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Greenhouse Gas Mitigation in a Carbon Constrained World: The Role of Carbon Capture and Storage[a]

Barbara Praetorius[b] and Katja Schumacher[c]

Abstract

In a carbon constrained world, at least four classes of greenhouse gas mitigation options are available: Energy efficiency, fuel switching, introduction of carbon dioxide capture and storage along with renewable generating technologies, and reductions in emissions of non-CO2 greenhouse gases. The role of energy technologies is considered crucial in climate change mitigation. In particular, carbon capture and storage (CCS) promises to allow for low-emissions fossil-fuel based power generation. The technology is under development; a number of technological, economic, environmental and safety issues remain to be solved. With regard to its sustainability impact, CCS raises a number of questions: On the one hand, CCS may prolong the prevailing coal-to-electricity regime and countervail efforts in other mitigation categories. On the other hand, given the indisputable need to continue using fossil fuels for some time, it may serve as a bridging technology towards a sustainable energy future.

In this paper, we discuss the relevant issues for the case of Germany. We provide a survey of the current state of the art of CCS and activities, and perform an energy-environment-economic analysis using a general equilibrium model for Germany. The model analyzes the impact of introducing carbon constraints with respect to the deployment of CCS, to the resulting greenhouse gas emissions, to the energy and technology mix and with respect to interaction of different mitigation efforts. The results show the relative importance of the components in mitigating greenhouse gas emissions in Germany. For example, under the assumption of a CO_2 policy, both energy efficiency and CCS will contribute to climate gas mitigation. A given climate target can be achieved at lower marginal costs when the option of CCS is included. We conclude that, given an appropriate legal and policy framework, CCS, energy efficiency and some other mitigation efforts are complementary measures and should form part of a broad mix of measures required for a successful CO_2 mitigation strategy.

[a] The discussion paper reports on a case study within the research program on "Transformation and Innovation in Power Systems" (www.tips-project.de). It draws from an earlier publication co-authored with Corinna Fischer (Fischer and Praetorius 2008), a book chapter co-authored with Martin Pehnt (Praetorius et al. forthcoming) and work conducted jointly by Katja Schumacher and Ron Sands (see e.g. Schumacher and Sands (2007)or Schumacher (2007). The usual disclaimers apply. We would like to thank Thure Traber for helpful comments. We gratefully acknowledge funding by the German Ministry for Education and Research (BMBF) within its Social-Ecological Research Framework (SÖF).

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1 Introduction

The generation and consumption of energy is associated with substantial damages for the environment, the climate and, thus, 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 the dominating 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 a "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_2 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_2 emission points and oil drilling places. In Norway, the company Statoil started injecting CO_2 in the Sleipner Field in 1996 (approx. 1 Mill. t CO_2 per year). Other examples are storage in the Weyburn oil field, Canada, and in the gas exploration field of In Salah, Algeria, since 2004.

One of the main differences between enhanced oil recovery (EOR) and CCS is that the former is not concerned about the long-term fate of the injected CO_2. Leakage is, therefore, not an issue and neither is liability. CCS with a focus on CO_2 emissions in the energy industry, however, is still in an early stage of development. Some first implementations of integrated gasification combined cycle (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_2 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 (2005b).

CCS is at an early stage of development and market formation and leaves 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_2 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_2 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_2 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_2 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_2 is then captured, preferably through a chemical absorption process.

In the case of **pre-combustion capture**, the fuel is directly converted to CO_2 and a carbon-free combustible, e.g. hydrogen, followed by separating CO_2 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_2), and CO_2. 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_2 capture in the power plant process, as the synthesis gas leaves the gasifier with high pressure and CO_2 can be absorbed through physical processes.

The **oxyfuel combustion** process obtains a highly concentrated CO_2 stream by burning the fuel with a mixture of oxygen and recycled CO_2 instead of air. The resulting flue gas consists of highly concentrated CO_2, together with water vapor and small amounts of pollutants. Thus, a nearly pure CO_2 stream can be produced relatively easily. The theoretical minimum efficiency loss is only 0.5 percentage points (Göttlicher 1999).

Transport. Theoretically, CO_2 can be transported via pipelines, by tank wagons and by ship. However, as power plants produce huge flows of CO_2, pipeline transport will be the only cost-effective option onshore, if large-scale use of CCS takes place. Thus, pipeline transport will initially be most likely the main means of CO_2 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_2 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 2005b). For all these storage options the density of the stored CO_2 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_2 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_2 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_2 from storage and transport processes, and the increase in resource depletion resulting from the supplemental energy need for the separation of CO_2.

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_2 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_2 along the CCS process chain (non-permanence of CO_2 storage and transport losses) is probably amongst the most important issues. Such diffusion of CO_2 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. Any leakage rate greater than zero means that most of the CO_2 stored will have escaped some day. Geological expectations, however, are that most of the CO_2 gas will be stored in the mineral and in the structure of the storage rock such that it cannot escape or be recovered. Also, leakage is most likely a non-linear process). In any case, 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_2 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 2005b).

Even if leakage occurs, postponing the emission of CO_2 has a value in itself (Praetorius et al. forthcoming). Switching from a sudden release of CO_2 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_2. These changes of the environmental damage caused might be a result of the fact that the kinetics and thermodynamics of slow versus sudden CO_2 release might lead to different CO_2 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_2 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_2 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_2, 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_2 recovery by chemical absorption, an integrated gasification combined cycle (IGCC) power plant without CO_2 recovery and an IGCC with CO_2 separation by physical absorption; for detailed input data see Pehnt and Henkel (Pehnt and Henkel forthcoming). The time frame of the analysis includes a horizon of 100 years, implying an essentially zero leakage emission of CO_2.

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_2 capture with monoethanolamine (MEA) as a chemical solvent leads to a significant increase of the impacts in most categories. 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_2 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_2 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 allow for 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_2. 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_2 emission certificates. Expressed as costs of mitigating a ton of CO_2, the cost of CCS give an indication of the level of CO_2 price which would allow to offset these cost. The respective range of estimates given by IPCC (2005) is substantial and varies from 31 to73 €/t CO_2 for conventional coal technology, 21-73€/t CO_2 for IGCC and 41-94€/t CO_2 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 2006a). WI et al. (2007) estimate CCS costs to be around 40-45 €/t CO_2 for coal plants and around 60€/t CO_2 for NGCC plants in 2020. This includes transport and storage, which together account for about 10-13€/t CO_2. 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_2 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. (2005b) expect the costs to come down to a little more than 50€/t CO_2 for gas based plants, and 38-40 €/t CO_2 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_2, 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_2) 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_2 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.

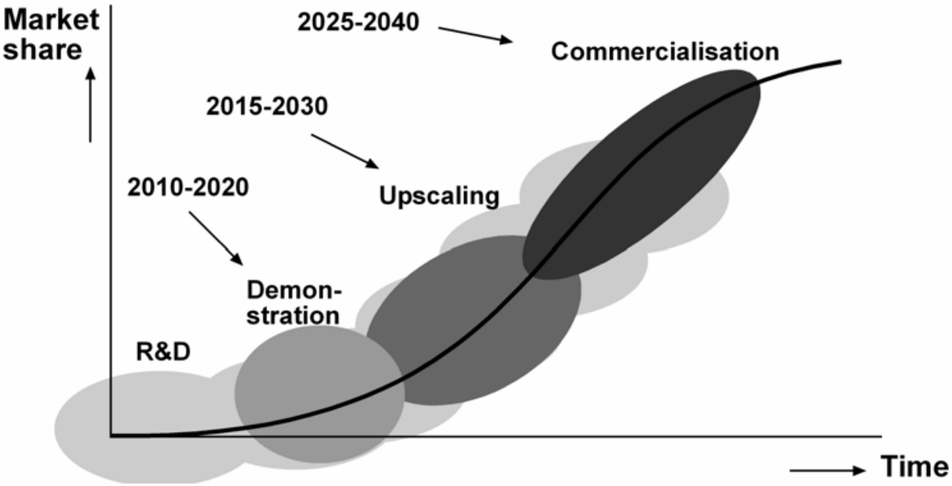

Fig. 1 Expected development of CCS (de Coninck and Groenenberg 2007)

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_2 price of at least 30 €/t CO_2 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, networks and activities

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 2005b) 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_2 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_2 for enhanced oil recovery and could benefit from CCS in two ways: first, by receiving CO_2 from the electricity industry which they need for EOR and secondly, by offering and selling off the related CO_2 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_2 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
International level		
CSLF	International forum, since 2003	Interministerial platform to foster the deployment of CCS
IEA clean coal centre (IEA CCC)	International cooperation, since 2002	Research, database & information centre based on 'Implementing Agreement' of IEA. Originally established as IEA coal centre in 1975, reformed to IEA CCC in 2002. Funded by members (Governments, industry, research).
EU level		
CO_2STORE	Research project, 2003-2006	Storage of CO_2 in aquifers. 19 industry & research partners. EU FP5.
CO_2NET	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_2SINK	Pilot plant research consortium, 2004-2009	In-situ R&D Laboratory for Geological Storage in Ketzin (GER). Industry & research institutes. EU FP 6.
National level (Germany)		
GEOTECHNO-LOGIEN	Special research program, since 2000	Projects on CO_2 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 planned for 2008
IGCC+CCS	Demonstration plant	RWE, 450 MW, launch planned for 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_2. Meanwhile, both environmentalists and renewable energy lobbyists are confident that cost reductions in renewable energies and a reasonable price for CO_2 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 unconducive 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 a 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 of 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 (WI 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_2 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_2 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 is required. The latter could also include a “capture ready” standard as suggested from the EU Commission (European Commission 2007a). 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 and would make high emission prices dispensable for CCS.

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 detailed 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_2) 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_2 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_2 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_2 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 2007b), 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_2 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_2 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 with regard to 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 Potential impact on the future electricity system

A future electricity system may look different if CCS is included, or not. The result strongly depends on the development of the price for CO_2 emission certificates. This concerns the absolute and relative shares of fossil fuels such as lignite and hard coal (and of natural gas) on the one hand, and the structure of the system on the other. Coal may benefit from the “reconciliation” of coal combustion and climate protection that CCS promises. Conversely, CCS costs might negatively impact on coal’s competitiveness compared to energy efficiency and to other – renewable – means of generating electricity. At the same time, demand-side energy efficiency will grow in relevance and reduce the need for electricity generation. CCS might also affect the degree of centralization of the future system: as it is only feasible for large point sources of emissions, it may be at odds with a more decentralized structure of renewable technologies.

In this section we will discuss the economics of CCS as compared to other mitigation options, with a focus on energy efficiency. We look at different levels of a CO_2 policy and assess the resulting mix of electricity supply options and of energy efficiency. We start with an overview of existing information on the economics of CCS and of scenario analyses of CCS. This will be followed by own scenarios calculated with the Second Generation Model (SGM) for Germany.

3.1 Economics of CCS and Mitigation Scenarios

The market potential for CCS depends mainly on whether CCS is economical compared to other CO_2 reduction strategies. Carbon capture increases the cost of coal-based electricity generation because of the additional plant equipment and the "energy penalty", i.e. the efficiency loss mentioned earlier. The latter is smaller for pre- than for post-combustion processes, with corresponding economic effects. Due to the comparatively high cost of retrofit, CCS is therefore more likely to be implemented in new power plants once it is commercially available.

In the relevant literature, the range of estimated costs is great, depending on the underlying assumptions, in particular those on investment costs, conversion efficiencies, interest rates, fuel prices and the cost of CO_2 emission certificates. The costs (without transport and storage) range from 7.6 to 68.1 EUR/t CO_2. Vattenfall expects cost of around 20 EUR/t CO_2 for the capture process in its Oxyfuel demonstration plant. Depending on the distance, transport would add another 6-40 EUR/t CO_2, and storage another 1-4 EUR/t CO_2 for old gas and oil fields, and up to 2-6 EUR/t for saline aquifers (4,5–12 EUR/t for offshore aquifers) (UBA 2006b).

Hence, on average, CCS combined with IGCC could be economically viable at a CO_2 price in the range of 30 to about 50 EUR/t. For conventional hard coal plants, CCS would increase the costs of electricity generation by about 3-4 cents (EUR) per kWh; for IGCC the increase amounts to about 2-3 cents. This is in accordance with the IPCC assessment (IPCC 2005a).

Thus, whether CCS will make economic sense, first and foremost depends on the existence and level of CO_2 prices and the corresponding climate policy goals. In any case, commercial availability is not expected any earlier than 2020 and 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 large-scale electricity generation.

A number of scenarios include CCS as an option within the future generation mix in Germany. They consistently conclude that ambitious emission reduction targets can be achieved at lower cost when CCS is included into the possible set of mitigation options. For example, Martinsen et al. (2007) assess the future role of CCS within a German national mitigation strategy with IKARUS, a bottom-up optimization model. Energy demand is a function of economic activity and energy prices, while no active energy efficiency policies are modeled. The model is sensitive to price and cost changes and shows that all newly built power stations would include CCS at a CO_2 price of 30 EUR or above.

In the 2005 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" (Dadhich et al. 2005: 350). For CCS, they consider the "choice of the technology path" an impact factor more important for the pace of deployment than other factors (ibid.). Both 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_2, but rather a portfolio of technologies in addition with other social, behavioral and structural changes. The models also estimate a carbon permit price that allows to stabilize CO_2 concentrations at 550 ppm. In both models, the level needed for an increased deployment of CCS (again approx. 30 EUR/t CO_2) is reached in the middle of the century only, with the consequence that CCS is mostly implemented in the second half of the century. 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 2005-2020 and beyond 2050. In both models, after 2050, the contribution of energy efficiency and energy conservation is smaller compared to CCS.

The following assessment of potential future developments of the German electricity system use these assessments as a reference for modeling its own mitigation scenario.

3.2 Scenarios with SGM Germany

In this section, we use a general equilibrium model (SGM Germany) to analyze the combined effect of a CO_2 policy on energy efficiency, fuel shifts and CCS. The model employs an economy-wide framework, which allows analyzing interactions between various users and producers of energy (demand and supply side) in response to changes in production costs. Such changes in production costs may be induced, for example, by climate policies. The modeling framework allows for an economy-wide and simultaneous response in form of output adjustment, structural change, demand and supply side efficiency improvement and shifts in electricity technologies towards more advanced and efficient technologies, such as advanced coal power plants, IGCC, or NGCC with and without CCS. In contrast to a pure bottom-up perspective that puts an emphasis on representing the entire energy system in terms of specific technologies, but generally takes energy demand and macroeconomic development as given and does not allow for demand and supply side feedbacks, and in contrast to a pure top-down economic approach that neglects to include technology detail in its analysis of demand and supply side behavior, the current model attempts to combine features from both approaches.

The Second Generation Model (SGM) is an economy-wide top-down computable general equilibrium model that embodies technology detail for the electricity sector based on engineering information. With these features CO_2 mitigation is possible through i) improvement in energy efficiency, ii) fuel switching, and iii) introduction of innovative technologies, such as CCS and advanced electricity generating technologies. Energy efficiency options apply to the supply and demand side of the economy and are represented in the standard format for a general equilibrium model; producers and consumers are able to substitute other goods for energy in consumption and production as the price of energy increases relative to other goods in response to a CO_2 policy. Moreover, the electricity sector with its technology detail provides opportunities for fuel switching and the deployment of advanced and more efficient electricity generating technologies with and without the option of CO_2 capture and storage. As the CO_2 price increases (for example as the result of stricter reduction targets), the cost per kWh of generating electricity changes across the generating technologies. Technologies that use carbon-intensive fuels, such as pulverized coal, receive a lower share of investment in new capital than before. An elasticity parameter determines the rate that investment shares change in response to changes in the relative cost of generating electricity.[1] Detailed information on the Second Generation Model can be found in Edmonds (2004); the technology-based approach for electricity generation in SGM is demonstrated in Sands (2004) and Schumacher and Sands (2006).

SGM-Germany allows the introduction of advanced and more efficient electricity generating technologies with and without CCS and the projection of the future electricity mix with these technologies in a base case and under different assumptions about a CO_2 policy. It thus presents a flexible tool for simulating CO_2 emissions that can accommodate a wide variety of assumptions about electricity technologies, CO_2 prices, fuel prices, and baseline energy consumption.[2] Our methodology relies on engineering descriptions of electricity generating technologies and how their competitive positions vary with a CO_2 price or change in fuel price.

[1] This parameter therefore determines the rate that one technology can substitute for another. Or in other words, it determines the price response of electricity technologies. Technologies with lower unit costs provide a larger share of output. For more detail, please refer to Schumacher and Sands (2006).

[2] A feature inherent to general equilibrium models is that they do not account for negative or no-cost greenhouse gas mitigation options. These models are based on the recognition that the economy is in a state of equilibrium a priori the policy incentive, and imply that mitigation options are not appropriable without any costs (such as transaction costs, information costs, and/or adjustment costs) because of existing market imperfections.

We apply a CO_2 policy scenario that includes a stepwise increase of a CO_2 price from 10 EUR per ton of CO_2 in 2005, to 20 EUR per ton of CO_2 in 2010 and continues to increase to 50 EUR per ton of CO_2 in 2025; CO_2 incentives are targeted to the electricity sector and energy-intensive industries (i.e. those covered by the current EU emissions trading scheme). This approach corresponds to a national emission-trading scheme with a fixed CO_2 allowance price in each period.[3] It would imply that power stations with CCS require CO_2 allowances corresponding to their CO_2 emission.[4]

3.3 Economic comparison

This section focuses on economy-wide emissions reductions in Germany in response to a CO_2 policy. A more detailed view of the electricity sector is provided in the section thereafter. For any selected year, we can express emissions reduction potential and according costs in the form of marginal abatement cost curves. This is done in Fig. 2 and Fig. 3 for two different time periods (2020 and 2040) with separate components for efficiency based emissions reduction, fuel switching, and CO_2 dioxide capture and storage. While fuel switching refers to emissions reductions in the electricity sector, efficiency improvement covers reductions on both the producer and the consumer side of the economy (except for electricity generation).[5] The marginal abatement cost curves provide a graphical view of the relative sizes of reduction potential across these options of CO_2 mitigation options, and how that varies across CO_2 reduction targets and time. Although we generated these sets of marginal abatement cost curves with a number of constant CO_2 price scenarios, they correspond to the marginal abatement cost curves that would result from a national emissions trading system with different targets. This means that for any given reduction target the curves reveal the implied marginal costs (CO_2 price) and the set of mitigation options employed. Specifically, we ran the CO_2 price scenarios at 10, 20, 30, 40 and 50 EUR per ton of CO_2 starting in 2005. For the latter three

[3] CO_2 allowances may be auctioned or allocated free of charge. In either case, we assume that the covered industries pass on the additional costs (or opportunity costs in the case of grandfathering) to final consumers.

[4] The current EU ETS framework does not provide an allocation rule for the case of CCS. The economic incentive to invest in CCS depend on whether allowances are grandfathered or partly auctioned to power stations and whether power stations with CCS are equipped with allowances for the full amount of potential emissions (including those captured and stored) or for the remaining emissions only (i.e. emissions not captured and stored), cf. Dietrich and Bode (2005).

[5] This implies that output adjustments in response to climate policy in form of, for example, production lost to other countries is included in efficiency improvement. Future research would involve a more thorough decomposition of emissions reductions due to fuel switching, supply side efficiency improvement, demand side efficiency improvement and output adjustment (the latter including, for example, leakage to other countries).

scenarios, the CO_2 price is introduced in 2005 at 10 EUR per ton of CO_2 and increased to 30, 40 and 50 EUR respectively by 2010.

As can be seen for the year 2020 in Fig. 2 and even more pronounced for the year 2040 in Fig. 3, mitigation of energy-system CO_2 increases gradually along with time and with the CO_2 price and has large potential at high CO_2 prices (corresponding to high CO_2 reduction targets). Energy-system emissions reductions come from more energy-efficient industry and household behavior and from fuel switching (the latter including efficiency increases in the electricity sector). These options to reduce emissions are economically viable at relatively low CO_2 prices and provide a steadily increasing contribution as reduction targets become stricter and CO_2 prices rise, and as time moves on. In addition, CCS is introduced as a mitigation option after 2015. CCS is not economically available at low emissions targets and correspondingly low CO_2 prices, but can be a significant contributor to emissions reduction when climate targets require more significant emissions reductions.

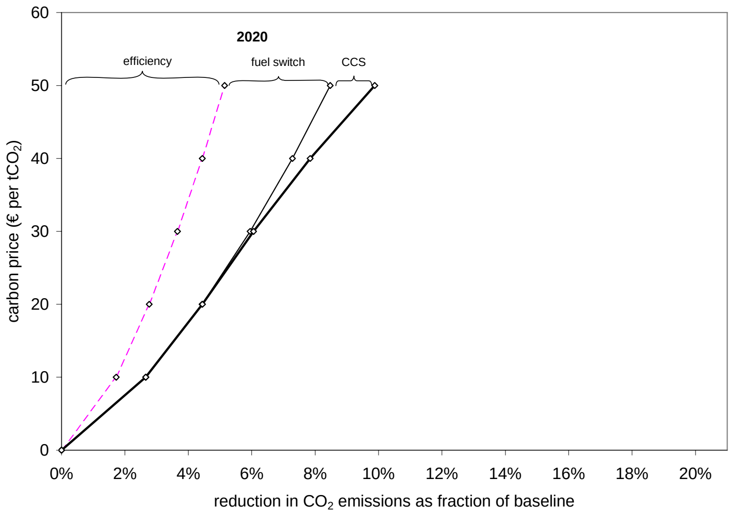

Fig. 2 Simulated economy wide emissions reductions over a range of CO_2 prices, Germany 2020

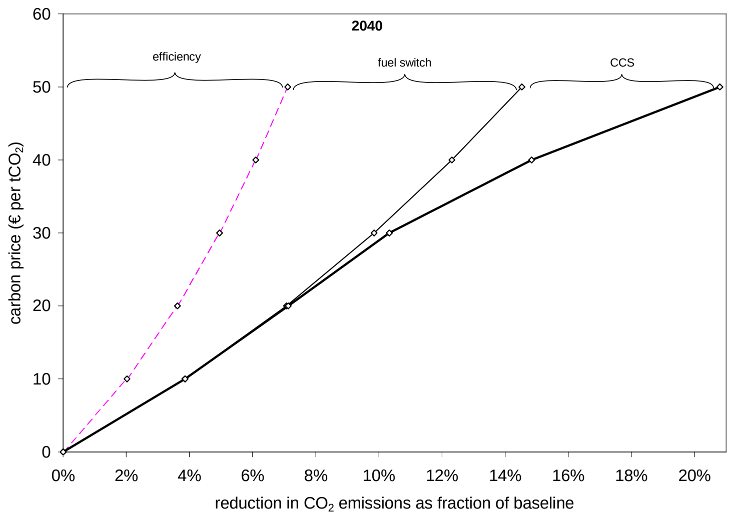

Fig. 3 Simulated economy wide emissions reductions over a range of CO_2 prices, Germany 2040

Including CCS in the analysis implies that a given reduction target can be achieved a lower marginal costs, especially in the longer run.

For each electricity generating technology that can use CCS, there exists a break-even CO_2 price where the cost per kWh of generating electricity is the same with or without CCS. At this CO_2 price, we assume that half of any new investment in that generating technology uses CCS. We have not included a retrofit option for CCS; we assume that all CCS is installed on new generating plants. Therefore, the rate of CCS installation is limited by the rate that capital stock turns over in the electricity generating sector. This can be seen by comparing the contribution of CCS to CO_2 mitigation over time at relatively strict emissions reductions targets and correspondingly relatively high CO_2 prices. Fig. 3 shows the higher mitigation potential of CCS in 2040 compared to 2020. A similar, but not quite as pronounced, case can be made for energy efficiency and fuel switching. Over time, both of these options experience an increasing economic potential and can, by 2040 and with an ambitious emissions reduction target (20% compared to the base year 1995), contribute to emissions reductions at almost equal shares with CCS.

Fig. 4 shows emissions reductions and the contribution of different mitigation options, i.e. fuel switching, efficiency, and CCS, for a stepwise CO_2 price increase. Such a stepwise increase may result from increasing reduction targets in a CO_2 policy case. Compared to the baseline, such a stepwise CO_2 price increase would lead to reductions of up to 150 million tons of CO_2 by 2030. Over time as more capital retires and new and advanced technologies come into place even higher emissions reductions can be obtained at the same marginal cost.

Initially, an increase in energy efficiency on the producer and consumer side plays the dominant role in achieving emissions reductions in response to an increasing CO_2 price. As time moves on and new technologies become available an increasing share is taken up by fuel switching, mainly driven by changes in the electricity generation mix as discussed in more detail below. Similarly, the introduction of CCS technologies in the electricity sector after 2015 plays a major role. At a CO_2 price of 50 EUR (year 2025) CCS is economically competitive and takes on an increasing share over time.

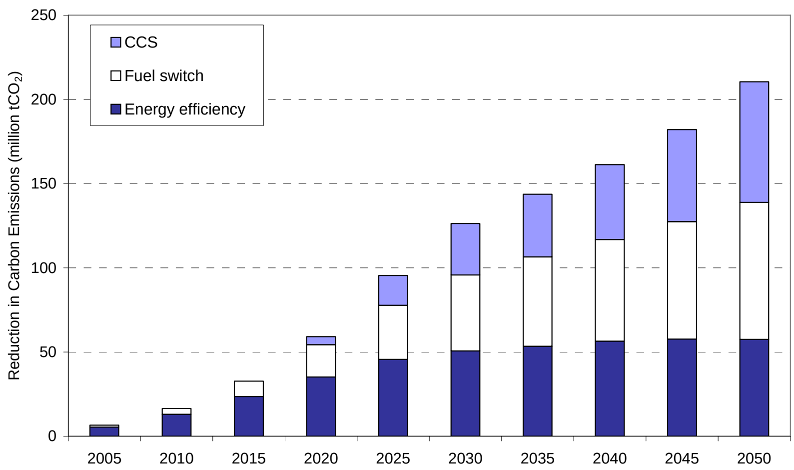

Fig. 4 Decomposition of economy wide emissions reductions at stepwise increase of CO_2 price

The analysis shows that all three mitigation options (efficiency increase, fuel switching, and CCS) respond to a CO_2 policy with varying degrees of sensitivity. An increase in energy efficiency is stimulated already at low levels of CO_2 policy (low reduction targets and therefore low CO_2 price) and depends on the development of energy prices as well as relative prices of goods and inputs. Over time as capital retires and with a higher CO_2 price (corresponding to a higher target) fuel switch adds to emissions reductions as does CO_2 capture and storage.

Excluding the option of CO_2 capture and storage from the analysis reduces overall emissions reductions for any given CO_2 price path by the amount of CCS related emissions reductions as shown in Fig. 4. This implies that for a given CO_2 price path lower emissions reductions would be achieved if CCS was not available. No significant addition in efficiency improvement or fuel switch would replace CCS. This is because the effect of the CO_2 price on unit costs of electricity generation within the model horizon is the same whether CCS is available or not. The share of CCS based electricity generation is chosen exactly in a way that it breaks even in terms of generation costs with its non CCS counterpart. With no difference in electricity costs, the effect on producer and consumer behavior is the same similarly to the effect on fuel switching. In this sense, efficiency and CCS are complementary options.

3.4 Electricity sector results

This section provides more detailed results for the electricity sector. Fig. 5 shows the share of electricity generation by technology for a stepwise increase of CO_2 price as well as total electricity generation for an SGM-Germany baseline through year 2050. CO_2 capture and storage is assumed not to be available in this first setting. In the baseline total generation rises gradually over time. In the case of a stepwise CO_2 price increase, total electricity generation rises initially and then levels off for a period of time as the CO_2 price rises. Total electricity generation in the policy scenario is lower than in the baseline. As electricity prices are already quite high in Germany, the additional costs induced by the CO_2 price do not have a very big impact, thus affecting electricity demand only slightly.

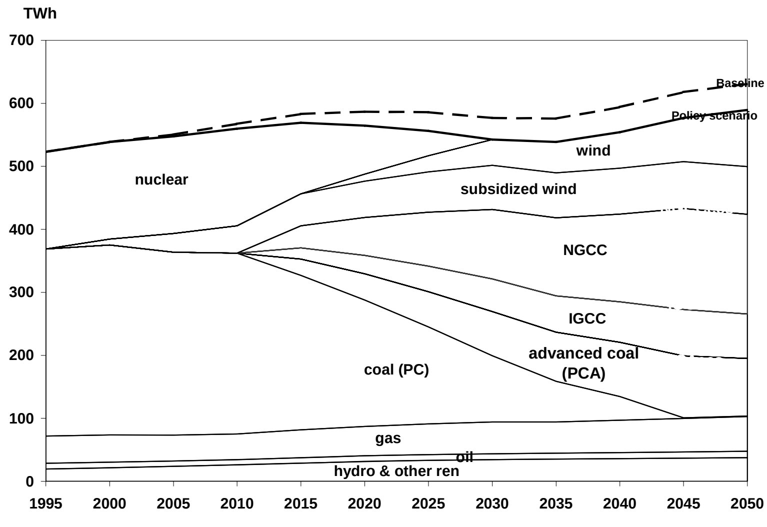

Fig. 5 Electricity generation mix without CCS technologies at stepwise increase of CO_2 price (policy scenario) vs. baseline total electricity generation

New electricity generating technologies are introduced to the model beginning in 2015. The share of nuclear power is exogenously reduced to zero by 2030, reflecting the German nuclear phase out. Wind power subsidized by the German renewable energy law rises steadily and accounts for a share of 12% of total electricity generation by 2030 and stays at this level thereafter. Advanced wind power that is assumed to not benefit from the renewable energy law accounts for a small share of electricity generation, but its cost per kWh is still high relative to other generating technologies. Shares of NGCC and IGCC grow rapidly to replace all nuclear power and much of pulverized coal. All generating plants are modeled with a lifetime of 35 years.

Fig. 6 shows the same set of results as above but with the option of CO_2 capture and storage included. Again, total electricity generation is lower in the CO_2 price case than in the baseline. CO_2 capture and storage is introduced after 2015, but has no market share in the baseline; its share increases with the CO_2 price and as old generating capital is retired. SGM-Germany operates in five-year time steps and capital stock is grouped into five-year vintages. New capital has flexibility to adjust to a new set of energy and CO_2 prices but old capital does not. Therefore, the full impact of a CO_2 price is delayed until all old capital retires.

The CO_2 price in later time periods (50 EUR per ton of CO_2) is well beyond the breakeven price for CCS with IGCC, so a large share of IGCC capacity includes CCS by 2050. A CO_2 price of 50 EUR per t CO_2 is below the breakeven price for CCS with advanced pulverized coal (PCA) and NGCC, so less than half of PCA and NGCC capacity includes CCS by 2050. CCS in this scenario applies to new generating plants only, and is phased in as old plants retire. With the CO_2 price, energy technologies that are less carbon-intensive increase their share of electricity generation. At lower levels of CO_2 prices (20 to 50 EUR per t CO_2), CO_2 capture and storage technologies as well as advanced wind still come into place, but with a reduced share of generation.

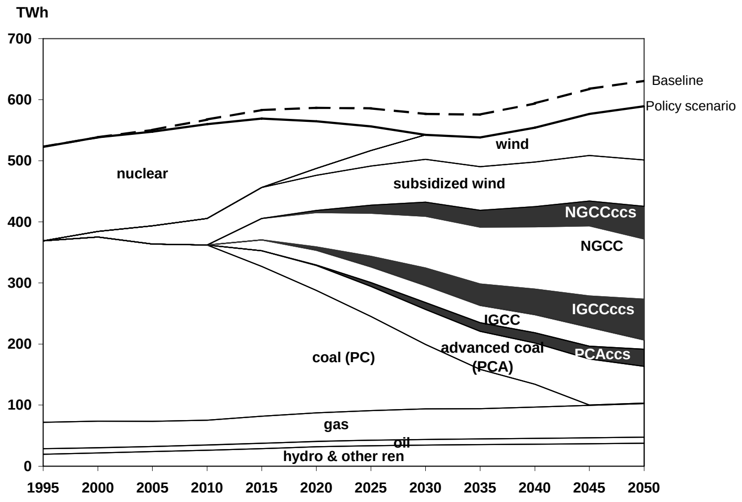

Fig. 6 Electricity generation mix with CCS technologies at stepwise increase of CO_2, price and baseline total electricity generation

With respect to CO_2 emissions in the electricity sector, an increasing amount can be reduced over time and with a higher CO_2 price as the capital stock turns over. The largest and most increasing share of emissions reduction in the electricity sector is taken up by fuel switching as one technology is substituted for another, i.e. as natural gas based and wind based electricity generation assume a higher share and replace coal-based generation (compare Fig. 5). In addition, a slight decline in overall electricity generation takes up a share in emissions reduction. This decline is due to decreasing demand from subsequent sectors in response to the CO_2 price. It thus stands for an energy efficiency increase in sectors and processes that use electricity.[6]

4 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

[6] As indicated before, these different electricity sector emissions reductions (with the exception of CCS) are included in the mitigation category labeled fuel switching.

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_2. In particular, many geological issues such as the impact of underground CO_2 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 (more than 500 MW), 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_2 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_2 has a price and CO_2 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). Alternative instruments such as a feed-in tariff for CCS are a potential alternative and should also be investigated with regard to the expected impact. 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_2 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_2, 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_2 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_2 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.

5 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 negotiating 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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