incl. CO_2 Capt.	35,4	25,8-32,2
Electricity Generating Costs	US$/$MWh^{-1}$	No CO_2 Capt.	44	45,3
	US$/$MWh^{-1}$	Incl. CO_2 Capt.	61,2	58,4-82,5
Costs of CO_2 Avoidance	US$/$tCO_2$		27	14-45

Source: IPCC 2005a

Compatibility
Generally, the oxy-fuel combustion approach is compatible with all types of power plant technologies. Depending on the power technology, retrofits require major or minor modifications. Oxygen-blown IGCC plants are a particular promising solution since IGCC designs incorporate the use of steam and oxygen for coal gasification at high pressure. As oxy-fuel combustion is based on existing technology for coal-fired plants, it is moreover considered as an attractive option for retrofits at operating coal-fired steam power stations. To date, an Australian-Japanese team is conducting a feasibility study on oxy-fuel combustion retrofits at an existing coal-fired plant (Callide A, $30MW_{el}$) in Queensland, Australia (Fischedick et al. 2005: 10). The required modifications for retrofits comprise the installation of air separation units and CO_2 compression and transportation infrastructure. Even though adjustments are rather minor in comparison to post-and pre-combustion technologies, many experts consider the application of oxy-fuel technologies in new plants as more likely since this option may diminish electricity losses by 6% towards retrofits (Thambimuthu et al. 2002: 58). In addition, boiler materials of existing coal power stations could be unsuitable for the extremely high flame temperature of oxygen-blown combustion (Jordal et al 2004a: 5). High combustion temperatures would furthermore necessitate a substantial redesign of conventional steam turbine technologies that makes retrofits unfeasible.

Experience
Practical experiences with oxygen-based combustion derive from their commercial application in glass and steel melting furnaces. Oxy-fuel combustion in power generation applications has so far only been demonstrated in small scale test rigs (Jordal et al 2004b: 13). In 2008, Vattenfall Europe plans to commission an oxy-fuel-fired pilot plant[13] which will be located in Germany and is expected to cost US$47,9million. It will be fuelled with lignite, incorporating a capacity of $30MW_{th}$ (Vattenfall 2005b: 3), and shall increase the competitiveness of oxy-fuel technology. In Ottawa, Canada, the CANMET Energy Research Centre intends to construct an industrial-scale oxy-fuel demonstration system for CO_2 capture (Canadian CO_2 Capture & Storage Network 2002: 2). Both demonstration projects plus the Australian-Japanese feasibility study are framed by further international activities which rather focus on technology development than demonstration.

Time of Availability
Development initiatives dealing with oxy-fuel combustion need to tackle several technical challenges: reduction of the energy consumption of air separation procedures, adaptation of coal-fired boiler designs to modifications in combustion and heat transfer processes as well as the development of new gas turbine processes (Jordal et al 2004b: 16). Experts expect oxy-fuel electricity generating technology to be commercial in 2020 (Vattenfall 2005b: 9). Similar to post- and pre-combustion capture options, the technology is constrained by a foreseeable demand for power plant retrofits and replacements. In the 2010s, NGCC will become the dominant generating technology and in the 2015/2020s, IGCC is expected to diffuse (IEA 2004b: 205). This enables first-generation IGCC plants to be equipped with oxy-fuel technology or being planned as capture-ready plants. Contrary, new gas-fired plants are likely to be operated without CO_2 removal due to the lower carbon content of natural gas. Hence, it is essential to pave the way for oxy-fuel retrofits at IGCC plants and, in particular, gas-fired units.

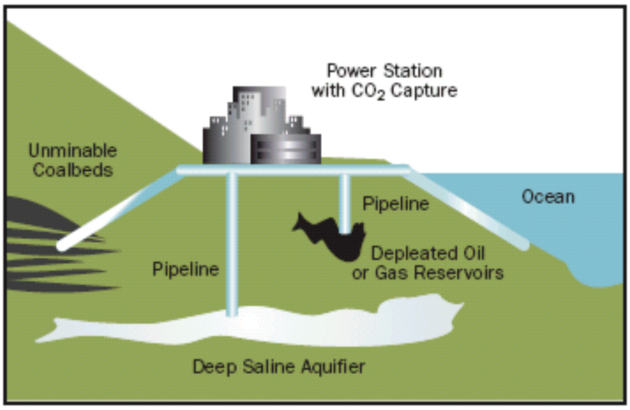
Environmental Impacts
Because of potentially lower efficiency losses, experts consider oxygen-based carbon capture technologies as an important component of future low emissions power plants. Current drawbacks, such as the energy intensity of air separation units, are expected to be significantly alleviated in the future (IEA 2004a: 53). Besides capturing CO_2, oxy-fuel combustion entails the opportunity to co-capture SO_2 and suppress the formation of NO_x emissions (Jordal et al 2004a: 4). Both features improve the overall environmental and economic performance of power plants as they would omit SO_2 and NO_x removal equipment.

3.1.2 Carbon Storage Technologies
Carbon storage procedures imply less economic and technical drawbacks to CCS diffusion than carbon capture technologies and, thus, are discussed more briefly.

[13] The pilot project comprises an oxy-fuelled boiler that produces steam which may be feed in an existing power plant.

There are two major options for storage of CO_2 from power plants: Ocean storage and storage in geological formations. This chapter focuses on geological storage options since the overwhelming majority of countries (except Japan) involved in CCS-related RD&D activities do not advocate ocean storage. CO_2 can be stored in abandoned or active and uneconomic oil and gas reservoirs - particularly where enhanced oil recovery (EOR)[14] or enhanced gas recovery (EGR)[15] may be used to increase economic benefits – and in deep saline aquifers and unminable coal seams.

Figure 3-5 CO_2 Storage Options (IEA 2002: 15)



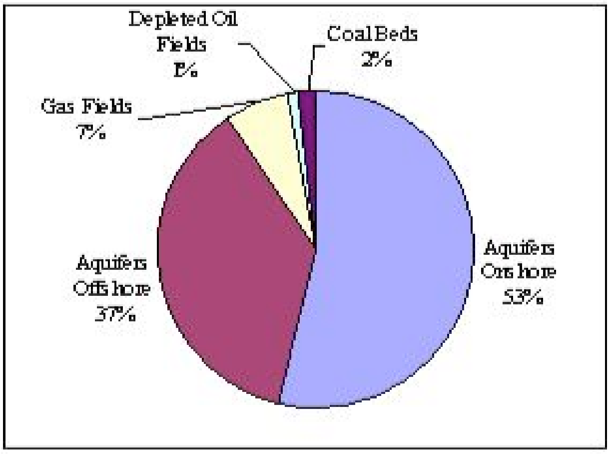
Source: IEA 2002: 15

In EOR operations, CO_2 is injected into oil reservoirs to increase the mobility of the oil and, thus, the reservoir's productivity, whereas in EGR processes, CO_2 displaces the native CH_4 gas and re-pressurises the reservoir. Aquifers appropriate for CO_2 storage are typically formed in carbonate or sandstone, contain saline water and have a cap of low permeability to minimise CO_2 leakage. Below that cap need to be layers of high porosity and permeability, allowing large quantities of injected CO_2 to be distributed uniformly (Anderson et al 2004: 124). In coal beds, which are located at suitable depths and imply a sufficient permeability, CO_2 could be stored by displacing coalbed methane (CBM) that is adsorbed on the coal surface (Wildenborg et al 2002: 64). Doing so, CO_2 storage would enhance coalbed methane recovery (ECBM)[16].

Estimates on the global potential of CO_2 storage sites come to strongly varying results. Dooley et al assume a global geological CO_2 storage potential of 2.867GtCO_2, with aquifers representing the major share of suitable formations. Other research institutes, such as Ecofys, present to results which display a higher relative share of natural gas fields and oil fields (Ecofys 2004 : IV). Since Dooley et al give detailed information about regional storage potentials which are utilised in chapter 3-2, figure 3-6 illustrates the capacities of different types of underground reservoirs in accordance to that study.

[14] EOR is a well-proven and commercially applied process (see table 4-5).
[15] EGR is not yet proven commercially (see table 3-5).
[16] ECBM is at an advanced stage of development or an early state of demonstration (see table 3-5).

Figure 3-6 Estimated Worldwide CO_2 Storage Potential per Type of Underground Reservoir



Source: Dooley et al 2004: 3

Competitiveness

The costs of carbon storage account to less than 30% of carbon capture and storage processes (Sasaki 2004: 12) since the injection of CO_2 is a simple and mature process. Enhanced recovery methods might lead to further economic benefits. EOR enhances oil recovery rates by 8-15% of the total quantity of original oil in place, leading to an increase in total recovery by 50% for an average field. EGR is expected to recover another 5-15% of the initial gas in place and ECBM could achieve a coalbed methane recovery rate of 90-100% (IEA 2004a: 85-88). However, the state of development of the divergent enhanced recovery methods differs considerably (see table 3-4).

Table 3-4 Storage Costs by Depth; in US\$/tCO_2

Storage Option	**Depth of Storage (m)**		
	1000	**2000**	**3000**
Aquifer onshore	2,4	3,6	7,2
Aquifer offshore	6	8,4	13,2
Natural gas field onshore	1,2	2,4	4,8
Natural gas field offshore	4,8	7,2	9,6
Empty oil field onshore	1,2	2,4	4,8
Empty oil field offshore	4,8	7,2	9,6
	Estimated Revenues from Enhanced Recovery Options		
	Low	**Medium**	**High**
EOR onshore	-12	0	12
EOR offshore	-12	3,6	24
ECBM	0	12	35,9

Source: Ecofys 2004: III

The bulk of CO_2 injection costs arise during the drilling process. They range from US$1,9 to 9,6/t$CO_2$, depending on the depth, permeability and the type of the storage reservoir (Ecofys 2004: III). Onshore storage is generally less expensive than offshore storage as the latter requires a platform. In the case of EOR and EGR, costs are additionally linked to the oil and gas price. If oil or gas prices are high, there is a strong incentive for exploration and production companies to increase recovery rates. ECBM is more expensive than other enhanced recovery options as it entails a large amount of wells.

Taking into account all procedural steps of CCS, including CO_2 capture, transport and storage, the technology leads to divergent mitigation costs per tonne of CO_2 for different power plant types. According to the IPCC CCS Special Report, total mitigation costs range from US$14-53/t$CO_2$ for IGCC, US$39-91/t$CO_2$ for NGCC and US$30-71/t$CO_2$ for conventional pulverised coal plants (IPCC 2005a: 347). The cost estimates include different carbon capture processes which, as mentioned before, constitute the major share of total mitigation costs. Contrary, the share of storage options is rather low and does not constitute a major barrier to CCS diffusion.

Compatibility

CO_2 injection processes imply a high technical compatibility with established processes like oil and gas recovery or natural gas storage. CO_2 storage is, however, constrained by geographic and geological parameters. Since most of the conventional oil and gas production resources are located in the Middle East and the former Soviet Union, far away from regional centres of CO_2 pollution, long transports impede the utilisation of economic CO_2 storage options like EOR and EGR (IEA 2004a: 83). Furthermore, only oil fields with a depth of more than 600 metres which contain more than 20-30% of the original oil are suitable for EOR procedures. With respect to gas reservoirs, EGR is restricted to fields where 80-90% of the gas has been produced. ECBM is mainly impeded by the need of highly permeable seams. Saline aquifers suited to CO_2 storage necessitate a reasonable size as well as a structure preventing upward mobility (Wildenborg et al 2002: 64). It may be concluded that the application of CO_2 storage technologies demands a high degree of geological compatibility, calling for a careful field-by-field assessment, whereas technical aspects do not constitute a barrier.

Experience

As many carbon storage methods are closely related to existing technologies, a substantial baseline of technical information and experience exists. EOR is being practiced for several years. About 70 fields worldwide, mainly in North America, use about 60 million m^3 of CO_2 per day for EOR processes (IEA 2002a: 16). Contrary, EGR is still in the phase of desk studies, with experts being at odds if the method is feasible at all (Wildenborg et al 2002: 62). ECBM is at an early demonstration stage with uncertain prospects (IEA 2004a: 90). More information exists on CO_2 storage in saline aquifers. Statoil's demonstration project at the Norwegian Sleipner field[17] has confirmed the technical feasibility of CO_2 storage in aquifers (op. cit.). Further experiences entail from the storage of natural gas to level winter peaks in gas transmission (see chapter 2.3.1.3).

[17] CO_2 is separated from natural gas produced at the Sleipner field and stored in the Utsira aquifer below the gas field (Kårstad 2002).

Despite considerable experiences, the reliability, duration, stability and integrity of carbon storage reservoirs as well as possible impacts of CO_2 leakage are uncertain and call for further demonstration efforts. The mentioned Norwegian storage project represents the most important aquifer storage initiative. Concerning EOR, a large-scale demonstration project is carried out at the Canadian Weyburn field. Major ECBM pilot projects are taking place in the U.S. (San Juan Basin), Canada (Alberta basin) and Poland (RECOPOL).

Time of Availability

Since most carbon storage options are at a demonstration stage or are commercially applicable under certain circumstances, the technical and economic availability of carbon storage opportunities does not create an obstacle to CCS diffusion. Instead, CO_2 sequestration is affected by environmental concerns, a lack of social acceptance and controversial institutional and legal issues. Storage in depleted oil reservoirs, including EOR, and gas fields are the most promising near-term options as the required technology is mature and economically applicable (Anderson et al 2004: 123). Representing approximately 70% of the global potential for carbon underground storage (Ecofys 2004: IV), near-term opportunities for CO_2 sequestration in oil and gas fields are cornerstones towards CCS diffusion. However, the described geological and geographic constraints limit the potential of enhanced recovery options. ECBM storage represents a mid- to long-term option, whereas storage in saline formations is near-to commercial. Saline aquifers do not offer economic benefits but imply a better geographical match with major emission sources than oil and gas reservoirs. Hence, they are an important option when enhanced recovery potentials are exhausted (Anderson et al 2004: 124).

Table 3-5 Current State of Carbon Storage Technologies

<table>
<tr><th>Carbon Storage Technology</th><th>Research Stage</th><th>Demonstration Stage</th><th>Economically Feasible under Specific Conditions</th><th>Mature Market</th></tr>
<tr><td>EOR</td><td></td><td></td><td></td><td>X*</td></tr>
<tr><td>EGR</td><td>X**</td><td></td><td></td><td></td></tr>
<tr><td>Gas or Oil Fields</td><td></td><td></td><td>X</td><td></td></tr>
<tr><td>Saline Formations</td><td></td><td colspan="2">X</td><td></td></tr>
<tr><td>ECBM</td><td colspan="2">X</td><td></td><td></td></tr>
</table>

*CO_2 injection for EOR is a 'mature market' technology but when used for CO_2 storage, it is only 'economically feasible under specific conditions'; ** According to Wildenborg/van der Meer 2002: 62

Source: IPCC 2005a: 11

Environmental Impacts

Geological CO_2 storage raises concerns about negative environmental impacts and security. Gradual leakage of CO_2 may have hazardous effects on plants, subsoil animals and groundwater. Abrupt leakage, e.g. through injection well failures, can seriously harm animals or humans. While the technical feasibility of geological storage options has been widely explored, the same is not true with respect to their ecological implications. Currently, there is little knowledge about potential leakage pathways through fractures or porous media, potential impacts on surface ecosystems, the potential for catastrophic release and monitoring and remediation methods (Jonhnston et al 2002: 106). Intensive research and site-specific assessment of possible hazardous effects are essential for the implementation of carbon storage. The described risks and the permanent character of CO_2 storage are expected to cause public opposition and constitute major barriers to CCS diffusion entailing from geological carbon storage (Interview G. Rosenbauer, 17.11.2005: 12).

3.2 Potential Markets for CCS Technologies

As carbon capture and storage technologies are suited to large-point CO_2 sources, future CCS markets are likely to be located in regions which indicate high discharges of carbon dioxide from large stationary pollutants such as power plants. In 2002, Asia (5,6GtCO_2/yr^{-1}), North America (2,69GtCO_2/yr^{-1}) and OECD Europe (1,75GtCO_2/yr^{-1}) were the world's largest emitters (IPCC 2005a: 83). Between 2000 and 2050, the bulk of emissions sources is projected to shift from industrialised countries to developing and transition regions like China or South Asia (op. cit.: 84). Potential CCS markets are, however, not only constituted by high concentrations of large-point CO_2 emissions. Their formation is furthermore driven by the following determinants: a good match of discharged CO_2 emissions and available storage sites, a country's dependence on fossil fuels (which is determined by its energy supply mix and available fossil energy reservoirs) and the positions of involved political, economic and societal actors concerning CCS. In the following sections, the given determinants will be investigated in five case studies - Germany, Denmark, the U.S., China and Russia – that include countries from each high-polluting world region and are of interest with respect to CCS.

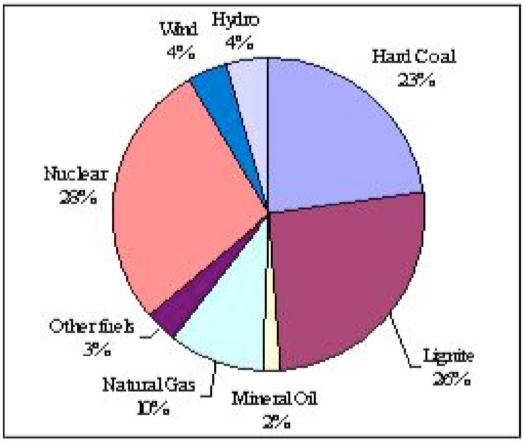
3.2.1 Germany

Energy Supply and Demand

Germany's power sector is dominated by coal since lignite and hard coal are the only considerable domestic energy resources. In 2004, more than 50% of the generated electricity and even a higher share of electricity production were coal-based. Coal-fired power plants accounted for about 42% (52,7 GW) of the installed power generating capacity, whereas natural gas-fuelled plants and nuclear plants made up only 15,5% (19,4 GW) or 17,1% (21,5 GW) respectively (German Ministry of Economics and Labour 2005). The important role of coal in the electricity supply entails the theoretical opportunity to apply CO_2 capture at coal-fired power plants. However, CCS deployment is affected by a substantial demand for new power stations and retrofits in the coming two decades. In 2010, approximately 40% of the installed conventional thermal generation capacity (30 GW) – including one third of installed hard coal-fired plants and 45% of existing lignite plants – have an age of at least 35 years and need to be replaced. Until 2030, additional 30 GW reach the end of their technical life cycle (Matthes et al. 2003: 2). Moreover, all nuclear power plants are expected to be decommissioned until 2025 as the former red-green government decided to phase-out nuclear energy. Taking into account existing surplus capacities, a total of at least 50 GW generating capacity needs to be replaced until 2030. This development is framed by projections which forecast an increase in electricity demand from 532 TWh in 2000 to 570 TWh in 2020 (UBA 2003: 6).

Despite political efforts to increase the share of renewable energy technologies, fossil-fuelled power plants are expected to remain the backbone of Germany's electricity sector in a mid-term perspective. That prospect will not necessarily lead to a broad deployment of CCS as the technology is costly and requires strong institutional incentives. Only if stringent CO_2 reduction targets are going to be implemented, CCS is projected to play a significant role in the German power sector (Marketwitz/Vögele 2004: 2). Otherwise, national electricity utilities are expected to select less costly CO_2 mitigation options like efficiency improvements.

Figure 3-7 German Electricity Generation by Fuels in 2004



Source: German Ministry of Economics and Labour 2005

Another obstacle to CCS diffusion arises from temporal mismatches of capacity replacements and CCS availability. As many old power stations need to be decommissioned before 2020, it is assumed that the bulk of capacities to be replaced "will be covered by the construction of highly efficient power plants without CO_2 capture since no cost-efficient capture technology or commercial power plant designs will be available" (op. cit.: 4). Hence, the design of capture-ready plants and a high technical compatibility of carbon removal technologies with operating power stations represent essential preconditions for CCS diffusion in Germany.

National CO_2 Discharge and Potential of CO_2 Storage Sites

Potential German geological CO_2 storage sites have a capacity of min. 18,37Gt and max. 47,37Gt. Depleted gas fields are the most promising storage method since their underground formations are well known from gas production. Contrary, the potential of empty oil fields is very limited. Deep saline aquifers and coal seams offer a high storage capacity but are either costly or immature options.

In relation to Germany's total annual discharge of carbon dioxide from power generation[18], which amounted to 272,62 Mt in 2003 (IEA 2005a: II.207), Germany's geological CO_2 storage potential would last for approximately 67 - 173 years[19]. However, it is unrealistic to assume that the national power plant fleet will be capable of capturing and storing all its future CO_2 emissions. Instead, a share of approximately 20% of power-related CO_2 emissions to be stored seems more likely. In the latter case, the country's overall storage sites would endure for more than 300 years and the capacity of depleted gas fields – the most mature method among available storage options – for approximately 46 years. However, there is literally no opportunity to outweigh the costs of CO_2 storage through enhanced recovery of oil or gas.

Table 3-6 Potential of Geological CO_2 Storage Options in Germany

Option	Deep Coal Seams	Depleted Oil Fields	Depleted Gas Fields	Deep Saline Aquifers (onshore + offshore)	Total
Capacity (Gt)	3,7-16,7	0,11	2,56	20 +/-8	**18,37 - 47,37**

Source: Gerling 2004: 5/Fischedick 2005: 11

The relation among potential storage sites and power plant emissions demonstrates that carbon capture and storage is a realistic option in Germany which could function as a bridge towards a carbon-free energy system. However, as the available geological formations do no include economic niches such as EOR, strong policy incentives that entail a significant increase in CO_2 prices are needed. Consequently, Germany offers a significant market potential for CCS but is unlikely to become a lead market.

Actors

The constellation of political, industrial and societal actors in Germany concerning the broad deployment of CCS is ambivalent. Emphasising the future importance of fossil fuels, the Federal Ministry of Economics and Technology functions as the main political driver and pursues CCS-related R&D activities within the COORETEC programme. Contrary, the Federal Ministry for the Environment clearly opposed any CO_2 storage strategy until early 2004 because of a strong preference for renewable energy technologies (CO_2 Capture Project 2004: 75). During the last months, the Ministry has become more open and considers CCS as a possible 'bridge technology' towards a regenerative energy system. At the time being, the political debate about CCS is limited to the Ministries, whereas the parliamentary parties play a passive role. The SPD considers CCS as one carbon mitigation option amongst others (SPD 2003: 1). CDU and FDP tend to support CCS (Fischer et al 2005: 8/German Bundestag 2003: 2), whereas the Greens are sceptical as the technology might justify the construction of new coal-fired power plants (B'90/Die Grünen 2003: 12). Die Linke/PDS clearly opposes carbon capture and storage and favours regenerative technologies (Interview U. Witt, 18.11.2005: 13). Environ-

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18 The national emissions data for power generation given in this and the following chapters contain the sum of emissions from main activity producer electricity generation, combined heat and power generation and heat plants. Emissions from main activity producer electricity and heat define as those undertakings whose primary activity is to supply the public.

19 The presented calculations on national CO_2 storage potentials in relation to a country's annual CO_2 discharge in this and the following chapters only provide a rough trend concerning the temporal applicability of CCS.

mental NGOs, including Greenpeace, Germanwatch and others, are critics of CCS (Fischer et al 2005: 7) and could significantly affect its social acceptance.

Among German electricity utilities and power plant manufacturers, only Vattenfall Europe is acting as a CCS driver. The company formed an interdisciplinary working group aiming to sound out the conditions for the technical development of CCS in 2002 and plans to put into operation an oxy-fuel pilot plant in 2008 (Vattenfall 2005b: 3). The position and commitment of other power producers – RWE, E.On and EnBW – corresponds to their share of coal-based generation, with RWE being the most active company. The utilities pursue a 'three horizons' strategy, which prioritises the broad application of state-of-the-art technologies and efficiency gains. CCS development and deployment is the third strategic step (RWE Power 2005: 41). Power plant manufacturers, such as Siemens, are generally open, although they recognise major technical and political barriers (Interview G. Rosenbauer, 17.11.2005: 10).

The constellation of actors indicates that most industrial companies with high economic competences and immense financial resources consider CCS as a possible long-term mitigation option. However, their commitment strongly depends on political impulses. At the political stage, the Ministry of Economy and Technologies promotes CCS but is facing a significant political and societal opposition entailing from preferences for renewable technologies. Consequently, it is doubtful if Germany will become a proactive advocate of CCS diffusion.

3.2.2 Denmark

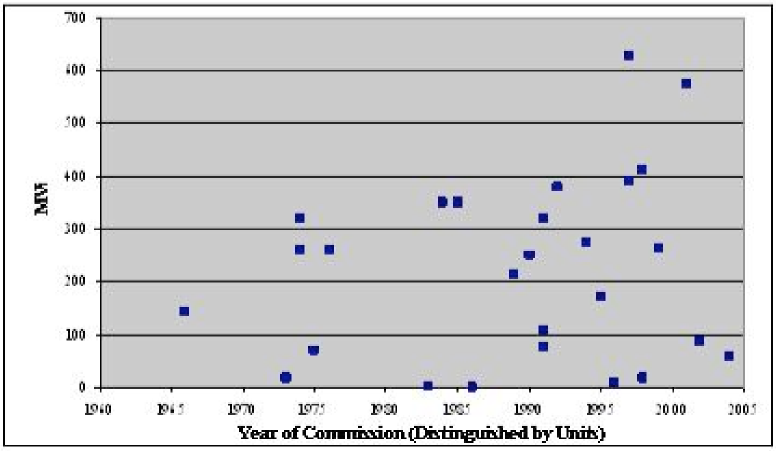
Energy Supply and Demand

Although a significant share of Denmark's electricity supply is generated by renewable energy sources, the country is a candidate for CCS as about 80% of its electricity production is based on fossil fuels. In 2003, Danish total electricity production amounted 46,2 TWh, of which 25,3 TWh (54,8%) and 9,8TWh (21,24%) respectively were generated by using coal and natural gas (Danish Energy Authority 2003: 8)[20]. The country's total 2003 installed power generating capacity was 13,6 GW, with natural gas- and coal-fired large-scale power plants accounting for 8,3 GW or 61% (op. cit.). Due to stringent environmental standards and a lack of domestic coal resources, Danish power plants run at a remarkably high average efficiency of 44,8% (Danish Energy Authority 2002: 16). Consequently, the power plant stock implies an adequate technical standard to take into account the operation of carbon capture plants. CCS retrofits are particularly relevant as the bulk of Danish power plants was built or modernised later than 1990, which entails that most plants are less than 15 years of age. Assuming an average lifespan of 35–40 years, most generating units are expected to be decommissioned not earlier than 2025. Hence, CCS retrofits might be considered - which is confirmed by the recent fitting of a post-combustion capture pilot plant to the Esbjerg Power Station. Some old units which started operation in the 1970s are expected to be shut down before CCS will be available and might be replaced by capture-ready plants. However, Energi E2 – one of two

[20] About 2,3TWh (5,02%) were based on oil, 5,6TWh (12,04%) and 3,2TWh (6,91%) were supplied by wind and other renewable sources (Danish Energy Authority 2003: 8).

major electricity suppliers – is sceptical about CCS retrofits as they affect the economic and energetic performance of operating plants (Interview O. Biede, 25.11.2005: 22). Hence, carbon scrubbing is unlikely to deploy before 2025.

Figure 3-8 Years of Commission and Net Capacities of Elsam and E2 Generating Units



Source: Elsam 2005/Energi 2005

National CO_2 Discharge and Potential of CO_2 Storage Sites

Taking into account Denmark's small size and the limited number of power stations, the country offers a high potential for CO_2 storage in saline aquifers and depleted oil and gas fields. All suited oil and gas fields lay offshore, which is why the decision to utilise them for CO_2 storage must be made relatively soon (GESTCO 2004: 9). Once the infrastructure has been removed, the costs of installing new field infrastructure, including a platform etc., would be prohibitive. Nonetheless, oil and gas fields in combination with enhanced recovery procedures are attractive storage methods. EOR could lead to an increase in oil recovery of 500 to 600 million barrels for the five biggest Danish chalk fields. This corresponds to a total value of US$12-24billion (Denmark Geological Survey 2004: 9).

Table 3-7 Potential of Geological CO_2 Storage Options in Denmark

Option	**Deep Coal Seams**	**Depleted Oil Fields**	**Depleted Gas Fields**	**Deep Saline A-quifers**	**Total**
Capacity (Gt)	0	0,18	0,45	16	**16,63**

Source: GESTCO 2004: 9/10

Relating available carbon storage capacities to the national 2003 CO_2 discharge from power plants (21,23 Mt; IEA 2005a: II.183), Denmark might store carbon dioxide for more than 790 years – a timeframe which reaches beyond conceivable planning horizons. Considering that only a share of approximately 20% of the discharged emissions from electricity generation is likely to be stored, the national storage potential would endure for an even longer period. This estimation indicates that the application of CCS to Danish fossil-fuelled large-scale power plants would not be constrained by limitations regarding possible storage formations. The foreseeable depletion of North Sea oil and gas reservoirs generates an additional incentive to store CO_2 via enhanced recovery processes. Experts assume that in approximately 10 years, Danish oil companies will develop a strong interest in EOR (Interview F. Nissen, 27.10.2005: 6).

Actors

Actors involved in Danish energy policy recognise that CCS constitutes a possible method to meet the national carbon mitigation target and to enhance the efficiency of North Sea oil recovery. The Danish government has, however, not yet decided on CCS as a means to reduce CO_2 emissions (Interview A. Mortensgaard, 14.12.2005: 53). This is, among other aspects, attributable to divergent positions of the responsible authorities. The Danish Energy Authority, which carries out tasks in relation to the production, supply and consumption of energy, is supportive of CCS as it has a special interest in EOR applications (op. cit.), whereas the Ministry of Environment is sceptical (Interview F. Nissen, 27.10.2005: 7). In general, the coalition pursues a climate policy strategy which emphasises the cost-efficiency of carbon mitigation methods. Since CCS is very expensive, the government is unlikely to act as a technology driver.

Elsam – which was recently merged with DONG, a state-owned gas and oil company – and E2 are in favour of CCS and participate in EU RD&D projects in order to gain knowledge about the technology's applicability. Among other projects, they are collaborating in the construction and operation of the pilot capture plant in Esbjerg which is part of the EU CASTOR project. Both utilities share knowledge and capacities and, thus, form a small technology-specific network. Lately, Vattenfall took over a certain percentage of the power generating capacities of Elsam and Energi E2. Since the Swedish company is a proactive driver of CCS (see chapter 3.2.1), it might foster the technology's application on the Danish market.

A lack of social acceptance is expected to be the main barrier to underground storage of CO_2. Environmental NGOs, such as NOAH – the Danish section of Friends of the Earth – and Greenpeace Denmark, strongly oppose the removal and disposal of CO_2 as it entails security concerns, rivals with renewable energy technologies and prolongs the dominance of fossil fuels (NOAH 2005/Interview F. Nissen 27.10.2005: 7). Experts consider it very likely that CCS project developers will face serious public resistance. In this context, the failure of an underground natural gas storage project in an onshore saline aquifer in the late 1990s as a result of public protests constitutes an interesting precedent (CO_2 Capture Project 2004: 71).

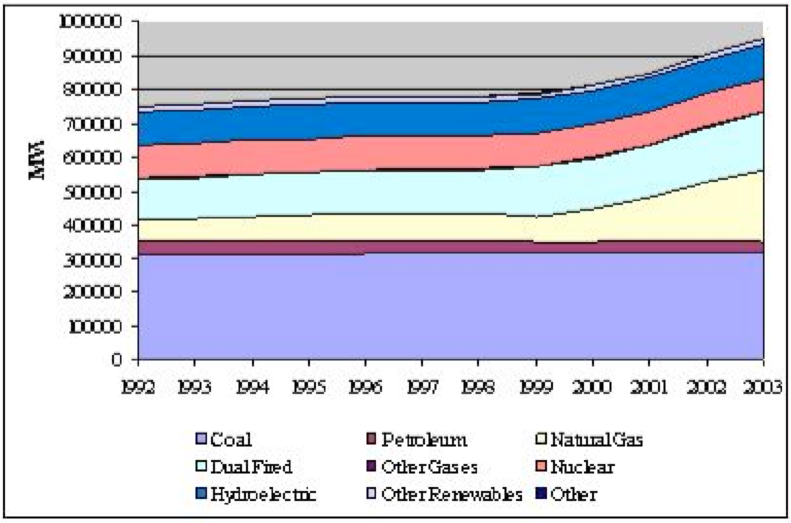
The behaviour of important Danish actors points out that there is a discrepancy among industrial and political entities: Whereas Elsam and E2 are already cooperating in RD&D projects, CCS-related considerations of the Danish government are at an early stage. This ambivalent situation is framed by the anticipation of strong public concerns with respect to underground CO_2 disposal. Consequently, CCS could be applied on a small scale in supplementation to renewable energy technologies or at remote offshore storage sites.

3.2.3 The United States

Energy Supply and Demand

Coal, oil and natural gas account for approximately 90% of the U.S primary energy supply (U.S. EIA 2005a: 75). Net electricity generation is based on coal by about 50% (1976,3 GWh), followed by nuclear power (788,6 GWh/20%), natural gas (699,6 GWh/17,7%) and hydro power (269,6GWh/6,8%). In line with the power generation fuel mix, the major portion of U.S. power capacity is coal-fired (see figure 3-9). Despite an increase in natural gas-fired capacities, power stations using coal are expected to supply the bulk of electricity through 2025 with an increase in output up to 2,9GWh (op. cit.: 88).

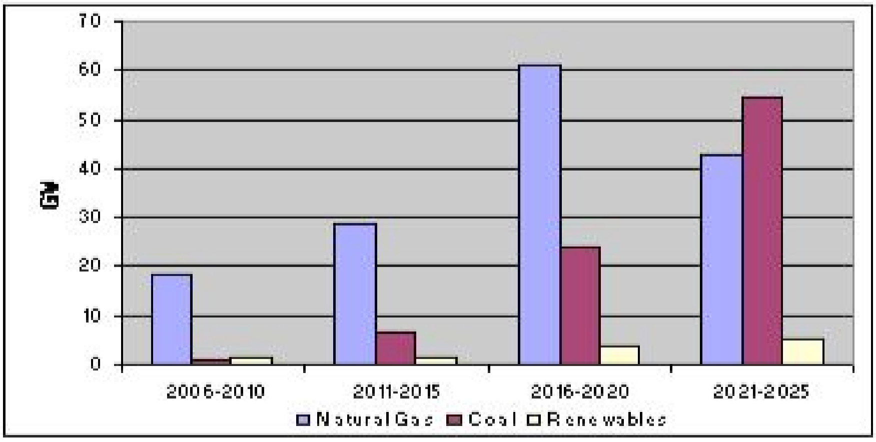
Figure 3-9 Existing Net Summer Capacity by Energy Source (1992–2003) in the U.S.



Source: U.S: EIA 2003

Within the coming 20 years, a significant amount of new generating capacities needs to be installed because of the retirement of 43GW and a growing electricity demand. By 2025, 281GW of new capacity will be needed. Old oil- and natural gas-fired steam plants are projected to constitute the lion's share of retirements, along with smaller amounts of old oil- and natural gas-fuelled combustion turbines and coal-fired capacities (op. cit.: 87). More than 60% of new capacity additions are estimated to be NGCC plants or distributed generating technologies (see figure 3-10).

Figure 3-10 Forecasted U.S. Electricity Capacity Additions 2006–2025; GW



Source: U.S. EIA 2005a: 87

However, due to an increase in gas prices, coal-fired plants become increasingly competitive and account for nearly one-third of capacity expansion. Most of the new coal capacity is expected to use advanced pulverised coal technology and to begin operation after 2015. About 16GW will use advanced clean coal technologies (op. cit.).

The striking dominance of fossil-fuelled plants and the fact that the bulk of capacity additions and replacements is scheduled for 2015–2020 and beyond – the timeframe when CCS becomes available - shows that the U.S. electricity sector implies a high potential for CCS technologies. Retrofitting seems to be less relevant because of the high age of existing power plants. This fact constitutes a positive determinant of CCS diffusion as new plants remove CO_2 more efficiently. With most of the new coal-fired plants applying advanced pulverised coal technology, their combination with oxy-fuel combustion is an important option for the U.S. market. The fact that the majority of added capacities will be NGCC stations does furthermore demand more efficient capture technologies for this type of plants since CO_2 removal devices for gas stations are not as well developed as those for coal-fired plants.

National CO_2 Discharge and Potential of CO_2 Storage Sites

In 2003, the U.S. emitted a total of 5,7 Gt of CO_2 emissions from fuel combustion which is by far the largest national carbon dioxide discharge worldwide (IEA 2005a: II.371). The power sector's share amounted to 1,9 $GtCO_2$ (op.cit.). Despite this high annual discharge of CO_2, the U.S. carbon storage potential allows CCS to be considered a long-term carbon mitigation option because of an immense stock of storage sites.

Table 3-8 Potential of Geological CO_2 Storage Options in the U.S. (Dooley et al 2004: 3)

Option	**Deep Coal Seams**	**Depleted Oil Fields**	**Depleted Gas Fields**	**Deep Saline Aquifers (onshore)**	**Deep Saline Aquifers (offshore)**	**Total**
Capacity (Gt)	16	3	10	745	248	**1022**

Source: Dooley et al. 2004: 3

Taking the total of 2003 CO_2 emissions from power generation as a basis, the country's total storage capacity is estimated to last for more than 530 years. If CCS was only applied to a limited number of fossil power plants, the storage potential would multiply. Consequently, the number of available storage formations is a driving force for CCS in the United States.

This assumption is underlined by the fact that the U.S. exhibit a comparatively high potential for economic storage options such as oil and gas fields or coal seams – even though not all of these formations are suitable for enhanced recovery methods. In the past, the U.S. functioned as a lead market for EOR (IEA 2004a: 84). In the future, the country might become an early adopter of ECBM. To conclude, the high CO_2 storage capacities and the continuing dominance of fossil fuels in the national power sector make the U.S. a promising market for CCS. These favourable conditions for CCS diffusion are framed by a strong support of political and economic actors.

Actors
The U.S. actor constellation related to CCS shows a high degree of institutionalisation as the Bush administration pursues a strongly technology-centred climate policy approach in opposition to the Kyoto path. Due to a preference for fossil-fuelled power technologies, carbon capture and storage technologies are considered as a central element of this strategy (U.S. House of Representatives 2004: 3). In contrast to investigated European countries, all involved governmental agencies – the Environmental Protection Agency (EPA) and the Department of Energy (DOE) – are in favour of CCS (Interview S.M. Forbes, 8.12.2005: 41/42). Both agencies employ several full-time officials that are fully dedicated to CCS and gather a considerable degree of technology-specific expertise. The government's fossil-centred energy policy finds broad support in the U.S. Congress which appropriated more funds for coal programs in FY 2006 than DOE requested (U.S. DOE 2005a). Regional actors become increasingly aware of CCS. Seven States have established Carbon Sequestration Advisory Boards and, thus, carried technology-specific institutionalisation to the State level (Chan et al 2005: 4). Furthermore, regional sequestration partnerships, initiated by DOE, broaden the range of involved actors as they seek to integrate local government agencies, NGOs, research communities and private sector participants (U.S. DOE 2003: 10). Consequently, regional and national CCS networks are evolving.

U.S. power utilities display varying positions. For example, whereas American Electric Power actively promotes CCS, other producers like Southern Company oppose it. The companies' behaviour is determined by the impact of CO_2 mitigation on their business interests (Interview S.M. Forbes, 8.12.2005: 40). Contrary, oil, gas and coal industries are highly supportive of CCS since it offers efficient recovery methods and would allow the utilisation of fossil fuels despite stringent climate policies (op. cit.: 40/41). Environmental NGOs show divergent positions in line with their general attitudes on coal and IGCC (op. cit.: 42). The National Resources Defense Council (NDRC) considers CCS as a supplementary mitigation option to renewable energy and energy efficiency and urges the congress to establish CCS incentives (NDRC 2005: 15), whereas Greenpeace opposes the technology's diffusion (Interview S.M. Forbes, 8.12.2005: 42). Consequently, the behaviour of environmental NGOs is more ambivalent than in Germany or Denmark.

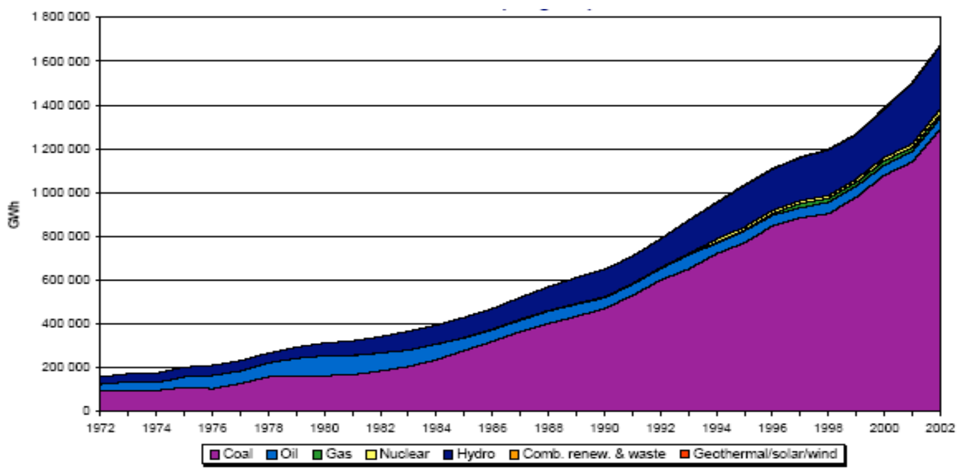
Overall, the actor constellation favours CCS since decisive political players unanimously support its deployment and foster technology-specific institutionalisation, networking and capacity building. Due to the ambivalent attitudes of environmental NGOs, societal actors are unlikely to form a broad opposition against the technology. The combination of favourable parameters with respect to national power supply, CO_2 storage sites and actors make the U.S. a probable lead market for CCS diffusion.

3.2.4 China

Energy Supply and Demand

China is the world's largest consumer and producer of coal as it has the third largest national coal reserves (about 400Gt) (Xiaoli et al 2004: 6/7). Hence, coal accounted for 74,6% of the national TPES in 2003 (China Statistics Press 2003). The national power sector is the major coal consumer. In 2002, 646million tons of coal, approximately 49,12% of the total domestic coal consumption, were used for the production of 1350TWh of electricity or 78% of the total electricity supply (Zhufeng et al 2004: 25). The electricity sector's striking dependence on coal creates a significant potential for carbon capture from coal-fired power plants. About 290GW (74,1%) of a total of 391GW of installed power generation capacities are coal-fired (Weidou 2005: 11). However, operating at an average efficiency of only 32% compared to 39-40% in industrialised countries (IEA 2004a: 63), most existing Chinese power stations are not suitable for CCS retrofits since low electric efficiency rates lead to high abatement costs. The age of existing generation capacities is another parameter of CCS diffusion. Most coal-fired power plants are under 15 years of age and likely to operate for another 15-25 years (op. cit.: 62). This may, on the one hand, retard the replacement of existing units with power stations suitable for CO_2 capture for about 10-15 years. On the other hand, capture technologies are expected to be ready for diffusion at the time large shares of the Chinese power plant stock will be decommissioned. Hence, China shows a high long-term potential for CCS diffusion.

Figure 3-11 Evolution of Chinese Electricity Generation by Fuel



Source: IEA Energy Statistics 2005

Besides the replacement of existing plants, the immense growth of China's power plant fleet needs to be taken into account. Because of a vast increase in power demand, installed capacities are projected to boost up to 600GW until 2010 and 900GW until 2020 (Guanghua 2003: 19). This implies that China will construct an enormous amount of fossil-fuelled power generation capacities without carbon capture equipment in the coming decade as CCS is not expected to be commercially available before 2015–2020. It is therefore crucial that new power plants apply generating technologies which are adequate for CCS retrofits. To conclude, the promotion of more efficient electricity generating technologies is a fundamental precondition both for CCS retrofits and the construction of new plants including CO_2 capture after 2020. If there are no incentives to increase the efficiency of electricity production, China is unlikely to adopt CCS technologies in a foreseeable future.

National CO_2 Discharge and Potential of CO_2 Storage Sites

Having discharged 3,76Gt of CO_2 emissions from fuel combustion in 2003, China is the world's second largest CO_2 polluter (IEA 2005a: II.115). It will become the largest emittent in a near future and might constitute a key market for CCS. However, the probability of CCS diffusion is restrained by a significant mismatch among the amount of released CO_2 emissions and the available storage potential.

Table 3-9 Potential of Geological CO_2 Storage Options in China

Option	**Deep Coal Seams**	**Depleted Oil Fields**	**Depleted Gas Fields**	**Deep Saline Aquifers (onshore)**	**Deep Saline Aquifers (offshore)**	**Total**
Capacity (GT)	4	1	2	90	9	**106**

Source: Dooley et al 2004: 3

Up to now, there are only rough estimates of China's CO_2 storage potential. On- and offshore saline aquifers represent by far the largest share of available sites. Nonetheless, depleted oil or gas reservoirs and deep coal seems, including potential enhanced recovery operations, are considered the most important near- to mid-term options for CO_2 storage. However, they indicate low storage capacities and will therefore not play a major role in future storage scenarios.

Taking the 2003 total CO_2 discharge of Chinese power plants (1,78Gt) as a basis, the potential of national CO_2 storage sites would last for approximately 60 years. If only 20% of power-related emissions were captured and stored, China's storage reservoirs would endure nearly 300 years. This estimation makes clear that CCS must be only one element of a multiple CO_2 reduction strategy as available storage reservoirs would be only available for a limited period if a major share of power plant emissions was injected. Notwithstanding those constraints, China has to apply CO_2 capture and storage technologies if it aims to comply with the requirements of climate change due to its enormous growth in coal-fired power generating capacities. However, because of its low storage potential, China clearly needs to deploy carbon-free power generating technologies in supplementation to CCS.

Actors
The Chinese government is increasingly aware of CCS but does not actively support the technology due to its high costs and other political priorities. Officials display an open attitude towards international CCS initiatives in China, wherein Western companies or governments carry the financial burden. The government participates in international technology platforms, networks and bilateral partnerships in order to connect and exchange knowledge with prosperous and competent players (CSLF 2005a: 2). At the national level, the institutionalisation of CCS is at a very early stage. Up to now, China has made any indication which authority – the National Development and Reform Commission (NDRC), the Ministry of Science and Technology (MOST) or the Ministry of Commerce (MOFCOM) - should take charge of CCS. Facing the intertwined structure of the Chinese administration, CCS is likely to 'bog down' in the bureaucracy.

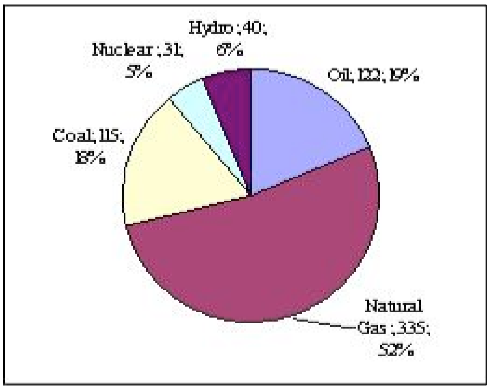
Similar to the national government, Chinese power companies are aware of CCS but unlikely to foster its development and deployment (Interview G. Hill, 15.12.2005: 58). Many power producers suffer from financial shortages and incorporate a 'traditional' management philosophy with only few managers that are open towards advanced clean fossil technologies (Vallentin/Liu 2005: 71). The public awareness of climate change issues is very limited. Hence, it is difficult to understand whether the perception of CCS is positive or negative. Since most NGOs in China have governmental backgrounds, they are unlikely to promote the technology unless the government becomes more proactive (CO_2 Capture Project 2004: 115). It may be concluded that Chinese actors consider CCS as a relevant option and are interested in gaining technology-specific knowledge and capacities. However, the government's strategy concentrates on impulses from industrialised countries which is why the commitment of Western actors is essential for CCS deployment in China.

3.2.5 Russia

Energy Supply and Demand
Russia is relevant for international CCS diffusion as it holds the world's largest natural gas reserves (1.680trillion cubic feet/Tcf), the second largest coal reserves (274 billion short tons) and the eighth largest oil reserves (60 billion barrels) (U.S. EIA 2005b: 2/6/8). Furthermore, it is an important consumer of fossil fuels. In line with the essential meaning of fossil resources for Russia's energy supply, oil, natural gas and coal account for nearly 90% of the national power generation mix. The total installed power capacity amounts to 215GW, including 148,2GW of thermal capacities, 44,3GW of hydro power and 22,7GW of nuclear plants (Grammelis et al 2005: 2). It is projected that the share of coal will increase in the future because of rising gas prices and the extension of gas exports.

The forecasted increase in coal-fired capacity creates the chance to install fossil-fuelled plants which allow CCS. Current generating facilities may not apply CO_2 capture processes since more than 50% of the installed capacities are older than 30 years and operate at efficiencies of 27–33%. About a quarter of the generation fleet ranges of 20–30 years and approximately 20% of 10–20 years (op. cit.: 3).

Figure 3-12 Russia Power Generation Mix; GW



Source: Grammelis et al 2005: 2

Assuming an average lifespan of 35–40 years, more than half of the Russian coal-fired power plant stock needs to be replaced or refurbished at a time carbon capture technology will not yet be available. Existing capacities which are expected to run for another 10-30 years could be theoretically substituted by capture plants. However, both the design of capture-ready plants and the construction of new capture plants would require strong financial incentives. At the time being, such a development seems to be unlikely (Interview T. Schneider, 3.1.2006: 62). Furthermore, it is doubtful if the power sector is capable of raising the necessary financial resources to invest in modern power technologies. Hence, international incentives and technology transfer projects are needed to spread CCS in Russia.

National CO_2 Discharge and Potential of CO_2 Storage Sites

Although the collapse of the Soviet Union and Russia's economic decline led to a dramatic decrease in CO_2 emissions in the early- and mid-1990s, Russia is the world's third-largest CO_2 source. In 2003, total national carbon dioxide emissions from fuel combustion amounted to 1,5Gt of which the power sector generated 278,5Mt (IEA 2005a: II.321). However, Russia's total CO_2 discharge is significantly lower than the emission rate of China and the U.S. . It is not expected to reach the 1990 level before the end of the first Kyoto commitment period.

Table 3-10 Potential of Geological CO_2 Storage Options in the Former Soviet Union

Option	Deep Coal Seams	Depleted Oil Fields	Depleted Gas Fields	Deep Saline Aquifers (onshore)	Deep Saline Aquifers (offshore)	Total
Capacity (Gt)	5	6	70	101	378	**560**

Source: Dooley et al 2004: 3

Country-specific data on Russia's geological CO_2 storage capacities are not yet available which is why the following discussion is based on the Former Soviet Union's portfolio of possible storage formations. In relation to Russian power sector emissions, the latter offers an immense theoretical potential for CO_2 storage which would last for more than 2000 years – a time period that can be hardly conceived. Deep saline aquifers represent the lion's share of potential CO_2 reservoirs but as Russia has the world's largest natural gas reserves, depleted gas fields also constitute an attractive option. Thus, the further development of EGR procedures might constitute an important opportunity. Empty oil fields and deep coal seams indicate a smaller but in comparison to the other case studies considerable storage potential. However, many oil, gas and coal reservoirs are located far distant from large fossil-fired power stations. CO_2 injection would, thus, require the construction of a gigantic pipeline system. With regard to current financial constraints and logistic problems, such a development seems to be unlikely.

As the given data take into account storage sites in the area of the Former Soviet Union, the discussed timeframe only describes a rough tendency of Russian CO_2 storage options. Nonetheless, it may be concluded that available geological storage sites display a high potential which is, however, constrained by the remote location of most fossil fuel reservoirs. As a consequence, high infrastructure and transportation costs would occur. Furthermore, the conditions for CO_2 capture from power plants are rather unfavourable due to the ageing structure of the Russian power plant fleet and financial shortages. Hence, there is currently little indication that CCS might deploy in Russia in a mid-term future unless strong financial incentives come up.

Actors

The Russian government and power producers are generally open towards advanced clean coal technologies such as CCS but focus on energy security and the restructuring process of the energy sector. The latter is currently binding considerable financial and personnel capacities of the government and the industry, impeding capital-intensive technology projects. Hence, the Russian energy sector lacks a positive climate for national and international CCS investments (Interview T. Schneider, 3.1.2006: 62). This barrier is consolidated by uncertainties concerning the market reform's outcome as the government obviously seeks to use gas and oil exports as a political leverage and due to striking financial shortages at the supply side caused by low electricity tariffs.

Similar to China, CCS-related activities in Russia mainly entail from international cooperation. The government is a member of the Carbon Sequestration Leadership and academic institutes, such as the All Russian Thermal Engineering Institute (VTI), participate in international networks which foster CCS development (Interview T. Schneider, 3.1.2006: 63). Concerning knowledge transfer and capacity building, the European-Russian Energy Dialogue could play an important role as it led to the establishment of the EU-Russia Energy Technology Centre (ETC) which is commonly led by Russian and German scientists. However, CCS is currently a top priority issue in this dialogue (op. cit.).

It may be concluded that – unless international partnerships such as the Energy Dialogue with the EU provide support - Russian actors are highly unlikely to take a lead in CCS development and deployment in a near- to mid-term future due to the low priority of climate policy and financial problems.

3.3 Institutional Systems Framing CCS Diffusion

The diffusion of CCS technologies strongly depends on institutional systems which either stimulate or restrain the deployment process. ‘Institutional systems’ cover regulations, policy incentives and technology initiatives like R&D activities or pilot and demonstration projects. In the following, international and national institutional systems framing CCS diffusion are discussed.

3.3.1 International CCS Regulations, Policies and Technology Initiatives

The main international institutional systems relevant for CCS activities are the Law of the Sea (UNCLOS), the marine environment protection framework and the climate policy regime. The first two policy areas determine the legal conditions for dumping wastes and other matter at sea. International climate policy is the most important policy area for CCS market deployment as it is capable of creating incentives for investments in CCS technologies and stimulating the introduction of national CCS policy frameworks. In the third sub-chapter, international technology initiatives are investigated as those represent the bulk of current activities on capture and storage technologies.

3.3.1.1 International Climate Change Policy

When the Kyoto Protocol was drafted, little was known about the opportunity of CCS and the role it could play. Nonetheless, the Kyoto Protocol “requires its Parties to implement and/or further elaborate policies and measures such as research on, and promotion development and increased use (…) of carbon dioxide sequestration technologies and of advanced and innovative environmentally sound technologies” (Kyoto Protocol 1997, Art. 2.1 (a) (iv)). Furthermore, the protocol requests the elaboration of guidelines and rules as to how changes in greenhouse gas emissions by sources and removals by sinks shall be treated with respect to the national reduction targets (Art. 3.4). These statements demonstrate that the Kyoto Protocol paved the way for the integration of CCS into the legal framework of international climate policy. The 2001 Marrakesh Accords constitute another step forwards in that they “encourage nations to cooperate 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 requests advanced industrialized nations to facilitate the participation of the least developed countries and other developing countries in this effort” (Marrakesh Accords 2001, Decision 5, III (26)). In the following years, carbon capture and storage was continuously discussed at the international stage without being explicitly mentioned in further declarations or decisions. In April 2006, modified IPCC Greenhouse Gas Inventory Guidelines are going to be adopted which will contain a chapter on CCS. A relevant question in this context is whether CCS should be treated as an option that reduces CO_2 emissions by source or as a CO_2 sink[21]. Categorising CCS as a sink enhancement like biomass stocks is problematic as the timescales and the characteristics of CO_2 release for CCS are very different. Hence, the revised Guidelines will

[21] The first option treats the captured CO_2 as if it had never been emitted. The second case considers it as emitted into the atmosphere, although it has been removed at the stack, and would report captured emissions under the category of Land-Use, Land-Use Change and Forestry (LULUCF).

chose the 'by source'-approach (Coninck et al 2005: 7). This choice has consequences for the treatment of CCS under the flexible mechanisms of the Kyoto Protocol as the category in the inventories is usually applied to the accounting rules for greenhouse gas reductions.

At the time being, it is unclear how CCS will be dealt with under the Kyoto regime. Experts consider the inclusion of CCS into the framework of flexible mechanisms as a crucial precondition for the deployment of CCS since it would create economic incentives. Concerning the Clean Development Mechanism (CDM), only one CCS project proposal for carbon capture and offshore EOR in Vietnam has been submitted to the CDM Executive Board which considered it in its 22nd meeting in November 2005. In the meeting report, the Board states that it could not come to an agreement and requested guidance from COP/MOP on whether CCS projects can be considered as CDM project activities, taking into account problematic issues like project boundary, leakages and permanence. At the COP 11 in Montreal, MOP requested the secretariat to organise a workshop on the treatment of CCS under the CDM, enabling the Executive Board to prepare recommendations on how to approve CCS projects as CDM projects by MOP 2 (Wittneben et al 2005: 14). The negotiation process indicates that the inclusion of CCS into the existing framework of international climate change policy is a highly complex task which has the potential to inhibit CCS investments. This is confirmed by the fact that some companies are currently assessing the opportunity to undertake CCS activities as CDM projects but are reluctant due to persisting regulatory uncertainties (Cozijnsen 2005: 28).

The international diffusion of CCS and its application under the CDM and Joint Implementation (JI) mechanism is strongly affected by the question if future carbon prices will compensate the costs of implementing CCS. Hence, establishing an international carbon market constitutes an essential prerequisite for the deployment of CCS technologies. In that context, the regulatory treatment of CCS under the European emission trading scheme (ETS) and the entailing impulse to the technology's diffusion provide an important precedence. To date, the European carbon market is characterised by a low volume of traded carbon permits and does not create a sufficient incentive for investments in capital-intensive CCS technologies as the power companies may incorporate carbon prices into the electricity tariffs. The development of the market is uncertain as it is strongly determined by future emission reduction targets and the allocation of carbon permits. With regard to regulatory issues, the EU ETS Directive does currently not contain specific provisions for CCS. Aiming to prevent a regulatory vacuum, the 2004 EU ETS Monitoring Directive encourages the member states to develop "guidelines on the monitoring and report of CCS under the ETS and submit them to the Commission in order to promote the timely adoption of such guidelines" (EU ETS Monitoring Directive 2004/156/EC, Annex I, 4.2.2.1.3).

For that purpose, the UK formed an 'Ad Hoc Group of EU Experts on Monitoring and Reporting for CCS in the EU ETS' which consists of more than 20 experts from academia, industry, government, the European Commission, NGOs and consultancy agencies. The group formulated a template for the monitoring of CCS under the ETS which was recently delivered to the European Commission. The guidelines involve "direct measurements of CO_2 flows across a CCS chain (capture-transportation-injection) with the subsequent application of a mass balance reconciliation" in order to cover all fugitive emissions along the chain (UK DTI 2005a: V). Doing so, the developed guidelines address the fact that not all facilities involved in CCS procedures are part of the EU ETS. For example, even though pipelines and geological storage sites are not per se covered by the EU ETS, the guidelines ensure that emissions occurring at these elements of the CCS chain will be reconciled with the allowance allocation of the addressed installation, e.g. a power plant (op. cit.: 17)[22].

Despite the mass balance reconciliation model, the limited range of facilities covered by the ETS Directive creates problems for CCS diffusion as it weakens the incentive to investments. Oil or gas production installations with CO_2 injection for EOR, ECBM or EGR are not included as the treated and injected carbon dioxide is regarded as process emissions[23] which are not object of the EU ETS (Conzijnsen 2005: 35). The case of zero emissions power plants (ZEPP) has not yet been clarified. On the one hand, ZEPP exceeding a thermal input of 20MW are a combustion installation for energy activities as covered by the ETS Directive. On the other hand, most planned ZEPP are pilot or demonstration plants which are explicitly excluded from the trading scheme (EU ETS Directive, 2003/87/EC, Annex I).

Another important issue concerning CCS diffusion is the accountability of CO_2 savings from CDM or JI projects to the EU ETS. In its recent Linking Directive, the Commission allows carbon reduction credits entailing from CDM or JI to be converted into allowances under EU ETS. No special requirements have been placed upon CCS projects, suggesting that the criteria for evaluating CCS projects under the CDM will be the regular ones (CO_2 Capture Project 2004: 12). This treatment is encouraging but if future provisions are going to induce CCS deployment remains to be seen.

To conclude, CCS is widely perceived as a relevant issue of future climate change policy. Due to high capital costs, their integration into the framework of flexible carbon mitigation mechanisms is an essential prerequisite for CCS diffusion. However, as the parties of the UNFCCC have repeatedly encouraged the development and diffusion of CCS, the current regulatory vacuum is not expected to be a barrier in the future. Concerning the inclusion of CCS into emission trading schemes - the most important Kyoto mechanism for the technology's deployment - the European example shows that the inclusion of CO_2 injections for EOR, EGR or ECBM is a key issue since enhanced recovery methods are the most economic viable storage options.

3.3.1.2 International Law of the Sea and Marine Environment Protection

Besides the international climate policy regime, offshore carbon storage is covered by the international law of the sea and several treaties addressing marine protection. The 1982 United Nations Convention on the Law of the Sea (UNCLOS) is the most significant international marine convention and provides a general framework for more

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22 A detailed list of the installations covered by the EU ETS is contained in Annex I, ETS Directive 2003/87/EC.

23 Process emissions are defined as „greenhouse gas emissions other than ‚combustion emissions' occuring as a result of intentional and unintentional reactions between substances or their transformation,…" (ETS Monitoring Directive 2004/156/EC, Annex I, 2 (o)).

specific treaties. The UNCLOS is not directly relevant for carbon capture and storage but leaves leeway for more specified documents. Doing so, the 1972 'Convention on the Prevention of Marine Pollution by Dumping of Wastes and other Matter' (London Convention) is the most important document regarding sea dumping of industrial waste or other matter. However, the convention only prohibits dumping from vessels, aircrafts, platforms or other man-made structures in the water column (London Convention, Art. III 1(a)). It is thus of limited relevance for offshore carbon storage since it does neither consider storage in the ocean seabed or its subsoil nor injection from a land-based pipeline[24] (IEA 2005b: 24). Moreover, the question if, or if not, CO_2 is considered as industrial waste needs further clarification. In November 2004, the Parties of the London Convention agreed that the issue of CO_2 storage should be included in their work programme and that legal, scientific and technical issues need to be examined (op. cit.: 25).

Beneath the London Convention, there are several regional treaties for marine environment protection. The one most widely known is the 1992 'Convention for the Protection of the Marine Environment of the North-East Atlantic' (OSPAR), which governs marine disposal from the Arctic to Gibraltar and from the East coast of Greenland to the West coast of continental Europe. Prohibiting each form of sea dumping, its regulations are considerably stricter than those of the London Convention. In 2004, the OSPAR Jurists and Linguists Group (JL Group) elaborated an initial strategy for the treatment of carbon storage which permits both CO_2 disposals from land-based and offshore sources. The usage of CO_2 for enhanced oil or gas recovery is explicitly permitted. Furthermore, a group of industrial CCS experts submitted proposals for the treatment of offshore CO_2 storage to the OSPAR Commission (Interview W. Heidug, 12.12.2005: 47). However, none of the documents has yet been translated into binding decisions.

Table 3-11 Proposal of the JL Group for the Treatment of CO_2 Storage under OSPAR

Method of CO_2 Disposal	**Permitted**	**Prohibited**
Discharges from land-based sources (e.g. pipelines, tunnels)	X*	
CO_2 disposal classified as dumping from a vessel		X
Carbon disposal from a vessel for scientific research	X	
Disposal of CO_2 produced at an offshore installation	X*	
Disposal of CO_2 generated at an offshore installation for scientific research	X	
Disposal of non-offshore CO_2 transferred to an offshore installation for the purpose of enhanced hydrocarbon production	X*	

* Authorisation or regulation is required

Source: IEA 2005b: 27

The OSPAR Commission is likely to take a lead in integrating offshore carbon storage into regional environment marine protection legislation. Even though the concept is only an initial step, it suggests that offshore CO_2 storage will underlie strict authorisations and regulations but is unlikely to be inhibited. Further debates on that issue are needed in order to provide a reasonable legal framework at the international level until CCS is expected to deploy. Especially the question if CO_2 is classified as waste constitutes a major uncertainty for CCS deployment and needs to be answered. Taking into

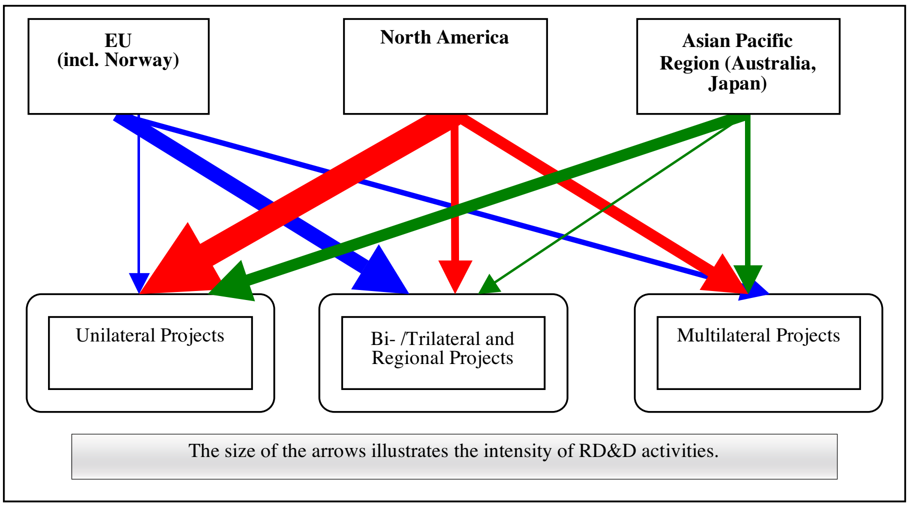
[24] In 1996, the London Protocol was designed to replace the London Convention. The treaty prohibits dumping and storage of waste in the water column as well as the seabed and its subsoil and is, therefore, more relevant for carbon storage than the London Convention. However, the Protocol did not yet enter into force as it was not ratified by a sufficient number of parties.

account that a high share of potential CO_2 storage sites, like oil fields, gas fields and saline aquifers, are located offshore, the impact of regulatory issues related to marine environment protection on the process of CCS diffusion becomes clear.

3.3.1.3 International CCS Technology Initiatives

The previous discussion of international treaties indicates that there is a vacuum concerning the legal treatment and political-economic inducement of CCS technologies. This phenomenon may be traced down to the strong international focus on RD&D efforts due to the early state of development of CCS technologies. Consequently, the time for policy instruments to stimulate the technology's broad diffusion is yet to come. According to the International Energy Agency, about 90 CCS RD&D projects are being conducted (IEA 2004a: 153). Three regional 'centres' of CCS development may be identified: The United States and Canada (North America), the European Union plus Norway and Japan and Australia (Asian-Pacific Region). On-going CCS projects imply different scopes and include unilateral (national), bi- or trilateral (often regional) and multilateral activities. Whereas the European member states focus on regional EU projects with rather few unilateral programmes, the U.S., Canada as well as Australia and Japan are more active at the national level. Actors from all regional centres are interacting at the international stage but only some projects have been organised as multilateral joint ventures, involving players from different regional CCS 'centres' (see figure 3-13). This situation might be explained by specific regional or national technology interests and increasing competition in the development of innovative power generating technologies.

Figure 3-13 Scope of CCS RD&D Projects



Source: Author

At the time being, the IEA Greenhouse Gas (GHG) Programme, the CO_2 Capture Project (CCP), the Carbon Sequestration Leadership Forum and the IEA Weyburn Monitoring and Storage Project are the most important multilateral CCS RD&D activities. The IEA GHG Programme is a collaboration of governments and industries from many countries, aiming to identify and evaluate possible carbon mitigation options. Since it was established in 1991, its main focus has been on CCS. The CCP is an international effort, seeking to develop efficient CCS technologies. The project's overall funding of US$28million is contributed by the U.S. Department of Energy, the EU and the Norwegian Klimatek programme plus nine of the world's leading energy companies (Hill 2003: 7). The Weyburn Project, which is facilitated by the IEA GHG Programme, coordinated by the British Geological Survey and managed by PanCanadian Resources, is a joint collaboration among research groups from the UK, the U.S., Canada, Denmark and Italy, investigating the degree of security at which CO_2 can be sequestered during large-scale EOR operations (op. cit.: 10).

Different from these projects, the Carbon Sequestration Leadership Forum aims at connecting international CCS advocates in order to stimulate the exchange and gathering of information. It was set up by U.S. DOE in 2003 and convenes 21 member countries. Considering the limited number of projects involving different regional CCS development centres, the CSLF's objective to strengthen international cooperation is of essential relevance for the diffusion of carbon capture and storage technologies. The coordination of national and regional research plans may reduce inefficiencies in technology development and foster the process of technology learning. Hence, the announcement of the Gleneagles Action Plan on Climate Change, Clean Energy and Sustainable Development – which was adopted at the G8 summit in August 2005 - to endorse the objectives of the CSLF and to encourage international collaboration constitutes an important step.

The G8 leaders furthermore emphasised the necessity to involve developing countries into CCS research, development and demonstration. Doing so, they touch upon an obvious flaw of current RD&D activities which are concentrated in industrialised countries. Even though countries like China, India or Russia are members of the CSLF, there is comparatively little collaboration among transition or developing countries and industrialised nations. At the time being, the Chinese-Canadian ECBM pilot project in Shanxi province, the application of EOR at the Liaohe oil field in China and the BP In Salah Project in Algeria are important activities of that category. Taking into account that the bulk of large-point emission is predicted to shift to South East Asia, China and Latin America (IPCC 2005a: 84), technology-specific capacity building as well as knowledge and technology transfers to these regions are important prerequisites for international CCS diffusion. Hence, the scope of international RD&D activities needs to be broadened.

This section's conclusion is that multilateral CCS RD&D joint-ventures are of particular importance as they cumulate expertise from different regional CCS centres and increase the efficiency of RD&D measures. Hence, the G8 statement to foster international cooperation under the roof of the CSLF is a commendable step. However, the key task with respect to future CCS deployment is to promote the technology in developing and transition economies like China, India and Russia. Even though carbon capture and storage is hardly possible under current conditions in these countries, capacity building and R&D efforts have to start now if CCS shall become a long-term option.

3.3.2 National CCS Regulations, Policies and Technology Initiatives

A coherent framework of national regulations and policy incentives which diminish legal uncertainties and economic risks constitutes a crucial precondition for CCS diffusion. Due to the one-dimensional concentration on RD&D activities, there is no country with a fully developed regulatory and political strategy for CCS – even though interested governments increasingly recognise the necessity to adapt national legislations to carbon capture and storage technologies in order to avoid regulatory gaps. This chapter investigates national regulations, incentives and technology initiatives related to CCS with specific respect to the five case studies selected in chapter 3.2. Moreover, the discussion summarises examples of initial regulations and incentives in other countries (see table 3-12). Those indicate that industrialised, fossil fuel-producing countries, which benefit from the exploitation of fossil energy resources and carry Kyoto targets, are more engaged and competent in regulating and inducing CCS than other nations. The following sections discuss if these assumptions also apply to our case studies.

3.3.2.1 Germany

The German discussion on carbon capture and storage technology is at an early stage due to the fact that the country has only small oil and gas reservoirs which enable the application of early opportunities for CCS projects. However, CCS is an evolving issue because of the high share of coal-fired power capacities and the obligation to comply with international carbon reduction commitments. To date, there is neither a specific regulatory framework to carbon storage nor a consistent strategy of the government for drawing up such a framework. Regulations which are likely to be extended to the requirements of CCS are federal laws for the exploitation and production of mineral resources (Berggesetz; BBergG) and waste disposal (Kreislaufwirtschafts- und Abfallgesetz; Krw/AbfG). At the time being, it is yet to decide if carbon storage would be regulated under the BBergG or Krw/AbfG. The former one includes provisions for the construction and operation of underground natural gas storages (BBergG, §126) and drilling activities (BBergG, §127) which could be adjusted to CCS activities. The Krw/AbfG controls the environmentally benign disposal of waste but does not include the regulatory treatment of CCS. Experts recommend to assigning the approval procedures for CO_2 storage projects to the BBerG as the responsible authorities have a high expertise in and experience of drilling and monitoring processes (Interview R. Sedlacek, 5.12.2005: 33). Because of the high compatibility of existing regulations and provisions required for geological CO_2 storage, regulatory issues are not expected to be a barrier to CCS diffusion and will most likely develop when the first large-scale projects come up. In the case of the European CO_2SINK project during which the first CO_2 injection in Germany was conducted, the lack of a specified legal framework did not inhibit the trial. Since the operation was part of a research project, which only involved the injection of a small amount of CO_2, the responsible local authorities merely required to give proof that the injections were safe (Interview W. Heidug, 12.12.2005: 45).

Table 3-12 Examples of Initial National Regulations, Policy Incentives and Governmental Technology Initiatives for CCS in Other Countries

Country	Regulations	Policy Incentives	Governmental Technology Initiatives
Australia	**South Australia Petroleum Legislation:** The South Australia Petroleum Act explicitly lists CO_2 as a regulated substance, regulating CO_2 pipeline transport (South Australia Petroleum Act, s4, s10 (1)(g)). The South Australia Petroleum and Gas (Production and Safety) Act regulates the licensing of CO_2 underground storage.	**CCS Funding:** In its recent Energy White Paper, the Australian government announced to invest US$371million to promote commercially viable abatement technologies, including coal-fired generation with CCS (Australian Government 2004). However, funding is focused on technology policies.	**On-going RD&D Projects (McLaren et al 2005: 48):** COAL 21: Investigates a variety of technologies, including CCS. 'Energy Transformed' project: Involves research into geosequestration technologies. Cooperative Research Centre for GHG Technologies (CO_2-CRC): Aims to bring government, industry and research bodies together to develop and apply CCS.
	Barrow Island Act 2003: The Act was designed to facilitate the Gorgon project. It prohibits CO_2 storage without ministerial approval, sets out the approval process and official consultation procedures (Mc Laren et al 2005: 57/58). **Regulatory Guiding Principles for CCS:** In 2005, the principles were presented by a Regulatory Working Group. The report identifies important CCS-related existing regulations and discusses possible legislative adjustments (Australian MCMPR 2005).		**Project Proposals (Australian MCMPR 2005: 14)** There are four proposals for commercial CCS projects: Gorgon project offshore Western Australia: Reinjection of 125million tCO_2 contained in natural gas. Two Demonstration Projects in Queensland (the Stanwell and CS Energy Projects): The projects aim to capture and store CO_2 produced from power generation. Monash Energy Project in Victoria: Storage of CO_2 from a lignite-based, coal to liquids project.
Canada	**Intentions to Develop a Framework:** To date, existing regulations for pipeline transportation, water protection and fishery are extrapolated to CCS. The government is currently aiming to develop a CCS-specific legal framework.	**CCS Royalty Credit Programme:** In order to facilitate CCS diffusion, the two-year programme supports CO_2-based enhanced oil and gas recovery in small-scale commercial projects that are near-economic. The level of funding that is available in each of the two years is US$7,5million (Natural Resources Canada 2004).	**On-going RD&D Projects (CCCSTN 2004b: 1):** At the time being, Canada is conducting or participating in about 25 CCS-related projects, allocating funding of more than US$114million. The following projects are among the most important ones: CANMET CO_2 Consortium: The project is conducting research on the demonstration of oxy-fuel combustion technologies for CCS. Canadian Clean Power Coalition: The coalition aims to operate a full-scale plant with CO_2 capture by 2012.

Nether-lands	**2003 Mining Act and Mining Degree:** Both regulations provide a regulatory basis for the storage of substances deeper than 100 metres (Netherlands Mining Act 2003, Art.4) and offshore storage. The regulations are kept general but the possibility of CCS is explicitly taken into account. **Gaz de France Demonstration Project:** For the offshore CCS project only an adjustment of the existing mining permit and environmental legislation was required (Cozijnsen 2005: 23).	**2003 Electricity Act:** The Act includes a tax exemption worth approximately US$30-48million in the first year which increases every year by between US$30-36million. It supports renewable energy, energy efficiency and climate neutral electricity, including CCS. **Investment Subsidy Support Programme** Recently, a CCS investment subsidy support programme of approx. US$180million has been dedicated into the 2006 budget for 'Clean Fossil Fuels' projects.	**On-going RD&D Projects:** The government is funding a number of CCS RD&D and pilot projects with increasing EU assistance: CRUST (CO_2 Reduction and Underground Storage): The project comprises feasibility studies for two projects looking at different technologies for gas field storage. The feasibility studies received subsidies of US$1,2million and a further US$11 million of funding was paid for implementing one pilot project. CATO: A CCS knowledge network formed in 2004.
Norway	**Adaptation of Existing Regulations:** The Norwegian Energy and Water Authority gives concessions for power plants and is expected to permit CCS projects. Other regulatory issues are unlikely to constitute a barrier as Norway has an extensive legal framework for gas storage and pipeline transport (Carbon Capture Project 2004: 44). **Gentlemen's Agreement:** In the case of the Sleipner storage project, regulatory concerns, such as safety issues, were covered via a gentlemen's agreement among the responsible State authority and the operator Statoil (Interview W. Heidug, 12.12.2005: 45). The lack of regulations did thus not affect the project.	**CO_2 Tax:** The Norwegian carbon tax was introduced in 1991 and covers approximately 64% of Norway's CO_2 emissions. A particularly high tax rate is imposed on oil and gas production at the Norwegian continental shelf. As CO_2 stored in geological formations is exempted, the tax induced the first commercial CCS project at the Sleipner field. **Demonstration Project Funding:** The previous government announced to set up a cooperation programme with the industry and an economic 'start-up package' including tax exemptions (Norway Ministry of the Environment 2002: 44). In 2003, it handed out US$2,3million for early demonstration projects. **Future Funding of CCS:** In November 2005, the new government announced its plan to allocate US$3million to CCS. Projects on legal aspects, the construction of a capture plant in Karstø and the commercial utilisation of CCS will come up in 2006 (Norway Ministry of Petroleum and Energy 2005a/2005b).	**On-going RD&D projects (CSLF 2004: 1)** KLIMATEK programme: Many national CCS projects are bundled under the KLIMATEK programme which was created to promote technology development for reducing GHG emissions. All KLIMATEK projects are partly funded by private actors. In 2004, the programme had a total budget of about US$76million. Approx. 60% of the budget is devoted to CCS. CLIMIT programme: The project is operational since January 2005 and prioritises research, development and testing of technologies for gas-fired power plants with CCS. GASSNOVA: The government established a new public facility to promote carbon abatement technologies. In 2005, Gassanova administered approx. US$14,9million. Snøhvit Injection: Industry-funded construction of a LNG export facility with CO_2 re-injection.

United Kingdom	**Gap Analysis of Existing Regulations:** In the British Carbon Abatement Strategy, it is announced that a gap analysis of existing regulations with respect to CO_2 storage will be conducted. Afterwards, a working group of regulatory agencies will be established to develop a legal framework for the storage and transport of CO_2 (UK DTI 2005b: 45).	**Possible Exemption from the Climate Change Levy (CCL):** The government considers exempting CCS from the CCL, similar to good quality CHP and renewable energy sources. This incentive would be comparable to the estimated 0,3-1,7 US$/kWh needed to make EOR viable. It would be insufficient to induce less economic storage options (e.g. in aquifers) which require funding of 1,7-4p/kWh (UK DTI 2003: 22).	**Proposed RD&D Projects:** British entities and experts are active in several international projects but there are no ongoing national initiatives. The following projects are planned: EOR Demonstration Project: The DTI has already prepared a study on the Implementation of an EOR Demonstration Project. Carbon Abatement Strategy 2005: The CAT Action Plan proposes to support a demonstration of a capture-ready power plant (UK DTI 2005: 49). Brown Fields Think Tank: In 2004, the PILOT initiative created an entity to evaluate technologies for increasing oil recovery, including EOR.

This example indicates that the responsible authorities do not generally oppose CO_2 storage. However, it does not create a precedent for future commercial CO_2 storage operations as regulatory provisions for small R&D projects are less stringent than for large-scale activities (Interview W. Heidug, 12.12.2005: 45).

Similar to the lack of legal prerequisites, Germany has not yet established policy incentives to the application of near-to economic CCS projects. This is mainly attributed to the fact that the government has yet to formulate a common position regarding CCS (see chapter 3.2.1). To date, national CCS activities are focused on technology research and development, being incorporated in the COORETEC programme. Furthermore, Germany is participating in EU projects on CCS, e.g. CO_2SINK and CASTOR. COORETEC supports the development of oxy-fuel-based post-combustion capture technologies and IGCC with pre-combustion separation processes as well as research on the underground behaviour of CO_2 (German Ministry of Economics and Labour 2005b: 27). The programme is funded with US$17,9million of government spending plus US$17,9million contributed by the industry. It is, however, not possible to assign a certain amount to CCS as the published data are not detailed enough.

Regarding mechanisms to stimulate the application of CCS technologies, the German government considers the EU ETS as the main policy driver for CCS diffusion. At the national level, no CCS-specific incentives are being planned. CCS is not mentioned in essential German climate policy documents - such as the 2000 and 2005 National Climate Protection Programmes, the Third National Inventory on Climate Change and the National Strategy for Sustainable Development – and, hence, is not yet considered to be an integrated part of the national GHG reduction strategy. However, as the decision to phase-out nuclear power until 2020 is expected to result in an expansion of fossil-fired electricity generating capacities, which might entail a significant growth of GHG discharges, the phasing-out process in combination with the Kyoto target provides an indirect incentive to CCS diffusion.

It may be concluded that the discussion on regulatory and political conditions for CCS in Germany is in its initial phase. The high compatibility of existing regulations, the nuclear phasing-out process in combination with progressive CO_2 reduction targets and the EU ETS have the potential to create a favourable environment for CCS diffusion. However, direct national policy inducements are unlikely to be established so that European and international policies will decisively determine national conditions for CCS diffusion.

3.3.2.2 Denmark

In its 2003 Climate Strategy Proposal, the Danish government recognised that the large CO_2 reduction potential of CCS “can cover all of Denmark’s reduction commitment” (Danish Government 2003: 16). However, there are no CCS-specific national regulations, policy incentives or technology initiatives as the government is waiting for further initiatives at the international stage (Interview F. Nissen, 27.10.2005: 7).

The most relevant regulation is the Danish Subsoil Act which provides general guidelines to "ensure appropriate use and exploitation of the Danish subsoil and its natural resources" (Consolidated Act on the Use of the Danish Subsoil 2002, s1 (1)). Besides the exploration and production of raw materials, the act applies to the "use of the subsoil for storage or for other purposes than the production of raw materials" and might regulate carbon storage activities. Doing so, CCS offshore projects would require an environmental impact assessment as well as a hearing of the public, authorities and organisations affected by the activity (s28a (1)). Local or national environmental associations or organisations may appeal against the decision of the assessment (s37a (2)). This significantly increases the influence of NGOs on the approval of carbon storage operations and strengthens their role in the deployment process. In comparison to offshore carbon storage, onshore CO_2 storage is expected to encounter more difficulties due to stringent groundwater regulations. Groundwater protection and the related legal realm of waste disposal are subjects of the Danish Environmental Protection Act which ensures that the disposal or storage of waste does not pollute air, water or soil (Consolidated Environmental Protection Act, s43 (1)). As a consequence, the future regulatory treatment of CO_2 storage in Denmark decisively depends on the international classification of carbon dioxide (see chapter 3.3.1.2). Experts come to the conclusion that stringent groundwater regulations in combination with uncertain regulatory conditions are likely to be a barrier to Danish CCS projects (Carbon Capture Project 2004: 72).

Due to the government's "wait-and-see" approach (op. cit.: 70), there are no national technology initiatives or policy incentives clearly devoted to CCS. A first research project was established several years ago but its funding has been subsequently reduced from more than US$16million to US$4,8million (op. cit.: 70). In 2001, Elsam initiated a project named 'CO_2 for EOR in the North Sea' (CENS) to develop a CO_2 pipeline infrastructure in the North Sea but its realisation failed due to a lack of interest by the concerned industries (Interview F. Nissen, 27.10.2005: 6). Instead of national activities, Denmark is participating in various European and international CCS programmes and networks, such as the CSLF and the IEA GHG Programme, and locates some international pilot projects[25]. The international orientation of Denmark's CCS technology policy suggests that the government is waiting for international initiatives.

This tactic is in line with the coalition's strategy regarding CCS policy incentives. The government directs its attention to international climate policy mechanisms, in particular the European ETS, and expects them to stimulate CCS development and deployment. Confirming this cautious approach, the Danish Proposal for a Climate Strategy announces that strong carbon mitigation instruments will not be adopted independently from the other European member states (Danish Government 2003: 22), emphasising the need to pursue a cost-effective CO_2 abatement policy. It may be concluded that regulatory issues do not constitute a serious barrier to CCS in Denmark. Instead, CCS diffusion strongly depends on the progress of European and international climate policy due to the national government's cost-oriented 'wait-and-see' strategy. Without international incentives, CCS diffusion is unlikely to appear in Denmark.

[25] Besides the post-combustion pilot capture plant in Esbjerg (see chapter 3.2.2), Statoil and a number of other European governments and companies obtained funding from the European Commission to investigate how CO_2 from the Kalundborg refinery can be injected into a formation to the North of the site.

3.3.2.3 The United States

In the U.S, there is no specific regulatory framework for CCS even though EOR has been conducted since the early 1980s. However, in all oil-producing states existing regulations are extended to carbon injection activities under the Federal Underground Injection Control (UIC) program (which is under the auspice of the Safe Water Drinking Act) in order to license EOR projects. Furthermore, current safety standards for natural gas storages - which are supervised with monitoring protocols to avoid leakages and negative environmental impacts - are expected to be applied to CO_2 storage.

Despite overlaps between CO_2 storage and existing regulations, there are important divergences among EOR operations or natural gas storage and CO_2 storage. Different from natural gas storage activities, CO_2 storage is not a temporary but a permanent solution and necessitates adjustments in the U.S. legislation. Concerning EOR, most operating projects reuse the injected carbon dioxide in order to reduce costs. There is a lack of an official permitting procedure for utilising EOR as a means of carbon mitigation that might lead to planning delays of CCS projects (Forbes 2002: 2). Until 2010, the U.S. Department of Energy aims to establish a monitoring and verification programme (U.S. DOE 2003: 6); regional sequestration partnerships shall address regulatory analogs for geological carbon storage (op. cit.: 11) in order to close the current regulatory gap. Nonetheless, U.S. activities on CCS-related regulatory issues are underdeveloped in comparison to the government's strong commitment to technology research and development. U.S. CCS RD&D activities are bundled in the Carbon Sequestration Project which is part of the Climate Change Technology Programme. The programme requested US$67million in the FY 2006 budget which means a US$22million funding increase relative to the 2005 budget (U.S. Senate 2005). The high amount of financial resources allocated to CCS projects underlines the technology's high priority for the U.S. government.

Similar to the development of CCS-specific regulations, the Bush administration has not yet adopted policy incentives for the market penetration of CCS technologies. To date, there are almost no inducements for commercial or near-to commercial carbon capture and storage projects as the U.S. carbon sequestration roadmap is dominated by technology policies. Previous EOR and ECBM operations have been encouraged through a tax incentive provided by section 29 of the U.S. Windfall Profits Act[26] which is, however, unlikely to be extended to additional CCS projects. Experts consider a federal emission trading scheme to be the most likely future carbon mitigation instrument as there is a growing number of legislative proposals in the U.S. Senate along those lines (Interview Sarah M. Forbes, 8.12.2005: 43). Presently, American climate change legislation only includes a voluntary GHG reporting programme for large-point sources under section 1605 (b) of the Energy Policy Act. The programme's reporting guidelines have been reviewed recently and explicitly take into consideration the accountability of emission reductions via carbon storage (U.S. Guidelines for Voluntary Greenhouse Gas Reporting, §300.8 (h) (3)). The reporting programme and the reviewed guidelines could provide a basis for a federal emission trading scheme which induces CCS investments.

[26] The section was designed to encourage the production of domestic energy from non-conventional sources.

Since the federal government does currently have no intention to introduce a national ETS, the momentum for CCS investments is coming from the grassroots (Interview Sarah M. Forbes, 8.12.2005: 42/43). Several states have developed GHG mitigation regulations[27] and regional alliances are evolving in order to coordinate efforts and resources to reduce GHG emissions. For example, the Western Governor's Global Warming Initiative, including the States of California, Oregon and Washington, is expected to adopt a common GHG registry system which will pave the way for a cap-and-trade system (Chan et al 2005: 15). Likewise, the Regional Greenhouse Gas Initiative (RGGI), comprising of Connecticut, Delaware, Maine, Massachusetts, New Jersey, New Hampshire, New York, Rhode Island and Vermont, is working to develop and implement a multi-state GHG emission trading market (op. cit.: 16). Even though it is not clear yet how CCS operations are going to be accounted in those regional schemes, they have the potential to create a momentum for abatement technologies like CCS. Hence, State-level activities may show a positive impact on CCS diffusion but to achieve widespread deployment, more ambitious carbon mitigation policies at the federal level are needed.

3.3.2.4 China

As shown in chapter 3.2.4, CCS development and deployment is an evolving but not a top priority issue in China since the political leadership's focus lays on economic development and energy security (Interview G. Hill, 15.12.2005: 58). During the last years, the Chinese government has been involved in international initiatives like the Carbon Sequestration Leadership Forum but did not set up a national legal or political framework devoted to CCS. General understanding is that none of the environmental regulations which address pipelines, gas storage, waste storage and ground water take into consideration CO_2 and its removal or storage (Carbon Capture Project 2004: 115). Nonetheless, legal aspects are unlikely to impair the adoption of CCS technologies as national and international efforts on CCS-related research, development and testing activities in China are increasing. Some basic EOR projects have been implemented and China is cooperating with Canada in a US$8,7million ECBM project in Qinshui, Shanxi province. The involved Chinese party, the China United Coalbed Methane Corporation Ltd. (CUCBM), is contributing about US$4,3million (Lakeman 2005: 4), with increases in coalbed methane recovery being its primary focus. The possibility of storing carbon dioxide is only perceived as an added benefit.

Chinese academic institutes, like Tsinghua University, are conducting research on carbon capture technologies in cooperation with foreign universities such as Stanford University and Harvard University. In the coming years, a further intensification of research activities is expected since CCS was recently integrated into the National Medium- and Long-term Science and Technology Development Plan and will be part of the 11th Five-Year Science & Technology Development Plan (2006-2010) (op. cit.). However, taking into account the hampered development and deployment of clean coal combustion technologies - which is considerably impeded by insufficient funding of RD&D initiatives (Vallentin/Liu 2004: 63) - it is doubtful if the announced RD&D measures are endowed

[27] As of June 2004, 40 states have voluntarily prepared GHG inventories, 28 states have climate change action plans (Chan et al 2005: 3).

with a budget suited to stimulate CCS development. To date, the high priority of competing policy objectives, such as economic development and energy security, and China's refusal to accept binding GHG reduction commitments create a strong disincentive to CCS diffusion (Interview W. Heidug, 12.12.2005: 49/Interview G. Hill, 15.12.2005: 58).

Because of such disincentives, initial national RD&D programmes need to be framed by an intense collaboration with industrialised nations and technology transfer projects. At the 8th EU-China Summit in Beijing in September 2005, a joint project on Near Zero Emissions Coal (NZEC) was announced, aiming to demonstrate CCS technology in China by 2020. A 3-year feasibility study will examine the viability of different carbon capture technologies and the potential for underground CO_2 storage in China. The Australian Research Council (ARC) and the Australian Cooperative Research Centre for Greenhouse Gas Technologies (CO_2-CRC) have a capacity building project in CCS funded by the Asian-Pacific Economic Corporation already in place. Technology-specific training modules have been developed and the first workshop was held in January 2004. China and the U.S. have formed a bilateral working group on climate change which identified CCS as one of ten areas for cooperative research and analysis (U.S. Department of State 2003: 2). The existence of bilateral collaborations implies that the country is broadly recognised as a future key market for carbon capture and storage. They might significantly accelerate the development of technologies applicable on the Chinese market. China's participation in the newly formed Asian-Pacific Partnership on Clean Development and Climate, which advocates a technology-devoted approach to tackle climate change without 'sacrificing' economic growth, might additionally speed up CCS development and demonstration in China. To date, the Partnership does not include concrete policy measures. CDM projects possibly are the most important opportunity to induce the introduction of CCS in China. The Chinese government now has a very positive attitude towards CDM projects and related regulations and policies are under discussion (Carbon Capture Project 2004: 115). Hence, clarifying the accountability of CCS projects under the international climate regime on the one hand and, on the other hand, easing foreign investor's access to the Chinese market are likely to unfold an inducing effect.

It may be concluded that China is increasingly involved in CCS-related RD&D activities. In spite of this positive development, national policies are unlikely to stimulate CCS development and testing in an adequate manner because of the technology's high costs and the low priority of carbon mitigation measures. Hence, the prospective for CCS in China strongly depends on international assistance, especially cooperation under the Clean Development Mechanism.

3.3.2.5 Russia

As pointed out in chapter 3.2.5, the inadequate technological standard of Russia's power industry and the restructuring process of the national energy sector restrain the development and diffusion of costly abatement options like carbon capture and storage. Therefore, CCS is not a top priority on Russia's energy agenda and no specified legislation, policy incentives or technology programmes are in place.

Regulatory issues are unlikely to constitute a barrier to future carbon storage projects as the country has a well-established legal framework for the treatment of subsurface oil and gas resources and is operating a large number of underground natural gas storages. The most relevant act is the 1992 Law on Underground Mineral Resources, also known as the 'Subsurface Resources Law' (IEA 2002d: 78). The law sets a legal framework for all mining operations, determines licensing procedures for the exploitation of mineral resources and could be adjusted to CCS in case investors come up with a first project. On the other hand, the 1991 Environmental Protection Law and the 1995 Federal Law on Ecological Examination establish quality standards and environmental requirements for economic activities and provide a basis for environmental impact assessment (DMT 2005: 36). The former regulation requires a permit for the discharge of hazardous substances and imposes a fee based on the type and amount of the pollutant (U.S EIA 2004c). With respect to CO_2 underground storage, these environmental regulations necessitate further specification.

Concerning incentives to CCS diffusion, the federal government is unlikely to introduce stimulating policies or technology initiatives due to a lack of financial resources and other political priorities. At present, the Russian administration puts strong emphasis on energy security. Hence, it 'freezes' electricity tariffs at a low level, entailing financial problems and uncertainties at the power supply side, which impede innovative foreign investment projects in the power sector (Lee et al 2001: 24). In official energy documents, e.g. the Russian Energy Strategy 2020, the federal government recognises ecological problems entailing from fossil-based power production but prioritises progress in energy efficiency and energy savings (Mastepanov 2002: 8). In a concept paper for the Russian G8 presidency in 2006, it underlines the necessity to support environmentally sound and safe energy sources and technologies like renewable technologies or CCGT. CCS is not mentioned (Russian Government 2005: 4). The government is, however, planning to provide an analysis of possibilities and choosing of technologies for CO_2 capture systems at Russian thermal power plants in 2005-2006 (Email A. Tumanovsky, 18.12.2005: 61). This indicates that CCS has been identified as a technical option, although political and financial issues remain unclear.

Due to a lack of national capacities, stimuli to the development and diffusion of carbon capture and storage technologies could develop from the Kyoto mechanisms and the EU-Russian Energy Dialogue. Aiming to interlink the European and the Russian electricity sector, the latter has the potential to induce significant enhancements of Russian carbon discharges from power plants since comparable environmental standards are a precondition for the collaboration (EU-Russia Energy Dialogue 2003: 2). Furthermore, the EU devotes financial resources to the modernisation of Russian power plants. The European CARNOT programme includes four clean coal projects related to the Russian power sector, e.g. pre-engineering studies for IGCC plants. Such projects might upgrade parts of the Russian power plant fleet to the technological standard required for the installation of carbon capture equipment. In October 2004, the European Commission together with several Russian agencies organised a workshop on 'EU-Russia Cooperation in Research on CO_2 Capture and Storage' which identified advanced separation techniques, mapping of geological storage capacity and production of hydrogen with CO_2 sequestration as interesting issues for a future research collaboration (EU-Russia Energy Dialogue 2004). Such bilateral research cooperation could function as an initial step towards CCS development in Russia.

As in other countries, the national Kyoto commitment and the flexible mechanisms should provide an essential stimulation to carbon mitigation. The Kyoto Protocol classifies Russia as a transition country, obligating it to merely maintain its 2008-2012 CO_2 emissions at the same level as 1990. Owed to significant CO_2 reductions after the collapse of the Soviet Union in 1991, Russia's Kyoto commitment does not induce investments in costly mitigation technologies like CCS. However, its ratification of the protocol creates the opportunity to participate in Joint Implementation projects which enable the introduction of innovative technologies to the national energy sector. For example, Gazprom is actively working with the government on issues related to the Kyoto Protocol and JI projects in particular (DMT 2005: 64). Hence, the Kyoto Protocol could imply a weak but perceptible effect regarding CCS development and diffusion in Russia.

It may be concluded that CCS is clearly not a prioritised carbon reduction option due to available low-cost mitigation opportunities, institutional investment barriers and divergent policy objectives. The country's power generation facilities need to be modernised or replaced before carbon capture plants may be installed; many carbon storage sites are far away from large fossil-fired electricity plants. As a consequence, regulations, policies and technology initiatives devoted to CCS have not yet been established. Nonetheless, the issue is slowly evolving due to impulses from the European and international stage and could become a long-term option for the Russian power industry.

3.4 Summary: Current Conditions for the International Diffusion of CCS

The previous chapters identified techno-economic, market-specific and institutional parameters of CCS diffusion. The following paragraphs summarise the preliminary results of this investigation in order to provide a basis for the discussion of optional policy instruments and divergent CCS diffusion paths.

Techno-Economic Parameters

The high costs of carbon capture technologies, deriving from their immense energy intensity, constitute a major barrier to CCS diffusion. Carbon removal processes entail costs per ton of CO_2 avoided of US$13-74, providing the lion's share of total CCS mitigation costs which range from US$14-91/t$CO_2$ for different power plant types. As CCS processes do not imply economic benefits, except niche market opportunities like enhanced recovery methods, their diffusion will not appear unless strong political incentives are in place. Besides economic issues, the technology's international market penetration is impeded by its limited technical compatibility with existing power plants and temporal availability. Although MEA scrubbing and oxy-fuel combustion equipment may theoretically be fitted to operating power stations, retrofits are constrained by practical and energetic problems. Hence, carbon capture technologies are more likely to be applied in new facilities or plants which have been designed as capture-ready power stations.

CO_2 storage implies less techno-economic barriers as it is largely based on mature and economic technologies from the oil or gas industry. Instead, negative environmental impacts, security concerns, a lack of experience and social acceptance constitute main obstacles. Little is known about the reliability, stability and integrity of carbon storage reservoirs as well as eventual impacts of CO_2 leakage. Most interviewees expect these uncertainties to result in public protests and to become a barrier to CCS deployment.

Market-Specific Parameters
The analysis of five potential markets for CCS technologies provides insights on national determinants of CCS diffusion. Firstly, the structure of a country's energy supply and the age of the power plant fleet significantly determine its interest in CCS. For example, in Germany, a high share of old power stations are expected to be decommissioned before 2020 – the point when CCS technologies become available. Consequently, their diffusion will be significantly delayed. Secondly, a nation's potential for CCS diffusion is affected by the matching among national CO_2 discharges and available storage sites. At the time being, the U.S. indicate the most promising conditions for CCS deployment and are likely to function as a CCS lead market, whereas China's potential CO_2 reservoirs indicate a rather limited storage capacity. Germany and Denmark show significant storage potentials in relation to their annual power plant emissions, Russia (or the FSU respectively) displays a large number of available storage sites which, however, are often located far distant from polluting power plants.

The possibility of the U.S. to become a CCS lead market is confirmed by a favourable constellation of national actors which constitutes the third market-specific parameter. In comparison to involved actors in Germany or Denmark which represent ambivalent positions, U.S. actors indicate a relatively broad acceptance of CCS as a carbon mitigation strategy. In developing and transition countries such as China and Russia, CCS diffusion is mainly hampered by the fact that public and private actors give low priority to climate policy issues and lack financial resources to foster research, development and deployment.

Institutional Parameters
The high mitigation costs of CCS technologies underline the importance of policy incentives. National and international policymakers are devoting increasing attention to the removal and disposal of CO_2 but, at the time being, most CCS-related activities are aimed at technology research, development or demonstration. Regulatory frameworks and policy incentives are yet to establish. At the national level, some governments – mainly administrations of fossil fuel producing countries – have adopted first regulations considering underground CO_2 storage as well as initial policy incentives. However, the discussed case studies show that many governments are reluctant to introduce climate policies suited to foster CCS as they are waiting for political and regulatory impulses from the international stage. Germany and Denmark consider the European emission trading scheme as the central policy mechanism to induce CCS. In the U.S., the momentum is coming from the State level but federal incentives are needed. Developing and transition countries like China and Russia are focusing on international technology transfer projects and knowledge exchange but are unlikely to adopt national CCS-related policies. Although most governments concentrate on the international level, no binding decisions have yet been made on the inclusion of CCS into relevant interna-

tional treaties such as the London Convention or OSPAR. It is still being discussed how CCS will be treated under the flexible Kyoto mechanisms. The planned integration of CCS into the European emission trading scheme might function as a precedent for the technology's treatment on a market for CO_2 certificates which is widely perceived as central inducement system towards CCS diffusion. The CDM Executive Board is currently assessing the treatment of CCS under the CDM which is essential for technology transfers to the developing world.

It may be concluded that a framework of climate policy mechanisms aiming to induce the diffusion of carbon capture and storage technologies needs to be based upon stringent carbon mitigation targets. In the absence of restrictive climate commitments, CCS deployment is unlikely to appear. However, the previous investigation shows that the technology's dissemination is moreover affected by market-related factors. Consequently, the discussion of CCS diffusion paths needs to consider both international climate policy developments and specific national environments, resulting in technology preferences, wherein potential CCS markets are embedded.

4 Optional Policy Instruments to Stimulate CCS Diffusion

The analysis of current conditions for the diffusion of carbon capture and storage technologies points out that, at the time being, international and national institutional systems framing CCS are one-dimensionally focused on RD&D activities, whereas there is an obvious lack of policy mechanisms inducing near-to commercial CCS applications. However, as CCS only results in emission abatement while not increasing energy security or economic efficiency (except enhanced recovery options), the importance of policy incentives addressing CCS diffusion cannot be overestimated. As stated in the previous chapter, CCS investments will only appear in case of a favourable policy environment due to the technology's high capital costs, energy intensity and complexity. Some national governments apply individual policy approaches to induce CCS, mainly comprising of market-based and financial mechanisms such as tax exemptions (the Netherlands), financial support for near-to commercial EOR and EGR projects (Canada) or carbon taxes on offshore fossil fuel production (Norway). Such domestic policies may initiate the market penetration of CCS in certain countries which indicate an essential interest to continue fossil fuel exploitation in a CO_2 constrained world but have only limited impact on international technology diffusion. Hence, many experts stress that national policies need to be 'roofed' by an initial international policy framework which stimulates a broad deployment. In line with that perception, the following analysis of optional policy instruments for CCS diffusion discusses both national and international measures with emphasising the international stage.

4.1 International Policy Options

The flexible Kyoto mechanisms – international emission trading, JI and CDM -, harmonised or international carbon taxes and CCS-specific technology initiatives are considered to be important international policy instruments with respect to the deployment of CCS technologies. The following chapters discuss their impact on the market penetration of carbon capture and storage applications.

4.1.1 International Emission Trading

International emission trading is widely considered the most effective driver for carbon capture and storage technologies. In a report on low-carbon fossil fuel technologies, the IEA underlines that "greenhouse gas trading schemes have a role to play in encouraging the further development and application of carbon control strategies (IEA 2003a: 11). Based on national emission limits of each participating country, the instrument creates a market for carbon dioxide which enables nations with high marginal abatement costs

(MAC) to acquire emission reductions from countries with low MACs. Doing so, emission trading has the potential to stimulate innovations and to ease the diffusion of carbon mitigation technologies.

However, due to the immense costs of carbon capture and storage processes, a high carbon price is needed to encourage CCS deployment. Table 4-1 relates a broad range of CCS cost estimates to possible carbon prices. It shows that the complete CCS process, including benefits from EOR, could be economically viable at a range of medium to high carbon prices, whereas CCS without EOR requires a carbon price beyond US$35. Other studies are more optimistic, suggesting that CCS systems might begin to deploy when carbon dioxide prices reach approximately US$25-30/t$CO_2$ (IPCC 2005a: 351).

Table 4-1 Net Economic Benefit of CCS under Various Assumptions (Kallbekken et al 2004: 10)

	Total CCS Carbon Mitigation Costs (US$/t$CO_2$)		
	Low (includes income from EOR)	Medium	High
	7-21	40-50	75-95
Assumed Permit Prices (US$/t$CO_2$)	**Net Economic Benefit**		
Low US$ 0-5	-21 to -2	-50 to -35	-95 to -70
Medium US$10-15	-11 to +8	-40 to -25	-85 to -60
High US$25-35	+4 to +28	-25 to -5	-70 to -40

Source: Kallbekken et al 2004: 10

Requiring a high carbon price, an international emission trading system only induces CCS deployment when emission permits are sufficiently scarce. The amount of traded emission permits is influenced by the following parameters: national emission limits, the marginal abatement cost curves of the participating countries, the availability of competitive biotic sink projects and the supply of 'hot air'[28]. Therefore, an emission regime including a limited number of nations with high abatement costs and stringent CO_2 targets may deploy CCS technologies sooner and more extensively than a global emission trading system with high quantities of circulating permits and lower carbon prices.

Considering the described set of determinants, a trading system aiming to foster CCS requires, firstly, stringent national carbon mitigation commitments. According to different studies, the Kyoto commitments would lead to carbon prices ranging from US$1,40 to 15,50/t$CO_2$ (Kallbekken et al 2004: 8). These estimates demonstrate that current reduction targets are insufficient to induce CCS. Hence, the deployment of carbon capture and storage technologies calls for significantly improved post-Kyoto reduction targets on the one hand and substantial CCS cost reductions on the other hand.

[28] The term ‚hot air' describes the excess permits allocated to Russia and certain Central and Eastern European states.

Secondly, an emission trading scheme fostering CCS needs to include large buyers of carbon permits which represent potential CCS lead markets. In that context, the integration of the United States into a future climate regime is highly relevant since the States are the world's largest CO_2 polluter and strongly advocate the future application of CCS technologies. In order to comply with their Kyoto commitment to reduce GHG by 7% in comparison to the 1990 baseline, the U.S. would have to reduce 600 million tons of carbon dioxide until 2010 (Manne/Richels 2001: 9). Hence, U.S participation in the climate regime and an international emission trading system is expected to significantly accelerate increases in carbon prices and to be of advantage for CCS deployment. Albeit there is little reason to believe that the present U.S. administration will change its attitude towards climate policy in general and the Kyoto Protocol in particular, future presidents of whatever party may have another attitude. Bipartisan initiatives in the U.S. Senate calling for mandatory GHG limits suggest that the cap-and-trade approach will be the favourite model for international climate policy by a future U.S. administration (Wittneben et al 2005: 22).

It may be concluded that an international emission trading scheme does not per se foster CCS diffusion. Instead, the technology's market penetration requires the simultaneous appearance of significant cost reductions on the one hand and high carbon prices on the other hand. In order to achieve a sufficient carbon pricing level, ambitious post-Kyoto targets are necessitated and large CO_2 pollutants with high abatement costs need to be integrated into the trading scheme. Generally, the cap-and-trade approach seems to be the most widely accepted means for tackling climate change.

4.1.2 CDM and JI

The instrument of Joint Implementation is defined in Article 6 of the Kyoto Protocol, allowing an Annex I country, or entities from the country, to contribute to the implementation of a project aiming to reduce emissions (or enhance a sink) in another Annex I country and to receive emission reduction units (ERU). The latter may help the investing country to meet its national reduction targets. The Clean Development Mechanism is described in Article 12 and permits countries with binding reduction targets or entities from such countries to allocate certified emission reductions (CER) from projects in countries without GHG limitations which contribute to its national commitments. For actors from industrialised countries, the main incentive to conduct CDM or JI projects are lower carbon abatement costs in developing and transition countries. The accountability of carbon reduction credits (ERU or CER) gained in CDM or JI projects to international or national emission trading schemes may provide an additional inducement to carry out project-based CO_2 mitigation initiatives, such as CCS-related activities. Hence, regulations like the recent EU Linking Directive (see chapter 3.3.1.1) are decisive for encouraging CDM and JI projects.

Both instruments are highly relevant for the international diffusion of carbon capture and storage since they are currently the only instrumental vehicles to transfer the technologies to transition or developing countries. As presented in chapter 3.2, economies like China or Russia are important future markets for CCS technologies but due to the priority of economic development and energy security plus strong financial constraints, they are very unlikely to deploy a capital- and energy-intensive technology which in most cases creates no economic benefits. Hence, project-based cooperation on CCS technologies among industrialised nations and developing/transition countries generates an important opportunity to access potential CCS key markets and to initiate technology-specific networks which foster capacity building. Furthermore, both mechanisms facilitate the adaptation of CCS to country-specific requirements and create examples of best practice which showcase the technology's applicability. Project-based mechanisms may not achieve CCS deployment but prepare subsequent diffusion which might occur in consequence of a post-Kyoto regime.

Table 4-2 Characteristics of Joint Implementation and the Clean Development Mechanism

	Joint Implementation	**Clean Development Mechanism**
Buyer	Annex B countries (Western Europe, Canada, Japan)	Annex B countries (Western Europe, Canada, Japan)
Seller	Annex B (mostly Eastern Europe or Former Soviet Union)	Non-Annex B (mostly developing countries)
Aim	GHG reductions; Diminish Kyoto compliance costs of Annex B countries	GHG reductions; Diminish Kyoto compliance costs of Annex B countries; Enhance sustainable development in non-Annex B countries
Unit	Emission Reduction Units (ERU)	Certified Emission Reductions (CER)
Requirements	Obvious GHG reductions; Additionality	Obvious GHG reductions; Additionality; Projects must imply a sustainable character
Accounting Time	2008-2012	10 years or 3 x 7 years after project start
Favoured Countries	Romania, Poland, Baltic states	Brazil, India, China

Source: Conninck et al 2005: 9

However, before CCS as a technology is eligible for project-based Kyoto mechanisms, the following aspects need to be clarified: an accounting baseline methodology should be developed, long-term storage should be ensured, additionality needs to be demonstrated and, for the case of CDM, contribution to sustainable development must be proven.

Baseline Methodology: CDM or JI projects need to determine the difference between what emissions would have been in the absence of the measure, the baseline, and actual emissions (IPCC 2001: 427). With respect to carbon capture from power plants, it is important to determine which power technology is most appropriate to function as the base case when CCS is applied. Furthermore, the baseline needs to take into account emissions from the whole process chain, including capture, transport and injection (Conninck et al 2005: 10).

Storage Permanence: As it cannot be guaranteed that geological reservoirs store CO_2 permanently, an acceptable way for incorporating this problem into the CDM and JI guidelines needs to be designed.

Additionality: The climate regime provides that emissions reductions entailing from CDM or JI must be additional to 'ordinary' mitigation efforts. As CCS, apart from few exemptions (e.g. EOR), merely serves the purpose of carbon mitigation, the requirement of additionality is expected to facilitate the eligibility of CCS under the CDM or JI.

Sustainable Development: Evidence for sustainable development might inhibit the implementation of CCS projects under the CDM as the technology mitigates carbon dioxide but does not necessarily contribute to broader sustainable development purposes (op. cit.).

The given aspects are highly relevant for ensuring CCS' compatibility with CDM and JI and, therefore, are essential with respect to CCS deployment in countries without incentives to apply the technology. It may be concluded that both mechanisms may positively affect the prerequisites for CCS diffusion in developing and transition countries through achieving market access, creating cases of best practice and fostering capacity building. However, the given implementation issues need to be addressed first. Furthermore, project-based mechanisms may not compensate the lack of effective climate policy incentives.

4.1.3 Harmonised or International Carbon Taxes

Harmonised or international carbon or energy taxes are an alternative market-based instrument to promote carbon capture and storage technologies. Whereas harmonised taxes would mandate participating countries to impose a tax at a common rate on the same source, with each country retaining the tax revenues, an international tax would be imposed and collected by an international agency (IPCC 2001: 405). The international community is ad odds concerning the effectiveness of carbon taxes, which is why the instrument has been only implemented at the national level so far. Nonetheless, an international taxation of carbon dioxide might be an effective tool to foster CCS. The Norwegian example demonstrates that the taxation of CO_2 from large-point sources may significantly contribute to the commercialisation of CCS applications (see chapter 4.2.2) but similar to international emission trading, the instrument's impact on CCS diffusion strongly depends on its design, namely the applied tax rates. Economic studies based on a range of possible tax levels suggest that, if they are to be effective in achieving meaningful reductions in CO_2 levels, they have to be relatively high (IEA 2003b: 11). According to the quoted total CCS cost estimates, a tax rate of at least US$25-30/t$CO_2$ is needed in order to deploy carbon capture and storage technologies.

Regardless of the high tax rate required for CCS diffusion, international or harmonised carbon taxes are unlikely to be adopted. The instrument was extensively discussed at the international stage but has proven unsuccessful in the course of climate negotiations, which is mainly attributed to its conflicting character. Countries are reluctant to accept the intrusion into their domestic policies that such a scheme would require. Furthermore, effective carbon taxes are difficult to implement as they arouse opposition from energy-intensive industries whose profitability is often better preserved through the allocation of tradable permits (IEA 2002f: 84). Because of these negative attributes, international or harmonised carbon taxes are improbable to be agreed on in future climate conferences and are not expected to play a major role in the process of international CCS diffusion. Hence, the instrument will not be considered in the scenario discussion in chapter 5. At the national level, however, carbon taxes constitute an important measure to motivate carbon mitigation.

4.1.4 Multi-,Tri- and Bilateral CCS Technology Initiatives

The term technology initiative is a summarising description of technology-specific research, development and demonstration activities which may be either organised in a multilateral, bi- or trilateral or national form. The latter will be discussed in chapter 4.2.3. International technology initiatives may be organised in various ways, for example as cooperation among at least two governments, collaboration among governments and private actors (public-private partnership) or projects which are organised by multilateral organisations such as the World Bank (IEA 2003b: 7/8).

In the analysis of institutional systems currently framing CCS deployment, it was criticised that international activities are strongly oriented towards research and development projects. That criticism does not deny the need of CCS-related RD&D activities but claims that market-based policy incentives should be supplemented by further international technology projects in order to overcome cost barriers. Consequently, RD&D activities do not directly contribute to the market penetration of carbon capture and storage technologies but increase the impact of instruments like an international emission trading scheme. In that context, a more stringent coordination of national and regional CCS projects as well as an increasing share of multilateral joint-ventures could enhance the efficiency and effectiveness of CCS-related RD&D activities. As already concluded in chapter 3.3.1.3, further emphasis of the coordinating role of existing international technology platforms, such as the IEA Greenhouse Gas Programme and the Carbon Sequestration Leadership Forum, is of essential importance.

Besides, CCS technology initiatives need to display a stronger focus on large-scale demonstration projects. Since the scale-up of new technologies to demonstration scale is costly and carries high risks of failure, private investors like power companies are rather reluctant to take the lead (op. cit.: 9). However, there is an urgent need to strengthen demonstration activities. The International Energy Agency estimates that if gigatonnes of CO_2 are to be captured over the next 20-30 years, at least 10 major power plants fitted with capture technology need to be operating by 2015 (IEA 2004a: 184). To date, no large-scale power plant with carbon capture is in operation. Consequently, international public sponsorship for CCS demonstration is required.

The main conclusion of this section is that, besides the necessity to develop and enforce policy incentives, international collaboration in testing and optimising CCS technologies lays the foundation for political diffusion mechanisms. Doing so, RD&D activities which stimulate technology learning are an important element of future CCS diffusion paths.

4.2 National Policy Options

Relevant national policy instruments for CCS diffusion are subsidies, national CO_2 taxes, technology and performance standards as well as CCS-related technology initiatives (comprising the research, development and demonstration stage) and informational measures. National emission cap-and-trade systems are another important tool but since most central aspects are identical with those discussed in section 5.1.1, the instrument will not be investigated in further detail.

4.2.1 Subsidies

The basic idea of an environmental subsidy is "to alter the price structure in favour of certain products or technologies that may lead to higher environmental standards" (Christiansen 2001: 30). In the context of technological change, subsidies have been frequently criticised as static and inefficient policy instruments which can delay technology cost reductions and lock-in incumbent devices. This criticism points out that the impact of environmental subsidies heavily depends on the way they are implemented. Generally, it is differentiated among direct subsidies, such as direct price support for certain energy sources, or indirect subsidies, like tax exemptions or feed-in tariffs. In the case of carbon capture and storage technologies, direct subsidies for coal – which persist in several countries – in combination with ambitious climate obligations function as an indirect subsidy for the deployment of cleaner coal technologies such as CCS. However, coal subsidies are widely perceived as a barrier towards a sustainable energy system and should not be accepted as an environmental policy instrument. Technology-specific direct subsidies, such as financial support for 'early opportunity' projects like EOR, seem to be more appropriate to support CCS in that they help to provide national CCS niche markets and pave the way for a broader deployment.

Among the broad variety of indirect subsidies, tax exemptions and feed-in tariffs have the potential to function as drivers for CCS diffusion at the national level. For example, electricity generated in power plants fitted with capture technology could be covered by a lower electricity tax rate than carbon-intensive power. The instrument of feed-in tariffs is an increasingly popular tool to support regenerative electricity. In this context, a feed-in tariff is a regulatory, minimum guaranteed price per kWh of electricity fed into the grid that electricity utilities have to pay to renewable generators (Sijm 2002: 6). Renewable feed-in laws might be extended to electricity generated by near-to zero emission power plants, including CCS-specific feed-in tariffs. Such as in the case of the German renewable energy law, the tariffs should be progressively reduced in order to foster the marketability of CCS.

To conclude, direct and indirect subsidies have the potential to set a strong impulse towards CCS diffusion at the national level and may be complementary to an international emission trading scheme. However, national subsidies have to be carefully combined with international measures in order to not thwart carbon mitigation polices.

4.2.2 National CO_2 Taxes

Whereas carbon taxes are no realistic policy option at the international level, the instrument is being applied or planned to be introduced in some European countries and other nations[29] (see table 4-3). National taxes impose highly different tax rates, ranging from US$3,14/t$CO_2$ (Netherlands) to US$150/t$CO_2$ (Sweden). However, many tax models include numerous exemptions, in particular with respect to power generation. For example, in Sweden, Finland and the Netherlands, CO_2 emissions which entail from electricity production are explicitly excluded. Hence, the taxes do not serve as an incentive for carbon removal from power plants. This confirms the repeatedly articulated fact that the impact of carbon taxes on carbon mitigation heavily depends on the instrument's design as the high costs of CCS technologies require a tax rate of at least US$25-30/t$CO_2$.

If carbon taxes imply a sufficient tax rate without distorting exemptions, they may provide a strong national incentive towards CCS deployment like the Norwegian example demonstrates. As listed above, Norway's carbon tax imposes rates of US$44 or US$50,18 respectively per ton of CO_2 produced through offshore oil and gas production. Covering the costs of CO_2 pressurisation and storage, the tax has been instrumental in fostering the first commercial CCS operation at the Sleipner field which captures and disposes CO_2 produced through gas processing procedures. The savings from the avoidance of the national CO_2 tax paid back the project's incremental investment costs in only one and a half years (IEA 2003b: 11). However, national carbon taxes most likely lead to conflicts with the addressed industries since the tax might cause competitive disadvantages at the international stage. As a consequence, many governments are reluctant to introduce carbon-based tax schemes. Nevertheless, the instrument represents an important tool to foster carbon mitigation and, thus, to speed up CCS diffusion.

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29 Several countries impose other forms of environmental taxes which, however, do not use the carbon content of fuels as a tax base.

Table 4-3 National CO_2 Taxes

Country	Year of Adoption	Approach	Tax Rate
Finland	1990	Fuels used for transport and production of heat are taxed according to their CO_2 content. Gas is exempted and peat is taxed using a different methodology; fuels for power production are not covered but electricity is taxed when delivered to the end user.	US$21,78/t$CO_2$
Sweden	1991	The carbon tax was introduced as a complement to the existing system of energy taxes, which simultaneously were reduced by 50%. Since then, the system has changed several times but a common feature are lower taxes for industry and electricity production than for other sectors.	*General level:* US$150/t$CO_2$ *Fuels for industry:* US$75/t$CO_2$ *Fuels used for electricity production are exempted*
Norway	1991	The tax includes different rates for CO_2 emissions from petrol and mineral oil; offshore oil and gas production.	*Offsh. Oil Production:* US$44/t$CO_2$ *Offsh. gas production:* US$50,18/t$CO_2$ *Petrol:* US$50,74/t$CO_2$ *Mineral oil (light):* US$29,61/t$CO_2$ *Mineral oil (heavy):* US$25,14/t$CO_2$
Netherlands	1992	The so-called 'ecotax' is levied on coal, taxes on other energy products are transferred to the energy tax and excise duties on mineral oils. Coal used for electricity is exempted. The tax is based 50% on the energy content of coal and 50% on its carbon content	US$3,1/t$CO_2$
Denmark	1993	The tax covers light fuel oil, heavy oil, diesel oil, LPG, coal and residual fuel; gasoline, natural gas and bio fuel are exempted. It distinguishes among processes and whether or not the company has entered into a voluntary agreement to apply energy efficiency measures.	*Standard tax rate:* US$16,06/t$CO_2$
New Zealand	2007	Carbon emission discharges will be levied on fossil fuels and industrial process emissions; covered activities are yet to be clarified.	*Planned tax rate:* US$10,28/t$CO_2$
Switzerland	Not yet decided	The Swiss government intends to introduce a carbon tax on fossil fuels in order to meet the national Kyoto commitment. Companies could be exempted if they submitted a voluntary declaration to reduce emissions. However, the parliament postponed the decision on the carbon tax until spring 2006 and might modify the currently planned tax rate.	*Planned tax rate:* US$27,2/t$CO_2$

4.2.3 Technology and Performance Standards

CCS-related command-and-control instruments comprise technology standards, which would mandate electricity utilities to install carbon capture technologies in new and existing power plants, and performance standards, which establish minimum requirements for the GHG discharge of power stations. Both instruments could generate a strong impulse towards broad CCS diffusion but are difficult to implement. Determining emission limits for each large-point source entails high administrative expenditure[30]. Mandating the installation or retrofitting of carbon capture technologies could arouse plant- or site-specific obstacles as CO_2 capture devices necessitate advanced power plant technology and a lot of space. Furthermore, the obligatory fitting of carbon removal technology entails immense technology investments at the supply side and might lead to increases in national electricity prices. Thus, the instrument would probably arouse strong public and industrial opposition.

In the context of increasing energy sector liberalisation, national governments are unlikely to impose strict regulatory approaches as they prefer to stimulate technological change through market-based and more cost-effective instruments. Hence, standardising the application of CCS technologies seems to be a rather improbable policy option which might appear only in countries with a minor share of fossil-based power generating plants, high technology standards and strict mitigation targets. A possible example could be Norway which heavily depends on hydropower and aims to construct efficient gas-fired power plants with carbon capture equipment (Norwegian Ministry of Energy and Petroleum 2005a).

4.2.4 National CCS Technology Initiatives and Informational Instruments

Similar to chapter 4.1.4, national technology initiatives – including research, development and demonstration projects - are important measures to pave the way towards further policy incentives. In contrast to multilateral CCS activities, most domestic initiatives are specified to concrete national needs. At the research and development stage, many governments sponsor projects aiming to explore national CO_2 storage capacities and the availability of early opportunities, such as storage via EOR, in order to generate information on the potential and costs of national CCS applications. At the demonstration stage, government sponsorship plays an essential role in that it reduces the high cost of first-generation facilities and diminishes investment risks. For example, the British government is currently planning the first national EOR demonstration project and helps to carry CCS technology to a larger scale (see table 3-12). Consequently, government funding for large-scale CCS projects is essential for the technology's future deployment.

In addition to technical measures, informational projects, for example educational programmes, which intend to inform the nation about chances and risks related to CCS, are considered to be important instruments in order to achieve widespread acceptance of geological carbon storage. It may be concluded that national CCS-related technological and informational initiatives are a valuable ancillary instrument to the described international activities if both stages are coordinated in a sufficient manner. Hence, policy incentives, RD&D efforts and information need to proceed in a synchronous manner.

[30] Source-specific emission limits are, however, required fort the implementation of national or regional cap-and-trade systems.

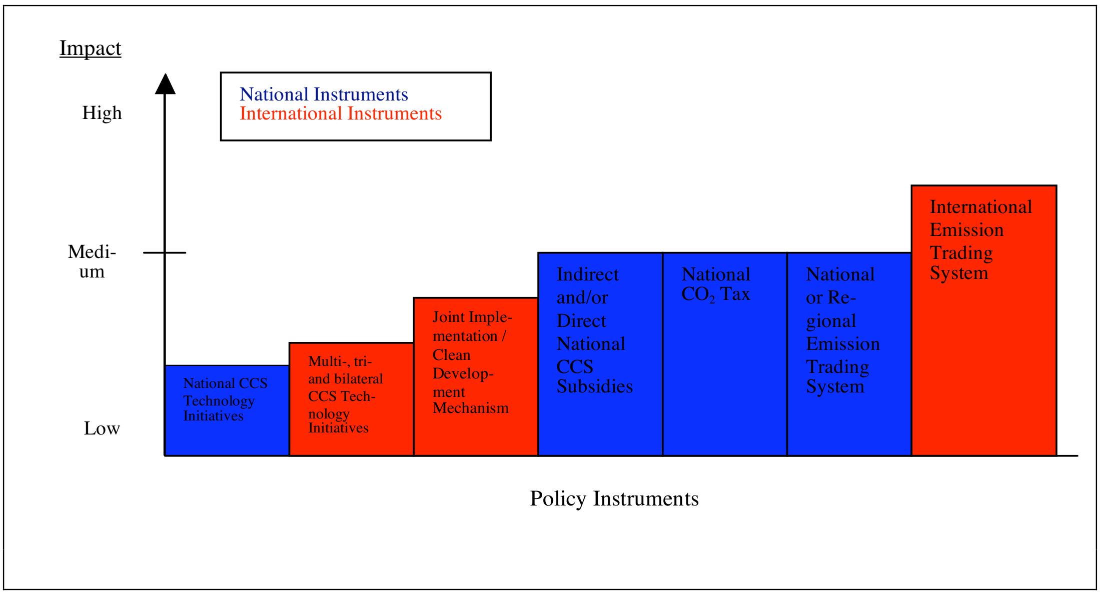
4.3 Impacts of Certain Policy Instruments on International CCS Diffusion

At the end of the chapter, the presented policy options are briefly assessed with respect to their impact on international CCS diffusion (see figure 4-1) in order to prepare the discussion of different CCS diffusion paths in chapter 5. International and harmonised CO_2 taxes as well as national CCS standards are not considered since the adoption of these instruments seems to be improbable.

National and international CCS technology initiatives are an important prerequisite of technology deployment but do not explicitly foster market penetration. Hence, they have a rather low impact on international CCS diffusion. JI and CDM provide access to future CCS key markets like China, Russia or India and enable the transfer of technology and knowledge. Paving the way towards CCS deployment in developing and transition countries, they imply a near-to medium impact on international CCS diffusion. The influence of CDM and JI can be increased if gained emissions credits may be accounted to national, regional or international emission trading systems. In this context, the price level of emission certificates is decisive.

Market-based national instruments, including subsidies, CO_2 taxes and national or regional emission cap-and-trade systems, may generate a strong impulse towards national CCS deployment – provided that they entail a sufficient financial incentive. National CCS deployment creates lead markets or frontrunner states and could stimulate international CCS diffusion. Favouring cost-effective solutions, international emission trading seems to be the policy tool which is most widely accepted to be utilised for inducing carbon mitigation. It is likely to become the central instrument in stimulating the deployment of carbon capture and storage technologies. If the quantity of traded permits is sufficiently scarce, international emission trading may set a strong incentive towards CCS diffusion. Hence, the effect of emission trading systems and most other climate policy instruments is decisively determined by the underlying carbon mitigation targets.

Figure 4-1 Estimated Impact of Various Policy Instruments on International CCS Diffusion



Source: Author

5 Three Energy Futures and the Diffusion of CCS

Previous chapters have analysed current conditions for CCS diffusion and identified optional policy instruments to stimulate the deployment of carbon capture and storage technologies. An essential insight of the analysis is that a broad spread of CCS requires stringent carbon mitigation targets. In the following sections, an ambitious CO_2 stabilisation target of 450ppmv until 2100 is subsequently added to three fundamentally different energy futures in order to present a discussion of divergent CCS diffusion paths until 2050. The stabilisation target was chosen as it requires mitigation efforts which reach significantly beyond the Kyoto path and is likely to lead to considerable modifications in the investigated energy futures[31].

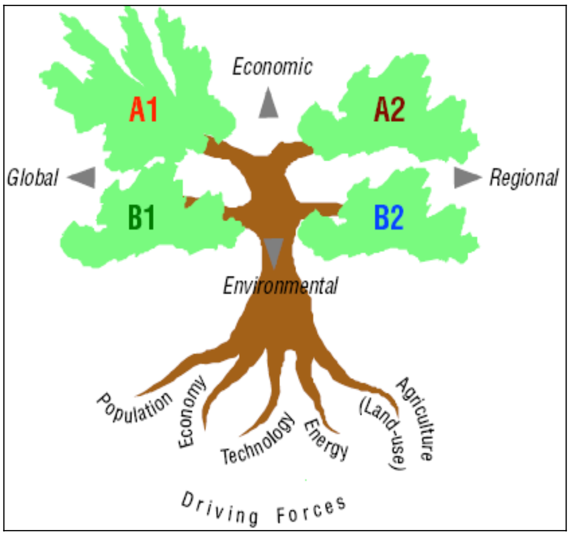
The discussion is based on scenarios which were elaborated in the IPCC Special Report on Emissions Scenarios (SRES), so-called SRES scenarios. The SRES approach comprises a set of four alternative scenario 'families' – A1, A2, B1 and B2 - which include a descriptive storyline and a number of alternative interpretations and quantifications of each storyline developed by six different modelling approaches (IPCC 2000: 169). All in all, the report encompasses about 40 alternative scenarios. Schematically, the four SRES scenario families can be depicted as branches of a two-dimensional tree (see figure 5-1). The two branches illustrate the priority of either economic development or environmental issues (A-B) and an either global or regional orientation (1-2).

The following SRES baseline scenarios have been selected for a discussion on CCS diffusion:

- **A1C:** The scenario displays strong economic growth and intense international cooperation, resulting in rapid technological change. A1C represents one branch of the A1 scenario family and is characterised by a heavy dependence on fossil fuels, especially coal, and, thus, immense carbon dioxide emissions.
- **B2:** The B2 scenario family implies high environmental awareness, which, however, is limited to the national and local decision-making level. This impedes effective global cooperation on climate change. Perpetuating several present developments into the future, the scenario has a 'dynamics-as-usual' character.
- **B1:** This path sketches a sustainable future with a balanced economic development and intense global cooperation to tackle environmental problems. Even though the scenario includes no specific climate change measures, it shows a comparatively low discharge of carbon dioxide.

[31] The selected target only addresses the stabilisation level of CO_2, not CO_2 equivalents (CO_2 eq.) which include other greenhouse gases. CO_2 eq is defined as "the concentration of carbon dioxide that would cause the same amount of radiative forcing as the given mixture of carbon dioxide and other greenhouse gases" (IPCC 2002: 711). Consequently, a stabilisation target of 450ppmv CO_2 implies a higher carbon discharge as a 450ppmv CO_2eq target. The latter is considered to be in line with the objective to keep global warming below 2°C.

Figure 5-1 Illustration of the SRES Scenario Families



Source: IPCC 2000: 71

SRES scenarios do originally not contain any climate policy measures. In order two discuss the impact of a 450ppmv CO_2 stabilisation target on these energy paths, detailed quantitative scenario calculations would have been necessary. However, this was beyond the scope of this report. Hence, the following methodological aspects need to be considered:

Firstly, the presented courses of CCS diffusion only represent qualitative estimations which were inspired by the results of the previous chapters. The assumed deployment paths are denoted as A1C-450, B2-450 and B1-450.

Secondly, the qualitative estimations are founded on a basis of quantitative information which was provided by so-called post-SRES scenarios. Post-SRES scenarios constitute a follow-up of the Emission Scenarios Special Report and have been published in the Third Assessment Report (TAR) of the IPCC. Hence, post-SRES scenarios are also denoted as IPCC TAR scenarios. In the TAR process, different CO_2 stabilisation targets were added to the baseline SRES scenarios in order to describe the deployment of carbon mitigation options such as CCS and their contribution to emissions reductions for achieving the given CO_2 stabilisation targets. TAR-based CCS deployment scenarios were also presented in the IPCC CCS Special Report. In the following, especially calculations on the impact of a 450ppmv target on the selected SRES baseline scenarios have been utilised[32].

[32] In order to ensure comparability of the quoted data, only scenarios calculated with MESSAGE (Model of Energy Supply Strategy Alternatives and their General Environmental impact) were used. MESSAGE is „a dynamic optimization (cost minimization) model for describing the long-term evolvement of the global energy supply system and its environmental impact“ (Schrattenholzer et al 2004: 17).

Thirdly, based on this quantitative information, the presented CCS diffusion paths estimate carbon prices which take into account the storylines of the selected baseline scenarios. The assumed carbon prices reflect the required climate policy efforts that are needed to achieve the 450ppmv stabilisation target.

5.1 Key Indicators of the Selected SRES Scenarios

The following paragraphs summarise the storylines of the selected SRES scenarios with regard to key indicators such as population prospects, economic growth, energy demand, resource availability, primary energy fuel mix, technological change and CO_2 emissions.

Population Prospects: Scenario B2 describes a continuation of historical trends and adopts the UN median 1998 population projection, wherein the global population is steadily growing to nearly 9,4 billion people by 2050 (op. cit.: 561). The assumed growth is thus higher than in the 'international' scenarios A1C and B1 which expect an increase up to 8,7 billion in 2050 due to a rising convergence of demographic trends in developing and industrialised countries.

Economic Growth: In B2, the economy grows at an average rate of 2,2%, largely taking place in developing countries. A1C indicates an even stronger economic development with an average rate of 3%. The B1 economy evolves in a balanced and sustainable manner, which translates into an average annual growth rate of 2,5% (op. cit.: 200).

Final Energy Demand: Final energy demand in scenario B2 grows in line with the historical trend (2050: 654EJ). It is higher than in B1 (604EJ) which emphasises energy saving. A1 indicates the highest 2050 final energy demand (1031EJ) caused by rapid economic progress.

Resource Availability: The A1C scenario shows the highest coal use among the selected scenarios, whereas B2 exhibits a strong dependence on oil. B1 indicates rather low utilisation of oil and coal but displays the highest share of gas.

Primary Energy Fuel Mix: In scenario B2, the exploitation of comparative regional advantages in energy resources leads to regionally different mixes of clean fossil and non-fossil supply. Until 2050, B2 indicates a low but rather stable share of coal and a growing portion of gas, nuclear, biomass and other renewables. B1 displays a transition to regenerative fuels, accompanied by an increase in nuclear energy, at the expense of coal. A1C shows a striking dominance of coal, supplemented by oil, gas, biomass and nuclear energy.

Technological Change: In B2, technological change proceeds in a moderate, heterogeneous manner since international strategies to tackle climate problems are not a central policy priority (op. cit.: 183). In 2050, the power sector is dominated by NGCC, nuclear and various renewable technologies; hydrogen fuel cells are unfolding. The share of

IGCC and conventional coal-fired plants has been surpassed by gas-fired power stations (op. cit.: 218). Relative to B2, A1C has a considerable higher energy output of conventional coal-fired plants, whereas it shows a lower share of advanced clean fossil technologies, such as IGCC and NGCC, as well as hydrogen fuel cells. The technology mix of B1 indicates low rates of fossil-fuelled technologies like IGCC, conventional coal plants and NGCC but a high output of hydrogen fuel cells and renewable technologies (op. cit.: 220).

CO_2 Emissions: Due to continued economic development and population growth, standardised B2 CO_2 discharges reach 11,01GtC in 2050 (op. cit.: 561). This is significantly higher than emissions in the sustainable path B1 (8,57GtC) but clearly lower than in the coal-centred future A1C (20,61GtC).

The given indicators show that the selected scenarios assume fundamentally different energy futures – ranging from a fossil-dominated to a sustainable energy system. The assumption of a 450ppmv target thus promises diverging courses of CCS diffusion.

5.2 A1C-450: CO_2 Mitigation in a Fossil-Centred World

Because of its heavy dependence on fossil fuels, the coal-intensive SRES A1C scenario shows high cumulative (747,4GtC) and standardised CO_2 emissions (20,6GtC) in 2050. Applying a 450ppmv CO_2 stabilisation target therefore necessitates mitigation efforts reaching significantly beyond current Kyoto commitments which are expected to lead to a concentration level of 690ppmv in 2100 with a strongly rising tendency (Onigkeit et al 2000: 20). According to the IPCC TAR scenarios, a reduction of energy-related CO_2 emissions ranging from 50% up to approximately 63% in 2050 compared to the corresponding SRES A1C emissions would be required to achieve the targeted 2100 stabilisation level (IPCC 2001: 153).

As a consequence of such high mitigation requirements, aggressive climate policies and incentives for clean energy technologies are needed. Since the A1 storyline assumes a rapidly advancing process of globalisation which entails intense international cooperation, a global climate change regime with restrictive and increasingly progressive carbon reduction targets needs to be established. From 2025, developing countries are assumed to be included and to accept binding mitigation targets. Due to the high priority of economically viable solutions, technological progress and international cooperation, the new climate policy commitments would be implemented through the immediate establishment of an international emission trading system, accompanied by concerted actions to promote carbon mitigation technologies. The carbon price is assumed to reach an average level of US\$30/tCO_2 until 2025 and climbs up to US\$50/tCO_2 until 2050.

As a reaction to rising carbon prices, technological change in the energy sector strongly focuses on carbon mitigation measures. Taking into account the importance of a diversified technology portfolio for addressing emission mitigation in a cost effective way, the scenario's stabilisation target translates into the parallel deployment of alternative options. Owed to path dependencies which favour centralised technology solutions, the optimisation of coal- and gas-fired power technologies, a switch to advanced nuclear technologies and large-scale biomass technologies as well as the promotion of carbon capture and storage technologies constitute essential carbon reduction measures. Other renewable energy technologies and decentralised options like hydrogen fuel cells are important alternatives and gain significant market shares but do not evolve as rapidly as in scenario B1.

The contribution of CO_2 capture and storage is largest in the A1C scenario compared to other post-SRES scenarios. The technology's development path is characterised by early and steadily increasing contributions, driven by high economic growth and carbon-intensive generating structures (IPCC 2005a: 355/356). Hence, the fossil-centred TAR scenario in the IPCC Special Report on CCS estimates that in 2050, up to approximately $70GtCO_2$ per year could be captured and stored if a 450ppmv stabilisation target was established (op. cit.: 357). The high rate of disposed carbon dioxide is a result of steadily increasing carbon prices on the one hand and, on the other hand, significant CCS cost reductions at the capture side which entail from technology learning.

In the IPCC Special Report on CCS, total mitigation costs arising from CCS processes (including CO_2 capture, transport and storage) are estimated to range from US\$14-53/tCO_2 for IGCC, US\$38-91/tCO_2 for NGCC and US\$30-71/tCO_2 for conventional coal-fired plants[33] (IPCC 2005a: 347). Assuming an initial carbon price of US\$30/tCO_2, IGCC plants fitted with CO_2 capture technologies would be competitive already at the beginning of the A1C scenario. CO_2 capture from conventional pulverised coal plants would be near-to commercial, whereas removal at NGCC plants implies the highest financial barrier. Adding benefits from EOR, which amount up to US\$12/tCO_2 (see chapter 3.1.2), all types of power plants could remove CO_2 in an economic viable manner within the given cost spectrum. This indicates that EOR is a good opportunity to start CCS diffusion. Pulverised coal-fired power plants in combination with enhanced oil recovery operations are expected to be the most common type of CCS projects in the 2010s due to the immature state of IGCC technology. From 2020, however, the latter, is expected to become the most important technology for carbon capture and storage. Since all IPCC TAR mitigation scenarios, including the A1C world, consider hydrogen fuel cells to be an important long-term option, the essential role of IGCC is strengthened by its bridging function towards a hydrogen economy (IPCC 2001: 159).

Relating the assumed carbon prices to current CCS costs confirms that the A1C-450 scenario enables early deployment of certain carbon capture technologies. Technology learning and continuously rising carbon prices would additionally foster CCS diffusion. Riahi et al estimate that as a consequence of accumulated experience in the construction of carbon capture technologies, their costs would be reduced by a factor of 4 at the end of the century (Riahi et al 2004: 555). Assuming that costs could be reduced by a factor of 2 until 2050, a steadily proceeding diffusion and the application of increasingly advanced CCS technologies may be expected. Figure 5-2 illustrates the estimated course of CCS deployment at different power plants with respect to their geographic distribution until 2050.

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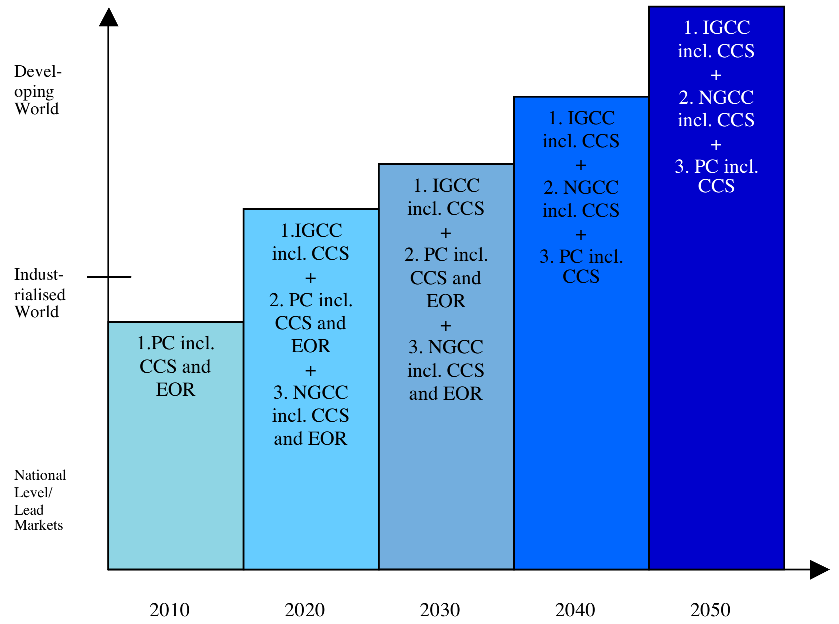
[33] The listed costs do not include benefits deriving from enhanced oil recovery.

Figure 5-2 Estimated Geographic Diffusion of CCS at Different Power Plant Types in A1C-450



Source: Author

The scenario's high mitigation targets are likely to lead to a deployment of CCS technologies throughout the world. However, the timing of the technology's entry into a particular region is influenced by local conditions such as fuel prices, the power plant stock, national carbon mitigation commitments and a country's carbon storage potential (McFarland et al 2003: 6/7). As the developing countries are assumed to be gradually integrated into the international climate regime from 2025, CCS deployment would initially concentrate in industrialised countries with binding reduction targets, whereas diffusion in developing countries is estimated to be delayed for approximately one or two decades. In 2050, the scenario implies high CCS deployment in the developing nations - tomorrow's largest emitters of CO_2. It is albeit probable that the lion's share of carbon emissions disposed in developing countries will occur after the year 2050 – which is beyond the timeframe of this scenario discussion – as technological infrastructures and capacities need to evolve first. The fossil intensive A1-450 IPCC TAR mitigation scenario assumes that in the second half of the century, the distribution of carbon capture and storage will convert from an initial concentration in industrialised countries to broad usage in the developing world. In order to realise this vision, extensive technology transfer through CDM projects as well as further international technology collaborations are needed to spread technical expertise and the awareness of the need to mitigate greenhouse gas emissions.

The scenario discussion shows that a carbon-intensive energy path in combination with high carbon prices, which entail from stringent international CO_2 mitigation instruments, may lead to a broad diffusion of capture and storage technologies. The high contribution of CCS in the developing world in the long run underlines the necessity to develop and utilise policy mechanisms which lay the foundation for CCS diffusion in these nations. However, it needs to be recognised that in a world characterised by centralised, fossil-based energy generating structures and strong path dependencies which consolidate these structures, a consensus on a 450ppmv CO_2 stabilisation target is hard to achieve. Nonetheless, international CCS diffusion is more likely to appear in coal-centred energy futures than in sustainable scenarios which favour regenerative technologies.

5.3 B2-450: Heterogeneous CCS Deployment in a Fragmented World

Due to a considerable economic development and steady growth of population, the SRES B2 baseline scenario indicates growing standardised (11GtC) and cumulative CO_2 emissions (561,5GtC) which are higher than in a sustainable world like B1 but significantly lower than the carbon dioxide discharges in scenario A1C. Hence, mandating a 450ppmv stabilisation level necessitates stringent carbon reduction efforts. Compared to B2 CO_2 emissions in 2050, the TAR B2 mitigation scenario implies reductions of approximately 37% (IPCC 2001: 151). Despite these mitigation requirements, the B2-450 scenario is likely to lead to a significantly different CCS diffusion path than the A1C-450 world. This is due to two reasons: Firstly, the described carbon mitigation requirements demand carbon reduction efforts which significantly surpass the Kyoto path but are less immediate and radical than in the fossil-intensive A1C-450 world (op. cit.: 153). Secondly, the storyline of the B2 scenario family draws a different picture of the global energy system and climate policy-making. In contrast to the increasingly convergent and globalising A1 future, B2 assumes a heterogeneous global energy system which entails from a strong preference for local and regional decision-making. Climate change impacts are thus not tackled through a broad international regime but divergent national and regional policy approaches.

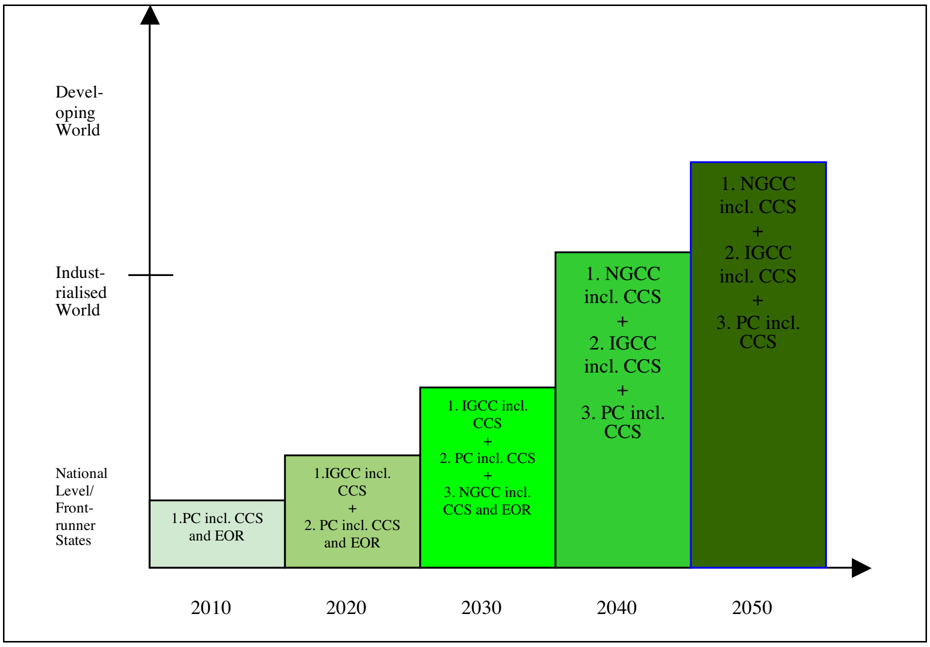
In the following discussion, it is assumed that high-income countries increasingly recognise the need for climate policy action and establish stringent national mitigation strategies to meet the stabilisation target. Developing countries are expected to intensify climate change policies when environmental impacts become more and more severe in the course of the scenario. This is, however, unlikely to appear before the year 2025. Industrialised countries are assumed to immediately establish various climate policy mechanisms – such as national carbon taxes, emission trading regimes and different types of subsidies - which correspond to their national policy approaches. As discussed in chapter 4, the listed policy instruments involve diverse effects on the national and international diffusion of carbon capture and storage technologies. In order to enable a general discussion, it is assumed that the established national carbon mitigation mechanisms lead to an average policy incentive of US$25/t$CO_2$ until 2025, climbing up to US$35/t$CO_2$ until 2050.

Entailing from the denoted incentive to reduce carbon dioxide emissions, carbon capture and storage technologies are fostered in national and bilateral research, development and demonstration projects, resulting in significant technological progress and cost reductions which albeit proceed at a slower pace than in the cooperative A1C-450 scenario. This is, among other aspects, attributable to the fact that the B2-450 world is less pinned down to fossil-based, centralised technology solutions. Varying national and regional technology preferences lead to divergent technology development and diffusion patterns, favouring different carbon mitigation measures. Overall, switching to gas, biomass, nuclear power and solar and wind energy in combination with demand reductions are considered to be important steps towards a cleaner B2 energy system (IPCC 2005a: 352). Carbon capture and storage technologies will be particularly relevant for fossil fuel-producing and carbon-intensive industrialised countries which are expected to function as CCS lead markets – both in a sense of technology development and diffusion.

Until 2030, CCS deployment is presumed to remain centred in industrialised countries, especially in the mentioned lead markets. Among the case studies investigated in chapter 3.2, the U.S. may become a major CCS pioneer, whereas countries such as Germany and Denmark are more likely to direct their attention to a broader portfolio of mitigation technologies. CCS' initial concentration in lead markets is, among other factors, owed to the lack of homogenous global path dependencies favouring fossil-fired technologies. Secondly, assuming a more heterogeneous economic and technological development, the scenario portrays a world in which technical expertise and financial capacities are concentrated in the developed countries. Consequently, CCS deployment proceeds in an uneven manner, being delayed by approximately two or three decades in developing countries. Thirdly, the estimated carbon mitigation incentive of US$25/t$CO_2$ until 2025 and US$35/t$CO_2$ until 2050 provides a significantly weaker inducement for CCS investments than the carbon price in the A1C-450 scenario. The assumed incentive would be insufficient to offset the current costs of most carbon capture and storage applications at power plants.

Figure 5-3 shows that in the first half of the investigated timeframe, CCS deployment in the power sector is likely to be restricted to a niche market of power plants which include benefits from enhanced recovery methods like EOR and IGCC plants. CO_2 capture and storage from NGCC power plants would be inhibited by a cost barrier of at least US$13/t$CO_2$ and is improbable to diffuse before 2025. Assuming additional cost reductions by a factor of 2 owed to technology learning (Riahi et al 2004b: 55), the deployment of NGCC plants including carbon capture and storage might significantly accelerate after 2025. However, as B2-450 suggests that the share of gas-fired electricity clearly surpasses coal-fired power, with NGCC plants becoming the major large-scale power generating technology (IPCC 2001: 159), the initial cost barrier to carbon capture from gas-fired power plants may considerably delay international CCS diffusion.

Figure 5-3 Estimated Geographic Diffusion of CCS at Different Power Plant Types in B2-450



Source: Author

As a consequence of the described development, the lion's share of cumulative CO_2 storage is expected to take place later than 2030 (IPCC 2005a: 357). From 2030 to 2050, the IPCC Special Report on Carbon Capture and Storage estimates that in a B2 world with a 450ppmv CO_2 stabilisation target, annual CO_2 storage shows high growth up to an amount of approximately 25GtCO_2 per year (op. cit.: 356). Besides the reduction of cost barriers, the sudden growth of annual CO_2 storage is caused by increasing climate change efforts in developing regions. After 2050, the CCS deployment curve is expected to gradually decline since competing mitigation technologies like photovoltaic, advanced nuclear power and hydrogen fuel cells begin to diffuse (IPCC 2000: 218).

Despite the unsteady diffusion path of CCS technologies, until 2050, the technology is likely to be globally deployed with a focal point in the OECD 90 region. Developing and transition economies are assumed to store lower but significant percentages of carbon dioxide. However, different from the A1C-450 scenario, the B2-450 future is not expected to shift the centre of diffusion from the industrialised regions to tomorrow's major emitters, like China or countries in Latin America. This aspect is of high relevance as for example China indicates an immense dependence on coal and, thus, offers a great potential for carbon capture from coal-fired power plants. Bilateral or multinational CCS initiatives and technology transfer mechanisms might significantly speed up the international deployment of CCS. However, it should be emphasised that an ambitious carbon dioxide reduction target is an essential political prerequisite for those mechanisms to foster broad CCS diffusion.

The presented scenario analysis indicates that mandating a 450ppmv carbon dioxide stabilisation target to a 'dynamics-as-usual' path with an inherent orientation towards national and regional decision-making may lead to a significant international CCS deployment which, however, is initially limited to industrialised lead markets and peaks in the mid of the 21st century. This is partly due to the fact that B2-450 implies a more intense competition among CCS and other carbon mitigation technologies, leading to a broad set of different national and regional CO_2 reduction strategies, since the scenario misses global path dependencies which favour fossil fuels. Instead, countries show divergent technology preferences. Another important reason for the delayed deployment of carbon scrubbing and removal technologies needs to be seen in the lack of international policy and technology cooperation. Provided that international policy mechanisms are designed in an effective manner, they may achieve significant increases in international carbon prices. Synergies deriving from international technology-specific collaborations make valuable contributions to improve the economic viability of CCS technologies and help to transfer the technologies to future key markets in the developing world. Hence, it may be concluded that a certain degree of international cooperation is needed in order to obtain early CCS deployment which reaches beyond industrialised lead markets.

5.4 B1-450: CCS as a Bridge Towards a Sustainable Energy Future

Due to high global environmental consciousness and a radical shift to renewable energy sources and decentralised technologies, B1-450 necessitates less CO_2 reductions in comparison to the baseline scenario than the previously discussed energy futures. Albeit the relative reduction requirement of about 36% in 2050 is very close to the mitigation commitment applied in B2-450, the sustainable B1-450 scenario includes significantly lower absolute CO_2 reductions as it displays decreasing carbon discharges even in the absence of climate policies (IPCC 2001: 153). Since the B1 storyline implies global cooperation in climate policy and high advances in international institutions aiming to foster carbon mitigation technology, a global emission trading system is assumed to be established immediately, with developing countries beginning to participate in 2025. It is estimated that the instrument entails a carbon price of US$20/t$CO_2$ until 2025 and US$30/t$CO_2$ until 2050.

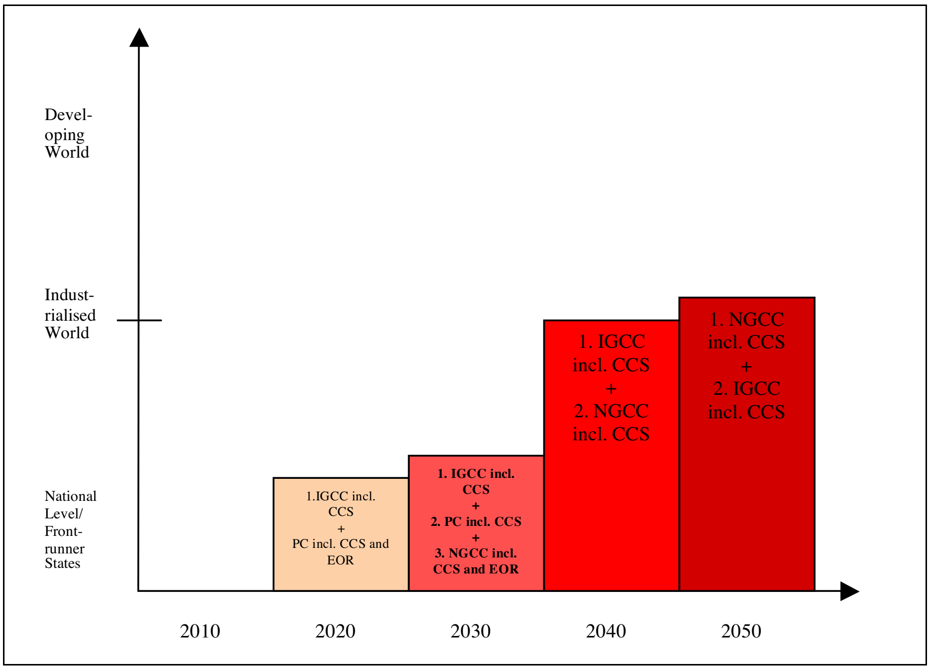
Owed to high environmental awareness and rising carbon prices, the B1-450 world invests a large part of its gains in clean energy technologies which results in a high rate of technological change. Different from the other two scenarios, this energy future shows a clear preference for renewable and decentralised energy systems. Hence, it may be assumed that the decline in CO_2 emissions is largely obtained through the broad market penetration of hydrogen fuel cells, wind power, photovoltaic and biomass energy. Conversely, the share of fossil fuels, especially coal, strongly decreases. Nonetheless, advanced coal and gas-fired technologies are expected to maintain significant market shares until 2050 since they function as a bridge to the deployment of regenerative carbon-free technologies. The proceeding de-carbonisation and decentralisation of the B1-450 energy future entails that the global energy system becomes increasingly incompatible with the innovation features of carbon capture and storage technologies which are primarily designed to remove carbon dioxide from large-scale power generating facilities. As a consequence, the B1-450 scenario is expected to show the lowest amount of cumulative CO_2 storage beyond 2050 among all discussed scenarios (IPCC 2005a: 356). It may be concluded that CCS constitutes a relevant but not prioritised carbon mitigation option in a sustainable B1-450 world.

Because of the global technology preferences for decentralised, regenerative energy technologies, the IPCC CCS Special Report expects CCS deployment to begin in 2020, climbing up to annual CO_2 storage of approximately 15GtCO_2 in 2050 (op. cit.: 357). In the following decades, CO_2 storage decreases due to the market penetration of alternative energy technologies. Consequently, CCS deploys in a fundamentally different manner than in the A1C-450 world - which displays a steeply increasing amount of CO_2 storage - although both scenarios apply a global emission trading scheme and include high international collaboration. Whereas A1C-450 considers CCS as an essential mitigation technology, CCS deployment in B1-450 CCS indicates that carbon storage is perceived as a 'necessary evil' on the way towards a transformed, regenerative energy system. This is, among other parameters, owed to a high political and public awareness of possible negative environmental impacts deriving from carbon storage. Thus, it becomes clear that besides designing issues, the impact of policy instruments decisively depends on the technological, economic and social environment they are embedded in.

Being considered as a temporary solution until more favoured options are ready for diffusion, the economic performance of CCS in comparison to other carbon mitigation technologies constitutes an essential parameter of CCS deployment in the B1-450 world. Assuming the same total costs of CCS at different power plant types as in previous chapters – IGCC: US$14-53; NGCC: US$38-91/tCO_2, conventional coal-fired power plants: US$30-71 – both carbon prices before and after 2025 provide incentives for CO_2 removal from IGCC facilities and PC plants in combination with EOR but do not induce carbon capture at gas-fired power stations. RD&D expenditures are likely to be focused on renewable energy technologies so that cost reductions resulting from technology learning will be achieved less rapidly than in scenario A1C-450 which is primarily focused on fossil-based CO_2 reduction technologies. Hence, it may be estimated that until 2025, the major share of carbon capture equipment is operated in few coal-fired power stations. After 2025, scrubbing and disposal of carbon dioxide from gas-fired plants gradually deploys in combination with enhanced recovery methods and, as a result of increased utilisation, becomes fully competitive. In the following decades, gas-fired power stations are likely to turn into the foremost plant type for CO_2 removal since NGCC technology grows to be the most widely applied power generating design

Beyond 2050, the B1-450 scenario is expected to pay increasing attention to alternative CCS applications, such as CO_2 removal at biomass-fired or co-fired power plants, in order to link the technology to renewable energy technologies. However, carbon capture and storage at biomass-fuelled energy systems is expected to be competitive in a world with carbon prices in excess of 54,5US$/t$CO_2$ and, therefore, requires a strong price increase (IPCC 2005a: 358/359). Figure 5-4 summarises the assumed course of CCS diffusion in B1-450.

Figure 5-4 Estimated Geographic Diffusion of CCS at Different Power Plant Types in B1-450



Source: Author

Concerning the geographic distribution of cumulative CO_2 storage, the B1-450 scenario describes a dissemination which is even more centred in industrialised countries than in the B2-450 future (op. cit.: 356). Contrary to B2-450, the strong concentration of CCS in OECD countries is not necessarily due to financial constraints since the B1 future sketches a convergent world. The scenario storyline describes a fast-changing world with massive income redistribution towards developing countries which increasingly catch up in terms of technological standards and sustainable development (IPCC 2000: 206). Hence, power sectors in the developing world evolve along a low carbon-path, supported by technology transfer projects which mainly focus on regenerative energy technologies, especially biomass, and nuclear power (IPCC 2001: 158). CCS in combination with advanced coal- or gas-fired power plants is most relevant in fossil fuel-constrained developing nations, such as China or countries in the Middle East, but even their energy supply becomes increasingly penetrated by regenerative energy sources.

The analysis leads to the insight that the impact of policy instruments is strongly affected by scenario-specific technology preferences. Favouring a transition towards a regenerative, decentralised energy system, carbon capture and storage technologies constitute a temporary and complementary solution which diminishes pollution from the remaining share of fossil-fired power plants. Since CCS is considered as a ‘necessary evil’, its deployment strongly depends on the cost development of renewable energy technologies and possible interactions with those technologies. Hence, carbon removal at biomass-fuelled power plants might be a relevant long-term option in the B1-450 energy world. However, the important role of technology preferences indicates that in a sustainable B1 future, CCS technologies only deploy when a low carbon dioxide stabilisation target necessitates stringent CO_2 reduction measures which may not wait for the transition of the power sector. At a higher target, such as 550ppmv, the scenario is likely to confine mitigation efforts to evolving renewable and decentralised energy technologies (IPCC 2005a: 356).

6 Conclusions

Having investigated conditions for a possible diffusion of CCS, it needs to be recognised at the beginning of this final chapter that the technology incorporates immense economic, political, technical, geological and environmental uncertainties. Hence, it is yet to prove if CCS actually is diffusible at a broad scale.

If the prevailing risks can be overcome, the United States constitute the most promising market for a broad adoption of carbon capture and storage processes as the national framework conditions include both favourable techno-economic, geological, political and actor-related conditions. Contrary, in Germany and Denmark, CCS diffusion is likely to be restricted by political or social opposition, whereas China and Russia lack the financial resources required for investments in the technology's development and market penetration. China, furthermore, only has a limited portfolio of suitable CO_2 storage reservoirs.

The problem formulation of this study reaches beyond the national level and raises the question: *Which policy strategy is needed to stimulate the international diffusion of carbon capture and storage technologies in the power sector?* The following paragraphs present five cornerstones of a possible policy strategy for international CCS diffusion:

Firstly, a strategy to deploy CCS technologies needs to be based upon stringent carbon mitigation targets. The analysis of current conditions for international CCS diffusion demonstrates that strong policy incentives are needed to initiate a broad deployment of capital-intensive CO_2 reduction technologies. Requiring a carbon price of at least US$25-30/t$CO_2$, CCS calls for reduction commitments that reach significantly beyond the Kyoto targets. The discussion of three CO_2 mitigation scenarios incorporating 450ppmv CO_2 stabilisation targets demonstrates that – despite fundamentally different key indicators – all scenarios display a significant degree of CCS deployment. Consequently, the restriction of CO_2 discharges to a level of 450ppmv in 2100 could constitute a guideline for future CO_2 reduction commitments which induce international CCS diffusion.

Secondly, the limitation of carbon dioxide emissions needs to be accompanied by intensive international collaboration. The scenario discussion indicates that a unilateral approach in terms of technology development and climate policies leads to a lower rate of technological change and, thus, less efficient carbon mitigation. CCS technologies are initially concentrated in few lead markets in the industrialised world which delays their broad spread, especially their transfer to developing regions – tomorrow's largest emitters. This shows that national policy and technology initiatives may facilitate the national or regional dissemination of carbon capture and storage technologies and help to adapt them to country-specific conditions. They may therefore function as a supplement to international policy means. However, national instruments are insufficient to replace international policy mechanisms as they are unlikely to achieve broad technology diffusion.

Thirdly, it is therefore necessary to build a global policy framework which provides a powerful incentive for technical innovations in order to meet the targeted CO_2 stabilisation level. As the cap-and-trade approach seems to be the most widely accepted policy vehicle for the stimulation of investments in carbon dioxide mitigation technologies, the establishment of a global CO_2 market might function as the instrumental 'roof' of a CCS deployment strategy. To create an incentive towards CCS, it is necessary to include major emitters, such as the U.S., in order to keep the amount of traded emission certificates sufficiently scarce. Although a cap-and-trade scheme does not entail a technology-specific impulse to CCS diffusion, it may deploy the technology in line with divergent national technology preferences, path dependencies and storage capacities. For example, countries that show a striking dependency on fossil-fired power generating structures in combination with high storage capacities are likely to utilise CCS as a central carbon mitigation option. Nations that display a preference for renewable energy sources would implement CCS at a smaller, temporary scale in order to bridge the transition towards a carbon-free energy system. Scenario B1-450 confirms that even in a sustainable energy future which favours renewable solutions, restrictive CO_2 mitigation policies would entail the application of carbon capture and storage technologies.

Fourthly, an international CCS policy strategy needs to include provisions and mechanisms for the inclusion of developing and transition countries into the climate regime. In the near future, Joint Implementation and the Clean Development Mechanism are expected to remain the most important tools for transferring carbon mitigation technologies to these world regions. It is thus essential to overcome current barriers to the accountability of CCS projects under CDM and JI as they facilitate the distribution of technology-specific knowledge. Both mechanisms are albeit not suited to achieve a broad deployment of CCS in the developing world. Hence, the technology's international dissemination requires the gradual inclusion of developing countries into the framework of GHG mitigation commitments.

Fifthly, climate policy incentives need to be complemented by CCS-related research, development and demonstration activities since those are crucial for the optimisation of energy-intensive carbon capture processes. It is recommended to intensify the collaboration among regional CCS 'centres' and to increase the number of multilateral RD&D activities, especially those including scientists from developing countries. Furthermore, the analysis presented in this report suggests to strengthening efforts regarding the upscaling of capture processes. With respect to CO_2 storage, further pilots are needed to reduce environmental uncertainties and security concerns. In that context, informational instruments, such as educational programmes which inform the public about the chances and risks related to CCS, are necessary in order to increase the social acceptance of geological carbon storage.

The given cornerstones demonstrate that the international diffusion of carbon capture and storage technologies requires an ambitious, complex carbon mitigation strategy. At the time being, it is unclear if the international community will agree on a global climate policy framework which is capable of providing an impulse sufficient to stimulate this process. If not, the application of CCS technologies will most likely remain limited to a niche market level of enhanced recovery storage methods or other options which entail value-added benefits.

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