

# **Diffusion of innovative technologies in the German electricity system: The case of Carbon Capture and Storage<sup>a</sup>**

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## **Abstract**

In the coal-dominated electricity system in Germany, the transformation towards a climate-friendly system is a major challenge. Options mostly discussed for the mitigation of climate gas emissions include renewable energies (both large and small scale), improved energy efficiency on the supply and demand side, and the low-emissions coal plant with integrated carbon capture and storage (CCS).

The paper discusses the compatibility of CCS with a sustainable future architecture of the (German) electricity system. After a summary of the technological and economic status quo and the ecological impacts, we discuss the institutional and policy setting required to generate optimal results from a societal long-term perspective? The paper reports on the results of an interdisciplinary analysis of innovation assessment and diffusion processes, focusing on CCS as example for a centralized system architecture. The study includes an environmental analysis, an economic assessment and an assessment of the actors involved, the networks built, and the institutional structures and setting in Germany for such innovations. The aim is to better understand the dynamics of innovation and the prospects for escaping the current carbon lock-in in Germany, in order to pave the way for a sustainable electricity system.

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# 1 Introduction

The generation and consumption of energy is associated with substantial damages for the environment, the climate and the economy. For a sustainable electricity system to come, significant improvements in energy efficiency and the substitution of fossil energies by less problematic energy carriers such as renewable technologies are required. Innovation, the process of generating novelty, can be assumed an integral part or even a precondition of such transformation. Innovation includes not only technological advances of products and processes, but also changes in the organisational and conceptual dimension of electricity provision (Voß et al. 2003). Accordingly, innovativeness should rather be conceptualized as a socio-technical innovation cluster and not as a technological innovation alone. The paper applies this conceptualisation idea to the case of Carbon Capture and Storage (CCS) on the one hand and micro generation on the other.

Coal is a major pillar of electricity generation worldwide, providing around 40% of total electricity generation (IEA 2006b). Emerging countries like China or India are continuously commissioning new large coal plants, in order to meet their massive increases in electricity demand. But also in Germany, coal and lignite are the major domestic energy resource and also the dominating input to electricity generation. Prospects for escaping this “carbon lock-in” and the related environmental and climate impacts are unfavorable at present (Unruh 2000; Unruh 2002; Perkins 2003; Unruh and Carrillo-Hermosilla 2006). In this context, Carbon Capture and Storage (CCS) promises to enable the low-emissions coal power station. CCS is an incremental innovation, representing a change within the existing system that does not endanger its overall structure. CCS may also be considered an innovation that “buys time” for radical restructuring and serves as a bridging technology towards a sustainable energy future. CCS could then be an innovation that paves the way out of the current carbon focus of electricity generation.

CCS as such is not a new technological concept. The technologies and practices associated with carbon capture and geologic storage have been in commercial operation within various industries for 10 to 50 years (Curry 2004). The oil industry has been injecting CO<sub>2</sub> into oil formations to recover additional oil since the 1970s. A network of pipelines was built in the Western USA in order to connect CO<sub>2</sub> emission points and oil drilling places. In Norway, the company Statoil started injecting CO<sub>2</sub> in the Sleipner Field in 1996 (approx. 1 Mill. t CO<sub>2</sub> per year). Other examples are storage in the Weyburn oil field, Canada, and in the gas exploration field of In Salah, Algeria, in 2004.

One of the main differences between EOR and CCS is that the former is not concerned about the long-term fate of the injected CO<sub>2</sub>. Leakage is, therefore, not an issue and neither is liability. CCS with a focus on CO<sub>2</sub> emissions in the energy industry, however, is still in an early stage of

development. Some first implementations of IGCC technology exist, however without CCS so far. Neither capture nor storage technologies are ready for deployment yet, so that the major focus is still on its development. This finds its reflection in the structure of actors involved in this area: globally, more than 60% of actors involved in CCS are situated in research institutes and universities. In Germany, about two thirds belong to R&D institutions, and one third to industry (Radgen et al. 2006).

In principle, any large point source of CO<sub>2</sub> emissions, such as coal and gas fired power stations, cement or steel plants or oil refineries, can be equipped with the option of carbon capture and storage (CCS) and can, thus, be converted into a low-emissions production site. To implement carbon capture and storage in an electricity or industrial plant, a number of different steps are required: i) the removal of the carbon dioxide from the industrial process, ii) its transport to an adequate storage site, and iii) the storage in long-term storage sites. Each of these steps can be realized in a variety of technological sub-options which will be outlined for application in power generation in the sections below. An extensive overview is given in IPCC (2005).

CCS is at an early stage of development and market formation and leave many questions open at the moment. Decisions have to be taken on the share of research and development (R&D) expenditures spent on CCS vs. other sustainable technologies, such as microgeneration including renewable technologies, or energy efficiency. Inversely, CCS, renewable energy technologies and energy efficiency may also be considered to belong to one and the same trajectory of a sustainable energy system: Given a sufficiently high price level of CO<sub>2</sub> emissions, energy utilities are induced to choose a portfolio of options to reduce emissions, including CCS, energy efficiency measures and renewable energy.

This paper sets out to explore these issues in more detail. We ask for the characteristics of CCS and whether CCS could contribute to a sustainable future electricity system, and whether it is likely to be available in terms of time, costs, and regulatory and institutional framework for meeting the challenges of climate change mitigation currently under discussion. We discuss the need for shaping the framework conditions for innovation in such a way that CCS may contribute to a sustainable electricity system to the extend that it is suitable.

## **2 CCS and the electricity system**

### *2.1 Sustainability characteristics of CCS*

#### **2.1.1 Technological aspects**

Removal of CO<sub>2</sub> can be integrated into power production at several stages of the power plant process: either as end-of-pipe by cleaning the flue gas, or upfront by removing CO<sub>2</sub> from the

fuel before the actual combustion process takes place. Currently, a number of separation options are investigated, of which the three most promising approaches today are the following.

**Post-combustion capture** implies the separation of CO<sub>2</sub> from the flue gas. The concept of post-combustion capture can be applied to conventional steam turbine cycle power plants. In this type of power plant, a fossil fuel is combusted with air. The flue gases leave the plant at atmospheric pressure through the stack. CO<sub>2</sub> is then captured, preferably through a chemical absorption process.

In the case of **pre-combustion capture**, the fuel is directly converted to CO<sub>2</sub> and a carbon-free combustible, e.g. hydrogen, followed by separating CO<sub>2</sub> from hydrogen. This is particularly relevant for Integrated Gasification Combined Cycle (IGCC) power plants where the (solid) fuel is gasified, resulting in a so-called synthesis gas that mainly consists of carbon monoxide (CO), hydrogen (H<sub>2</sub>), and CO<sub>2</sub>. This gas passes several gas cleaning steps, especially particulate removal and sulphur removal, before it is burned in a combined cycle process. IGCC technology is expected to be the technology that is best suited for integrating CO<sub>2</sub> capture in the power plant process, as the synthesis gas leaves the gasifier with high pressure and CO<sub>2</sub> can be absorbed through physical processes.

The **oxyfuel combustion** process obtains a highly concentrated CO<sub>2</sub> stream by burning the fuel with a mixture of oxygen and recycled CO<sub>2</sub> instead of air. The resulting flue gas consists of highly concentrated CO<sub>2</sub>, together with water vapor and small amounts of pollutants. Thus, a nearly pure CO<sub>2</sub> stream can be produced relatively easily. The theoretical minimum efficiency loss is only 0.5 percentage points (Göttlicher 1999). Thus, in the long term, oxyfuel technology appears to have the best prospects, compared to the other options.

**Transport.** Theoretically, CO<sub>2</sub> can be transported via pipelines, by tank wagons and by ship. However, as power plants produce huge flows of CO<sub>2</sub>, pipeline transport will be the only cost-effective option onshore, if large-scale use of CCS takes place. Initially, pipeline transport will be most likely the main means of CO<sub>2</sub> transport (BMWA 2003; Donner and Lübbert 2006). In the long term, with the exhaustion of local storage opportunities, ship transport may also become relevant, as more remote potential storage locations, for example in the Middle East and the former Soviet Union, will have to be used. Costs for transportation obviously depend on quantities involved and distances, but also on local geographical conditions. However, the transport costs are generally considered low compared to the costs of capture (Gielen and Podkanski 2004).

**Storage.** For CCS to be an effective means of mitigating global climate change and its high costs to be justified, the captured CO<sub>2</sub> must be stored for at a long time period. Additionally, storage must be in accordance with existing national and international law. Among the main

options for storage are oil and gas reservoirs, deep saline aquifers, unminable coal seams and the deep ocean (IPCC 2005). For all these storage options the density of the stored CO<sub>2</sub> must be as high as possible in order to use the storage space efficiently, which in practice results in a minimum depth of typically about 800 to 1000 meters. Storage in form of mineralization (mineral sequestration) is also investigated, but not discussed here, because the necessary huge mass flows are regarded as prohibitive (IPCC 2005).

The total theoretical storage capacity in Germany is estimated to be in the range of some 80-150 years, if all CO<sub>2</sub> from power plants (about 320 Mt/a) is to be stored (COORETEC 2003; GESTCO 2004). Actual technical and economical capacities are lower, depending on geological restrictions, cost and the location of the storage sites.

From presented values it can be concluded that large-scale application of CCS should be possible for some decades with utilization of oil and gas fields and aquifers only. However, for reasons of transport cost, the distance between CO<sub>2</sub> source and storage site should be minimized. In countries where geologic storage options are not available within an acceptable distance (e.g. Japan), other storage options would therefore have to be considered.

### **2.1.2 Ecological performance**

Along the process chain, various environmental consequences could result from a widespread application of CCS. The potential impacts can be broadly distinguished between local and global environmental issues. The most pronounced issues are leakage, e.g. losses of CO<sub>2</sub> from storage and transport processes, and the increase in resource depletion resulting from the supplemental energy need for the separation of CO<sub>2</sub>.

In fact, a major drawback of CCS is its negative impact on *power plant efficiency*. For conventional hard coal plants, the conversion efficiency decreases between 8 and 12 percentage points, for IGCC between 6 and 8 percentage points (Schumacher and Sands 2006). Both – leakage and conversion efficiency – are significant parameters for the global warming balance of CCS. Efficiency losses increase resource use, fuel extraction and amounts of CO<sub>2</sub> to be stored as well as associated environmental damage such as landscape destruction and pollutant emissions. All of this gives rise to substantial debates.

*Leakage* of CO<sub>2</sub> along the CCS process chain (non-permanence of CO<sub>2</sub> storage and transport losses) is probably amongst the most important issues. Such diffusion of CO<sub>2</sub> via various pathways cannot be fully excluded. Bore holes, diffusion through overlaying rocks, or through natural fractures and faults present possible leakage paths. Moreover, accidental releases as a result of high-pressure transportation via pipelines should also be taken into consideration. The likelihood of these dangers is not yet sufficiently known. A number of studies have been carried

out to address this issue (Hepple and Benson 2003; Chalaturnyk and Gunter 2004). Model calculations and natural analogies suggest that in many geological formations, leakage rates below 1% over 1,000 years are possible. Exhausted gas and oil fields and, to a lesser extent, salt caverns have been so far regarded as safe permanent storage sites. However, any leakage rate greater than zero means that most of the CO<sub>2</sub> stored will have escaped some day. Therefore, liability for expected or unexpected leakage is an issue to be debated. Doubts about storage safety have been fuelled by a recent US study showing that stored CO<sub>2</sub> can dissolve minerals in the ground and, by this means, cause leakage (Kharaka et al. 2006). Altogether, however, the IPCC 2005 report optimistically states that “the fraction retained in appropriately selected and managed reservoirs is very likely to exceed 99% over 100 years, and is likely to exceed 99% over 1000 years” (IPCC 2005).

Even if leakage occurs, the question is whether postponing the emission of CO<sub>2</sub> has a value in itself (Pehnt and Henkel forthcoming). Switching from a sudden release of CO<sub>2</sub> to a low-dose, but long-term emission profile might not only result in a change of absolute emission quantities, but also in changes of the specific damage that is caused by a given quantity of CO<sub>2</sub>. These changes of the environmental damage caused might be a result of the fact that the kinetics and thermodynamics of slow versus sudden CO<sub>2</sub> release might lead to different CO<sub>2</sub> concentrations in the atmosphere; or that the (slower) changes in concentration have less damage (because, for instance, animals and plants can adopt to this process); or that even though the consequences of the concentrations are the same (e. g. a temperature increase), they are counteracted by other processes (e. g. historical climate cycles) and thus have not the same damage effect. In addition, delaying CO<sub>2</sub> emissions could buy time for capital turnover and for developing new ways of mitigating GHG emissions (technical progress).

Other potential environmental impacts have a more local range. Underground CO<sub>2</sub> storage might cause structural changes in geological formations and thermodynamic properties could be altered, thus leading to micro-seismic activity. Also the build-up of high pressure in those reservoirs could affect the stability of geological layers above them and generate soil collapses.

To consider all up- and downstream processes, such as installation of the CCS equipment, transport and storage of the CO<sub>2</sub>, and altered operation characteristics of the power plants, life cycle analysis (LCA) are required. Only few studies have attempted this exercise. The LCA model developed by Idrissova (2004) and Henkel (2006) was applied to a conventional lignite power plant (LPP), a lignite power plant with CO<sub>2</sub> recovery by chemical absorption, an integrated gasification combined cycle (IGCC) power plant without CO<sub>2</sub> recovery and an IGCC with CO<sub>2</sub> separation by physical absorption; for detailed input data see Pehnt and Henkel

(forthcoming). The time frame of the analysis includes a horizon of 100 years, implying an essentially zero leakage emission of CO<sub>2</sub>.

Not surprisingly, CCS leads to a substantial decline in global warming impacts from electricity generation. With regard to the supplemental energy demand, the increase is less pronounced for IGCC than for the post-combustion capture and oxyfuel cases, as the energy penalty is lower. For the other impact categories, the effects are less predictable. Generally, absorbing CO<sub>2</sub> capture with monoethanolamine (MEA) as a chemical solvent leads to a significant increase of the impacts in most categories, especially in the SD case. This is found to be caused by the high energy penalty and the chemical solvent process. Impacts of the IGCC power plants with and without CO<sub>2</sub> capture are low compared to the conventional power plant, because of the inherently lower pollutant emissions from this power plant process. For the oxyfuel power plant, impacts depend extremely on the assumptions underlying the analysis, particularly on the assumed energy demand for oxygen production and, even more, on whether co-capture of other pollutants is possible or not. For the DD-case, the resulting impacts are extremely low, while for the SD-case the impacts are nearly as high as for post-combustion capture.

To summarize, the energy penalty due to the actual process of CCS – and potentially also leakage – are the most significant environmental parameters, while the effect of other life cycle stages (e. g. compression along the pipeline) and system components (e. g. construction of the pipeline) are of minor importance only.

### **2.1.3 Economic performance**

The market potential for CCS depends mainly on how economical the process is compared to other CO<sub>2</sub> reduction strategies. Carbon capture increases the cost of electricity generation because of the additional plant equipment and the decrease in conversion efficiency. The latter is smaller for pre- than for post-combustion processes, with corresponding economic effects. CCS is therefore more likely to be implemented in new power plants once it is commercially available than by retrofitting existing plants.

Retrofit requires large additional capital investment which is usually not anticipated in the upfront investment decision and may thus render some plants uneconomic before the end of their lifetime. In addition, because of its negative impact on conversion efficiency, it is only suitable for highly efficient plants. Alternatively, capture-ready plants may be set up which would anticipate ex-post installation of capture equipment. Capture-ready plants have higher upfront capital costs which would be part of the initial investment decision. However, this may defer some investment because the higher upfront costs increase investment uncertainty. The acceptance of higher initial costs depends on the expectation whether CCS will be implemented

or not, which in turn depends on climate and energy policies and the costs and availability of CCS versus alternative mitigation options.

CCS imposes additional capital, operation and maintenance and fuel costs for the capture plant as well as for transport and storage of the captured CO<sub>2</sub>. In the relevant literature, the range of estimated costs for electricity generation is great, depending on the underlying assumptions, in particular those on investment costs, conversion efficiencies, future interest rates, fuel prices and the cost of CO<sub>2</sub> emission certificates. Expressed as costs of mitigating a ton of CO<sub>2</sub>, the cost of CCS give an indication of the level of CO<sub>2</sub> price which would allow to offset these cost. The respective range of estimates given by IPCC (2005) is substantial and varies from 31 to 73 €/t CO<sub>2</sub> for conventional coal technology, 21-73€/t CO<sub>2</sub> for IGCC and 41-94€/t CO<sub>2</sub> for NGCC. Depending on the distance, transport would add another 6-40 €/t, and storage another 1-4 €/t for old gas and oil fields up to 2-6 €/t for saline aquifers (4.5–12 €/t offshore aquifers) (UBA 2006). WI et al. (2007) estimate CCS costs to be around 40-45 €/t CO<sub>2</sub> for coal plants and around 60€/t CO<sub>2</sub> for NGCC plants in 2020. This includes transport and storage, which together account for about 10-13€/t CO<sub>2</sub>. These values approximately represent the average in the range of IPCC estimates. Other estimates, given by for example Vattenfall for their Oxyfuel demonstration plant in Germany, are around 20 €/t CO<sub>2</sub> for carbon capture upon completion of their plant, excluding transport and storage.

It is to be expected that the costs of CCS will decline over time with more research and development and cumulative experience in applying the technology. For the year 2050, WI et al. (2005) expect the costs to come down to a little more than 50€/t CO<sub>2</sub> for gas based plants, and 38-40 €/t CO<sub>2</sub> for coal. Rubin et al. (2007) estimate cost reductions in the capture system due to technology learning to be as high as 40% for NGCC (post-combustion), 20% for IGCC (pre-combustion), 26% PC (pulverized coal post-combustion) and 13% for oxyfuel combustion after 100 GW of capacity.

In the IPCC Special Report on Carbon Capture and Storage, Dadhich et al. (2005) compare a large number of modeling experiences with a wide span of resulting energy and carbon futures. They conclude that “technological developments are at least as important a driving force as demographic change and economic development”. For CCS, they consider the “choice of the technology path” as an impact factor more important for the pace of deployment than other factors (ibid.). Both global integrated assessment models (MiniCAM and MESSAGE) referred to by Dadhich et al. (2005) show that there is no single mitigation measure adequate to achieve a stable concentration of CO<sub>2</sub>, but rather a portfolio of technologies in addition with other social, behavioral and structural changes. In both models, the level needed for an increased deployment of CCS (30 €/t CO<sub>2</sub>) is reached in the middle of the century only, with the

consequence that CCS mainly contributes to emissions reductions in the second half of the century along with the implementation of renewable energy, energy efficiency improvements and fuel switching. In fact, the literature body shows a wide span of estimations for the starting point of a commercial operation of CCS, ranging from somewhere between around 2020 to beyond 2050.

The individual components of CCS are at different stages of market development. CO<sub>2</sub> capture based on post-combustion pathways, for example, is already widely practiced e. g. in chemical industry. However, the combination of more components of the CCS process chain has rarely been realized, except in the case of Enhanced Oil Recovery (EOR) since the early 1970s. For power plants, however, estimations are that larger systems will not be available commercially much before 2020 (Fig. 1). For today's generation of power plants and those planned for the next decade, CCS may thus come too late for an optimal integration. Retrofit is only possible for post combustion or oxyfuel technologies. Both options lead to significant changes in the process layout and require large additional space (e. g. for solvent regeneration or oxygen supply) which is often not available at concrete power plant locations. Alternatively, capture-ready plants may be set up which would anticipate ex-post installation of capture equipment with regard to both space requirements and adjustments in technological regards. Both retrofit of plants and capture-ready set-ups have pronounced effects on capital investment and cost recovery. This again relates to the important question of the timing of CCS strategies.

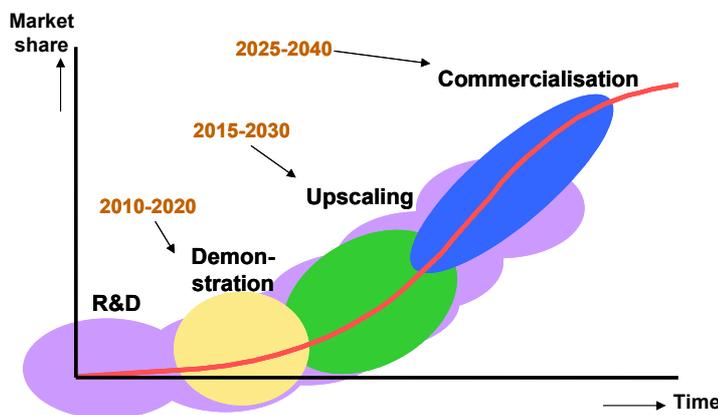


Fig. 1 Expected development of CCS (De Coninck and Groenenberg 2007)

Based on the economic assessment, a number of scenarios include CCS as an option within the future generation mix in Germany. They correspond in concluding that ambitious emission reduction targets can be achieved at lower cost when CCS is included into the possible set of mitigation options. They also agree that a CO<sub>2</sub> price of at least 30 €/t CO<sub>2</sub> would be a prerequisite for CCS to be included in investment decisions. In consequence, whether CCS will

make economic sense first and foremost depends on the existence and level of carbon prices and the respective climate policy goals. The degree to which it will be able to compete with other energy sources, such as renewable energy, remains an open issue. In any case, CCS will be most competitive for large, centralized power plants, ideally located close to the storage location. Correspondingly, the economic potential of CCS to contribute to climate change mitigation remains limited to the share of electricity generated centrally.

## 2.2 *Structural characteristics of the CCS innovation system in Germany*

### 2.2.1 **CCS actors and constellations**

For a long time, CCS had not been much of a political issue in Germany; most of the activities are rather recent. Initially, the debate took place almost exclusively in expert circles, involving a relatively limited set of actors. The main drivers were research organizations, the oil and gas industry and a few political bodies such as the economics ministry and the German Council for Sustainable Development.

More recently, the **debate has gained new momentum**. Climate policy is a re-emerging issue: the negotiations for the second commitment period of the Kyoto Protocol are taking off, climate change has been a topic at G8 summits and recent flood events and heat spells have heightened public attention. In parallel, CCS technology is being recognized on an international level by the climate policy community, as shown by the IPCC report on CCS (IPCC 2005) and the increasing number of technology platforms and research initiatives as described above. In this vein, political interest in CCS is beginning to increase. Substantial differences between actors arise in their **perception of risks and problems**. Environmentalists point to issues of storage safety, long-term CO<sub>2</sub> mitigation and possible impacts on ecosystems as described above, while electricity and power plant industry are concerned about cost and public acceptance. The latter do not reject climate policy outright but rather demand climate protection goals to be predictable and internationally harmonized in order to prevent market distortion.

The **oil and gas industry**, albeit not directly involved in electricity generation, has longstanding expertise in using CO<sub>2</sub> for enhanced oil recovery and could benefit from CCS with a double dividend: first, by receiving CO<sub>2</sub> from the electricity industry which they need for EOR and secondly, by offering and selling off the related CO<sub>2</sub> emission reductions to participants of the emissions trading system.

At a first glance surprisingly, the **coal mining industry** has remained rather passive so far. Associations which represent traditional coal and lignite mining industry, as well as electricity generators that rely on coal, have not been strong in promoting CCS. Aside from few

information sheets they do not appear as a driver or discussant in the actors' network yet. One possible reason in the case of hard coal is the "task sharing" between coal miners and traders on the one hand and electricity industry on the other. Mining industry leaves it to power industry to deal with an issue which is ultimately so closely related to power generation. Moreover, climate protection has never been much of an issue for mining industry as they consider coal to be indispensable for the time being in any case. Finally, CCS creates additional costs for power generation from coal which threatens to undermine its competitiveness compared to other, e.g. renewable energy technologies and fuels. On the other hand, CCS would open up a future for coal mining which may otherwise disappear in the case of stricter emission reduction targets. All in all, the rather passive position of coal miners may thus be explained with the still unclear relation of cost and benefits expected from CCS.

The involvement of the **electricity and power plant industry** was (and still is) dominated by a strategic pattern which they share with the coal mining industry, called the "Three-Step" or "Three Horizons" concept. It stipulates that fossil fuels should be made more climate-friendly in three steps: first, by applying existing "best practice" technology (and exporting it worldwide); secondly, by developing new power plants with increased conversion efficiency; and thirdly, by exploring possibilities for CCS. CCS is thus presented as a technology for the rather remote future. One major reason behind this reluctance to assign higher levels of importance to CCS is the expected loss in conversion efficiency and the increase in cost. In any case, the level of engagement neatly corresponds to the share of coal-based generation in electricity companies' German portfolio, i.e. those companies with high coal and lignite shares are more dynamically involved in CCS activities.

Yet there is a change in strategy that can be observed. Until recently, most industry players were involved in R&D activities in order to keep up-to-date with state of the art or future technologies. But they kept their engagement at rather low key, calling for public funding as a condition for an own investment. On the outset of the debate on CCS, they were not very active in publicly promoting the technology. This picture recently changed with rising natural gas prices and the likelihood of carbon prices also rising in the medium and long term – with the result that CCS is becoming more attractive. The three biggest electricity companies, E.ON, RWE and Vattenfall, and the power plant constructor Siemens PG now hold key roles in the EU Technology Platform ZEP and are all involved in a number of projects on both national and EU levels, aiming at the technological and commercial development of CCS. The "Three-Step" concept is still used in public communication but is increasingly being modified to endorse CCS in a more committed fashion (RWE 2006).

On the level of R&D, the last few years have witnessed a growing level of activities around CCS both nationally and internationally (European Commission 2004; Linßen et al. 2006; Radgen et al. 2006). An increasing number of pilot and demonstration plants as well as of storage projects are in the process of planning and design worldwide. The IEA set up a database on CO<sub>2</sub> Capture and Storage projects which, by the end of 2007, counted 133 projects on capture, transport and storage (IEA 2007). On the level of actors and networks, platforms and forums started in the last few years. A large number of research projects, consortia and networks followed, involving industry and research and sometimes national ministries (see Table 1).

Table 1: Overview of recent CCS activities

Name	Type and time of activity	Description, actors involved
<b>International level</b>		
CSLF	International forum, since 2003	Interministerial platform to foster the deployment of CCS
<b>EU level</b>		
CO <sub>2</sub> STORE	Research project, 2003-2006	Storage of CO <sub>2</sub> in aquifers. 19 industry & research partners. EU FP5.
CO <sub>2</sub> NET	Knowledge Transfer Network; resource and technical portal, 2002-2005; follow-up activities	To develop CCS as a “safe, technically feasible, socially acceptable option”. Network of 65 stakeholders from 18 countries. Initially under EU FP5, now self-funded by members.
CASTOR	Strategic project, 2004-2008	Focus on post combustion (65% of budget) and storage (25%). 30 industry & research organizations from 11 countries. EU FP6.
ENCAP	Research consortium, 2004-2009	Technology development. 6 large fossil fuel users, 11 technology providers, 16 R&T institutions. EU FP6.
Co2GeoNet	Research network of excellence, 2004-2009	Research & training/ dissemination network on storage-related issues. 13 scientific institutes. EU FP6.
ZEP	Technology Platform, since 2005	Strategic research agenda for low-emission power plants, involving industry, NGO, scientists, EU, etc. Funded by EU and industry.
ACCSEPT	Research consortium, 2006-2007	Assessment of acceptability. Research institutes & consultants. EU FP6.
CO <sub>2</sub> SINK	Pilot plant research consortium, 2004-2009	In-situ R&D Laboratory for Geological Storage in Ketzin (GER). Industry & research institutes. EU FP 6.
<b>National level (Germany)</b>		
GEOTECHNO-LOGIEN	Special research program, since 2000	Projects on CO <sub>2</sub> storage. 62 research institutes, 38 industry partners. Funding by BMBF, BGR and DFG.
COORETEC	Research consortium, 2003-today	Economics ministry, research, industry
Oxyfuel	Pilot plant	Vattenfall, 30 MW, launch in 2008
IGCC+CCS	Demonstration plant	RWE, 450 MW, in 2014

One might also expect that prospects for international markets stimulate power plant industry’s activities, for example with a view to China’s future energy need and its expected rise in the use of coal. However, the factual level of commitment is rather dominated by national

considerations. International markets seem to be more of a theoretical argument, even more since the biggest future coal users (like China) do not have climate commitments so far and it remains an open question to what degree they will be interested in climate mitigation technology and whether they have suitable storage opportunities. That might change before 2020, and if CCS is accepted under CDM, the picture will change even earlier.

**Environmental NGOs** and the Green Party have recently formed up to develop critical momentum. They demand a clear legal framework and registration rules for CCS, similar to the “Gold Standard” for projects in the Clean Development Mechanism. They also point to the fact that CCS does not make much sense as retrofit, so that most of the coal-based power plants currently being planned will not be equipped with carbon capture. In other words: in their view, CCS would come too late anyway, regardless the eventual options and related risks of storing the captured CO<sub>2</sub>. Meanwhile, both environmentalists and renewable energy lobbyists are confident that cost reductions in renewable energies and a reasonable price for CO<sub>2</sub> will make them competitive with coal and CCS. On the other hand, they fear that CCS might deduct funds from R&D on renewables and that it could be an excuse for investment in large centralized power plants which cement supply structures uncondusive to energy saving, decentralized renewable energies and CHP.

Last but not least, **public perception of CCS** by the general and local public is a white spot in the actors constellations as portrayed so far, yet it is an essential component of and prerequisite for any successful deployment of CCS. Unfortunately, little valuable information about public acceptance of – or opposition to – CCS is available to date, and no analysis has been published on Germany yet. Only a handful international studies on public perception and acceptability have been conducted (see (Curry 2004; IEA 2005; Peteves et al. 2005) for a comprehensive discussion). Most studies show very low levels of recognition of the technology and related issues. This deficiency has increasingly been recognized by policy, industry and other drivers of CCS. An assessment of social and acceptability issues in Germany, including an analysis of public risk perception as well as the perception of CCS more generally is now underway, with the ultimate aim to design an information campaign (Wuppertal Institute 2006). Similarly, pilot plant operators like Vattenfall investigate local and regional attitudes towards their pilot plant (Daniels and Heiskanen 2006). On the EU level, technology platforms and industry / research consortia increasingly include public awareness raising into research plans and dissemination strategies. The EU level project ACCSEPT (“Acceptance of CO<sub>2</sub> Capture and Storage Economics, Policy and Technology”) points into the same direction. Still, the eventual public perception remains the great unknown.

### 2.2.2 Institutional framework

The implementation of a suitable institutional setting for CCS is currently an issue in its beginnings. Apart from some R&D programs, no elaborated policy exists so far with respect to CCS. However, given the economic, technological and geological risks of CCS, a clear and reliable framework seems a precondition for its eventual deployment, but also for its development. It is against this background that all involved actors have been underlining the necessity of a reliable and stable long-term energy policy framework in order to provide security of investment (Fischer and Praetorius, forthcoming).

Such an institutional framework needs to regulate at least two major issues: First, a predictable and high CO<sub>2</sub> price is in any case necessary for making CCS competitive with conventional fossil power plants. This points to the relevance of future international climate regimes and the development of the EU emissions trading system for the future of CCS. Secondly, clear legal regulation of technology and liability issues are required. The latter could also include a “capture ready” standard as suggested from the EU Commission (European Commission 2007b). A third aspect of institutional relevance is the regulation of financial support for the development and the deployment needs proper institutional treatment. This includes regulations to prohibit unjustified technology subsidies, as included in the European competition law. Related to this, suggestions to remunerate electricity fed into the grid from “clean coal power stations” with CCS in analogy to the Renewable Energy Law in Germany would also require accurate legal rules.

On an international level, activities to develop the necessary regulatory framework have been underway for a couple of years now, but they have only started to be recognized in the German debate. This includes guidelines for including CCS into national greenhouse gas inventories as suggested by the IPCC (Eggleston 2006; IPCC 2006) and early IEA activities on legal aspects (IEA 2006a). In parallel, the EU Commission started the process of developing legislation for the topics of risk, liability, legal barriers and incentives including the embedding into the EU emissions trading scheme (Dimas 2006; Levefre 2006; Working Group on CCS 2006).

Any legal framework for CCS involves a number of detail problems to be solved. In fact, legal conditions need to be tackled individually for each process step: Capture, transport and storage: Capture is primarily a national issue, while Storage safety standards, and long-term monitoring, reporting and liability need to be addressed on both national and international levels (Öko-Institut 2007). A substantial number of details need clarification: is the captured product (CO<sub>2</sub>) to be considered a waste product, a by-product or an emission? For each category different rules apply. The same applies to the regulation of transport activity which will additionally depend on whether CO<sub>2</sub> is transported nationally or internationally. Moreover, for all storage options a

consistent policy framework is needed that takes into account the potential risk of long-term CO<sub>2</sub> leakage. One possible way towards this end could be to establish a market-based risk management system that addresses liability and internalizes the uncertainty and danger of CO<sub>2</sub> leakage, in particular in the longer run. Edenhofer et al. (2004) suggest to introduce Carbon Sequestration Bonds to provide monetary incentives for the selection of safe, permanent storage sites and to ensure liability and compensation in case of leakage and climate impacts.

As in many other areas of climate and energy policy, major institutional impulses for CCS increasingly originate from the EU Commission. In a Communication from January 2007 (European Commission 2007a), the EU Commission identified two major tasks for deployment of CCS: To develop an enabling legal framework and economic incentives for CCS within the EU and to encourage a network of demonstration plants across Europe and in key third countries. On 23 January 2008 the EU Commission proposed a Directive on CO<sub>2</sub> storage as part of a major legislative package on climate protection policy (European Commission 2008b). The Commission proposal intends to enable CCS by providing a framework to manage environmental risks and remove barriers in existing legislation. It also suggests its integration into the EU Emissions Trading Scheme, proposing to consider CO<sub>2</sub> captured and safely stored according to the EU legal framework as not emitted under the ETS. In Phase II of the ETS (2008-12) CCS installations can be opted in. For Phase III (2013 onwards), under the proposal to amend the Emissions Trading Directive, capture, transport and storage installations would be explicitly included in Annex I of the ETS.

With regard to capture ready plants, the EU Commission rejects suggestions to make CCS mandatory (European Commission 2008c; 2008a). It considers the related cost to be high, without clear advantage neither in stimulating technological development and improving air quality nor in promoting the earlier uptake of CCS by non-EU countries. In fact, it would imply to mandate a technology that is yet to be demonstrated on a commercial scale. In sum, the Commission follows economic arguments, pointing to the fact that mandatory CCS would run counter to the market-based approach of the European Trading System: “Whether CCS is taken up in practice will be determined by the carbon price and the cost of the technology. It will be up to each operator to decide whether it makes commercial sense to deploy CCS” (European Commission 2008c). In the end, however, the EU Commission does not completely rule out such a mandatory approach to CCS and suggests that, if commercial take-up of CCS is slow, a new look would be taken again at the idea of compulsory CCS.

### **3 Shaping the innovation process**

Theoretically, carbon capture and storage promises a low-emission fossil based electricity generation option that may contribute to a sustainable transformation of the electricity system. It

would allow keeping the existing system structures in terms of fossil fuel use and large scale electricity generation. Thus, not surprisingly, interest and activities on the side of the incumbent electricity system actors are increasing. Both research and advocacy networks and platforms are sprouting, and the necessary regulatory framework for its implementation is in work.

From a practical perspective, however, any sustainability evaluation of CCS is ambivalent at present, and many open issues remain. Knowledge about CCS is by far not complete: Substantial uncertainties and risks exist, which are related to the disadvantageous economics, but also to the required further technological development, and – last, but not least – to the security and reliability of transporting and storing CO<sub>2</sub>. In particular, many geological issues such as the impact of underground CO<sub>2</sub> storage are still unknown. Also, as a result of the decrease in generation efficiency, CCS causes comparatively increased resource and landscape depletion related to coal and lignite mining. Moreover, the existence of sufficient societal acceptance for CCS is still an open question.

In the light of climate protection policies, the economics of CCS compared to alternative mitigation options play an important role. At a sufficiently high carbon price, CCS will be cost competitive with conventional technologies, but likely also with other options, such as new and advanced renewable energy technologies, cogeneration and the like. This also implies a decision about the future character of the system, i.e. towards a more distributed generation structure, or rather a continuation of the present centralized structure with large power stations. For example, as CCS is only economically viable for large power plants, it is not compatible with combined heat and power generation, which needs to be located close to heat sinks such as cities, and is smaller sized. One question therefore is to which extend both trends are complementary or contradictory, and whether one will become dominant and exclusive at some point.

Uncertainty also includes the timing of large scale and commercial availability of CCS. Given the increasing risks of climate change, CCS may simply come too late for large scale application, for example in Germany, where much of the addition in generation capacity needs to be available before 2020. For this reason, an obligation for capture-ready implementation of new coal generation plants, as pursued by the European Commission, is currently considered an option. However, given the higher investment cost related to both CCS and capture-ready plants, the need for recovering capital cost may unintentionally add to carbon lock-in and path dependency phenomena, as companies may decide to continue their CCS plant instead of switching to less damaging technologies.

All in all, however, there is no “window of opportunity” that strictly closes in 2020, the year often mentioned as the end of a period of necessary massive reinvestment in Germany. It is rather a continuous replacement process that would still allow for a step-by-step implementation

of both retrofit and integrated CCS technologies after 2020, followed by a slow but steady decommissioning of CCS plants towards the depletion of CO<sub>2</sub> storage capacities.

CCS hence features both the chance for a smooth transition towards a sustainable electricity system, and the risk of prolonging the current carbon path unnecessarily and at the expense of society. The eventual outcome is still unknown. The major governance challenge therefore is to frame the future development of CCS in such a way that it will only be implemented when it proves its sustainability.

First and foremost, a clear and reliable climate policy framework needs to be in place to develop the portfolio of technologies and allow for a transition towards a low-carbon or even carbon-free future. This includes creating a continuous and appropriate price for carbon dioxide emissions, for example by means of an international emissions trading regime. Power generation cost must reflect environmental cost. For this, clear and stringent climate targets are needed, so that CO<sub>2</sub> has a price and CO<sub>2</sub> emissions become a relevant cost factor in electricity generation. This stimulates the development of efficiency and renewable technologies, and also of CCS. Such an emissions price is the precondition for economic viability of CCS (and of other mitigation options). All relevant actors accept or support long-term climate goals and policies, as long as they are stable, predictable and internationally harmonized. Policymakers should hence build on such consensus and offer a reliable framework. Moreover, the integration of CCS into climate policy regimes as mitigation option is likely to increase the motivation for countries such as the USA to join a post-Kyoto international agreement on climate protection.

Secondly, a precondition for CCS is a well-developed regulatory and institutional system, in order to ensure a secure operation and monitoring of storage sites, to prevent leakage and to regulate liability issues. Secure operation needs to be made a precondition for CCS implementation. A clear and conducive framework would need to cover site selection and licensing procedures, environmental and safety standards, risk assessment and management, monitoring and reporting, liability rules, regulation of international cooperation and compatibility of national and international legal frameworks. The EU Commission proposal for a CCS Directive (European Commission 2008b) suggests that a monitoring plan must be set up to verify that the injected CO<sub>2</sub> is behaving as expected, otherwise corrective measures will be required to return the site to a safe state. Analogously, Emissions Trading Allowances must be surrendered for any leaked CO<sub>2</sub>, to compensate for the fact that the stored emissions were credited under the ETS as not emitted when they left the source. With regard to the monitoring, national authorities are to ensure that inspections are carried out to verify that the provisions of the proposed directive are observed. Routine inspections must be carried out at least once a year, involving examination of the injection and monitoring facilities and the full range of

environmental effects from the storage complex. Under the proposed directive a storage site shall be transferred to the state when all available evidence indicates that the CO<sub>2</sub> will be completely contained for the indefinite future. Many actors point to the necessity of regulating these issues but very few detailed concepts have been worked out so far. We expect that, as the devil is in the details, concrete regulation of those issues will be a major source of conflict.

Thirdly, with regard to an appropriate research strategy, there are still many uncertainties and risks that need careful investigation and clarification. This includes the development of the different CCS technology elements and options, as well as transport and storage related issues, and also the economics which are currently rather unfavorable compared to other mitigation options. In this area, one of the most-debated issues is the direction, level and intensity of public R&D funding for CCS as compared to other (renewable or efficiency-oriented) energy or climate change mitigation technologies. So far, CCS is not dominating research budgets, yet the increasing level of attention for CCS finds its reflection in increasing research and funding sources already. One of the key issues here is that in a first phase of CCS development, it can be demonstrated that suitable storage sites exist, and that the potential risks associated with CCS are on acceptable levels.

In fact, given the speculative nature of the technology forecasts, a sensitive research and mitigation policy strategy must include all other options. The idea of CCS is to contribute to a CO<sub>2</sub> mitigation strategy. However, most experts expect CCS to be commercially available not earlier than by 2020. Until this – tentative – point of time of market introduction, other means of mitigation need to be explored in parallel. Therefore, CCS should not crowd out research on renewable energies or energy efficiency. A sensible decision could be to focus public involvement on basic research and on issues of public interest, like storage safety, while leaving commercial development of capture technologies as a task for industry R&D.

Last but not least, the implementation of a new and major technology such as CCS also presumes social acceptance. Without a broad acceptance among stakeholders and also by the broad public, transport and storage activities risk to be hold back by protest activities, organized by NGO. Thus, any successful strategy to implement CCS needs active and open public outreach activities combined with a well-developed regulatory framework, which must adequately be balanced with gold standard criteria as put forward by major NGO.

To summarize, given the risks and uncertainties still related to CCS, any political shaping of the innovation process should start from setting a proper framework which includes, first, a stringent climate protection framework with rules for integrating CCS projects under the Emissions Trading Scheme, and under the CDM, and secondly a strong regulatory and monitoring framework, with clear and adequate rules for storage site selection, transparent

monitoring and reporting, clear liability rules and a binding international framework. With such a setting, a level playing field for the different options for mitigation would be prepared, on which CCS may compete for its appropriate share.

## **4 Conclusions**

CCS is increasingly seen as a potentially attractive option within a portfolio of options to mitigate climate change and therefore moves from the fringes to the centre stage of climate policy and related innovation discourses. Our assessment has shown that there is no final answer to the question whether CCS is beneficial to a sustainable transformation of the electricity in Germany and abroad. On the one hand, there are various reasons why CCS could be seen as a bridging technology that allows for a smooth transition away from the current carbon focus of electricity generation towards a more sustainable future. CCS may reconcile fossil fuel use with climate targets, but this presumes storage capacity to be available, and safety to be guaranteed. In this case, it may buy time to advance with respect to renewable and alternative carbon free technologies. Also, CCS is more compatible with the prevailing electricity system structures than other mitigation strategies. First, it allows to postpone or reconsider radical changes in these system structures and it serves vested interests of existing actors. Second, it allows to continue the exploitation of domestic lignite resources in Germany and thus fits well into considerations of energy security and national employment. Third, national deployment of CCS allows German companies to pioneer with pilot and demonstration projects and may lead to first mover advantages. CCS may thus open up space for the concept of fossil fuels as “transitional” fuels. On the other hand, it may prolong the dominance of the current coal-to-electricity path to some 100 years instead of about 40 years. As carbon separation is only viable for high emission points, the current structure of centralized coal-fired power plants would be partly conserved.

Not all investment is likely to flow into such plants, though. Rather, a mix of central and decentralized options based on different fuels is likely to result. Such a trajectory seems reasonable as long as it is compatible with climate protection and other sustainability demands and as long as the transition period is used to develop alternatives to the fossil system that may ultimately result in a low-carbon future electricity system. The most important precondition for any further engagement into CCS is thus to create a reliable and stringent regulatory and climate policy framework, considering all relevant aspects of security and liability, and creating such a level playing field. A responsible future technology and climate policy needs to consider all the different mitigation options.

Aside from this, CCS is relevant not only for Germany. CCS will be a prominent discussion in the Post-Kyoto process, particularly if Parties see it as an easy way forward to reduce industrial emissions without having to make major structural changes in the current energy infrastructure.

This “advantage” may also attract countries like the USA to join into an international climate protection regime. Whether CCS will take off in emerging economies ultimately depends on the eventual international climate regime.

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