Carbon capture and storage vs. energy efficiency: Incompatible antagonists or indispensable allies?

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Abstract

Carbon capture and storage (CCS) promises the low-emissions coal power station. The technology is under development; a number of technological, economic, environmental and safety issues remain to be solved. With regard to possible trajectories towards a sustainable electricity system, CCS raises a number of questions. On the one hand, CCS may prolong the prevailing coal-to-electricity regime and countervail efforts to increase energy efficiency. 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. Energy efficiency could then be conceptualized as a natural ally of CCS, as it aims at reducing the consumption of energy and thus the amount of CO_2 to be captured and stored.

We discuss these issues for the case of Germany. After a survey of the current state of the art of CCS deployment and activities, we use a general equilibrium model to analyze the impact of introducing CCS to the German electricity system with respect to the energy and technology mix, the resulting CO_2 emissions and the interaction with energy efficiency measures. The model shows that, 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 in the analysis.. We conclude that, given an appropriate legal and policy framework, CCS and energy efficiency are complementary measures and should both form part of a broad mix of measures required for a successful CO_2 mitigation strategy.

Introduction

Coal is Germany's major domestic energy resource and electricity generation input. The country is a major lignite producer, while hard coal mining has declined in favor of imports. Altogether, coal provides almost 52 % of the fuel inputs for electricity generation. Under business as usual conditions, the picture is unlikely to change in the near future. Prospects for escaping this "carbon lock-in" are mostly considered unfavorable at present (Unruh 2000; Unruh 2002; Perkins 2003; Unruh and Carrillo-Hermosilla 2006).

With regard to sustainability, the extraction and combustion of hard coal and lignite for electricity generation is a heatedly debated issue. Coal proponents claim that coal use ensures security of energy supply at low cost. Under the conditions of the German nuclear phase-out, they see no alternative to it. Environmentalists argue that coal mining and combustion are responsible for landscape destruction and that they threaten the earth's climate more than any other single energy source.

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 (or that even reinforces) its overall structure. CCS allows for the continued use of fossil fuels, it can be combined with the existing infrastructure (that is, large-scale centralized power plants) and implemented by existing actors. Opponents therefore fear that CCS may further delay the transition to a carbon-free electricity system. But CCS could also be considered an innovation that "buys time" for radical restructuring and serve 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.

Another option to reduce climate gas emissions and resource depletion is to increase the energy efficiency of the economy. Improvements in energy efficiency can occur on both the demand and the supply side of energy. On the demand side, industry and private households may invest in more energy-efficient production and consumption equipment as well as in improved building features so as to reduce heating requirements. On the supply side, conversion efficiency is in the focus of energy efficiency activities. In this paper, we address both areas, albeit in different detail.

With respect to energy efficiency, CCS raises major issues. On the one hand, CCS is linked to a significant loss of generation efficiency which leads to a higher level of primary energy needs for electricity generation and thus higher resource depletion and related environmental and landscape damages. Also, a risk of leakage in CO_2 storage exists, which may offset mitigation efforts. The question hence is if CCS and energy efficiency are compatible or if CCS simply threatens to "eat up" the efficiency gains realized elsewhere in the economy without any benefit for the earth atmosphere. Besides, fears are that the focus of research and development (R&D) as well as investment expenditures may shift towards CCS, thus affecting adversely on efforts for other sustainable technologies such as renewable technologies and energy efficiency. On the other hand, the perception of CCS and energy efficiency as antagonists may not be appropriate to the issue at all, as both may contribute to a given CO_2 reduction target. Given an appropriate price for CO_2 allowances and a related increase in final energy prices, "the market" will then decide about the shares in CO_2 reduction delivered by the different mitigation options.

Against this background, our paper sets out to explore whether CCS technologies and energy efficiency are compatible or not. Does CCS – in view of both the energy and CO_2 perspective – make economic and environmental sense? How does the availability of CCS affect the impact of sustainable policy and system options? Does it simply prolong the existing carbon lock-in and hinder the diffusion of energy efficiency and sustainable energy generation technologies? Is CCS an antagonist or an ally to energy efficiency? Where do they compete, where do they support each other as part of an overall climate protection and sustainable energy transformation?

The paper is organized as follows. After an inventory of the state of the art of CCS and the current activities in Germany and Europe, we summarize economic assessments for CCS and the resulting outcomes of scenario analyses. We then introduce the Second Generation Model (SGM-Germany), a dynamic general equilibrium model, to analyze the impact of introducing CCS to the German electricity system. We investigate the effects with respect to the energy and technology mix, the resulting CO_2 emissions and the interaction with energy efficiency measures. In the last section we discuss our findings and draw conclusions for the policy framework required for a useful deployment of CCS.

CCS and Energy Efficiency: What Are the Issues at Stake?

We start our paper with a brief overview of the current state of CCS technology, its economics and its environmental performance, and procure issues coming up in the debate about a future deployment of CCS. We then briefly describe CCS activities and the general setting for CCS in Germany and discuss the interface of energy efficiency and CCS.

STATE OF THE ART

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, for example, has been injecting CO_2 into oil formations to recover additional oil since the 1970s (so-called enhanced oil recovery or EOR). A network of pipelines was built in the Western USA in order to connect CO_2 emission points and oil drilling places. One of the main differences between EOR and CCS is, though, 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.

In combination with electricity generation from fossil fuels, CCS is at an early stage of development and market formation, leaving several decisions to be made and a number of questions to be asked. It is possible for a number of fuel inputs. However, due to the respective levels of fuel prices, CCS is not likely to be economic in gas plants, and the German debate has been focusing on CCS from coal-based power plants. Several CCS processes are currently being developed: capture from the flue gas (*post combustion*), separation from the fuel gas (*pre combustion*) and *oxyfuel technology*, in which the fuel is combusted with pure oxygen, producing a high concentrate of CO_2 which facilitates its recovery. Post combustion is available for conventional power plants, while pre-combustion is applied in integrated gasification combined cycle plants (IGCC). Retrofit is only possible for post combustion. Technologically and economically, IGCC appears to be the most promising today (Watson 2005; Radgen et al. 2006).

Worldwide, a large number of plants and storage projects are in the process of planning and design. The IEA database on CO_2 Capture and Storage projects (IEA 2007) counts 135 projects on capture, transport and storage. A detailed assessment of the current status of CCS is presented in a special IPCC report on the issue (IPCC 2005). In Germany, the first 30 MW oxyfuel pilot plant is being implemented by the energy utility Vattenfall. It is to be completed by 2008 and then followed by a demonstration station of 200 MW. RWE, also a major energy utility, meanwhile announced that it is to start generation in an IGCC plant of 450 MW by 2014.

The captured CO_2 can be compressed and led through pipelines or by ships or other carriers to a storage site in, e.g., saline aquifers, oil and gas fields or coal seams. The disposal of CO_2 in deep oceans is currently not regarded as an option in Europe, including Germany.[1] Its risks, particularly in terms of the time

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[1] However, the US and Japan are considering ocean storage, and international legal barriers have been recently changing the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, so that CO_2 no longer counts as a pollutant (Carbon 2006).

of storage and effects on the marine environment, are considered to be too high (WBGU 2003). In Germany, saline aquifers have the greatest storage potential. 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. Moreover, as many storage sites are cross-national, the distribution of rights and responsibilities requires clarification.

The major environmental risk (and perversion) of CO_2 storage is leakage. Model calculations and natural analogies suggest that in many geological formations, leakage rates somewhere below 1 % over 1,000 years are possible. Exhausted gas and oil fields and, to a lesser extent, salt caverns have so far been regarded as safe permanent storage sites. However, any leakage rate greater than zero means that most of the CO_2 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_2 can dissolve minerals in the ground and, by this means, cause leakage (Kharaka et al. 2006).

Among the most-debated issues are furthermore the level and intensity of public (and private) R&D funding for CCS as compared to other (renewable or efficiency-oriented) energy or climate change mitigation technologies, and the regulatory framework needed for safe storage. There is no doubt that further R&D is needed on its technological integration into the electricity generation process, but particularly on leakage and storage issues.

In addition to these concerns, public acceptance is a great unknown at the moment. A major fear articulated by potential investors is that the storage of CO_2 may trigger an avalanche of public protest activities, similar to those observed in the case of nuclear energy.

CCS ACTIVITIES IN GERMANY AND EUROPE

In Germany, CCS is still in an early stage of development. Apart from a limited R&D program, no elaborated policy exists so far. Rather, the process is in the agenda setting phase where issues for discussion and, potentially, decision making are brought to the fore. The last few years, however, have witnessed a growing level of activities around CCS both nationally and internationally (Commission 2004; Linßen et al. 2006; Radgen et al. 2006). In Germany, most activities focus on R&D, conducted by two electric utilities, and supported through various research programs by the Federal Ministry for Economics and Technology (BMWI), the Federal Agency for Geosciences and Raw Materials (Bundesanstalt für Geowissenschaften und Rohstoffe, BGR), and the Federal Ministry of Education and Research (BMBF). In contrast, the Federal Ministry for the Environment (BMU) runs a more policy-oriented approach for evaluating CCS and comparing it to renewable energy technologies from a climate-policy perspective. The program includes a dialogue between different actors by means of a number of workshops (WI et al. 2004b). The Federal Environment Agency (Umweltbundesamt, UBA) also assessed CCS technologies (Radgen et al. 2006) and formulated a position paper, concluding that CCS could, at the utmost, be considered a bridging technology (UBA 2006). Furthermore, European initiatives are an important framework for German activities. On the European level, R&D in CCS has been increasingly supported (Levefre 2006; Dimas 2006a). On December 1st, 2005, the European Commission in cooperation with major industrial associations launched the Technology Platform for Zero Emissions Fossil Fuel Power Plants (ZEFFPP, later ZEP). It brings together actors from industry, research, NGOs and the European Commission in an effort to develop a "Strategic Research Agenda" and "Strategic Deployment Plan" for CCS (Commission 2006). Besides, Germany has been engaged in the Carbon Sequestration Leadership Forum (CSLF), a ministerial-level international initiative for CCS development, since 2003.

Most of these activities are rather recent. For a long time, CCS had not been much of a political issue in Germany. The debate had been taking place 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 Federal Ministry for the Economy and Technology (BMWI) and the German Council for Sustainable Development. The oil and gas industry, albeit not directly involved in electricity generation, has longstanding expertise in using CO_2 for enhanced oil recovery and would benefit from CCS with a double dividend: first, by receiving CO_2 for EOR and secondly, by offering and selling off the related CO_2 reduction opportunities to participants of the emissions trading system.

Electricity and power plant industry shared a pattern of arguments with coal mining industry, called the "Three-Step" or "Three Horizons" concept. It stipulated 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 was thus presented as a technology for the rather remote future. The main reason behind this reluctance was the expected loss in conversion efficiency and increase in cost. Industry was involved in R&D activities in order to keep up-to-date but kept its engagement rather low key, called for public funding as a condition for an own investment, and did not do much to publicly promote the technology.

The coal mining industry has, surprisingly, 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 strongly promoting CCS. Some possible reasons emerge: first, in the case of hard coal, it is a question of 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. Secondly, 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 may undermine its competitiveness.

Now the time seems mature for more actors to join in. Climate policy is re-emerging as an issue: the negotiations for the second commitment period of the Kyoto Protocol are beginning, climate has been a topic at G8 summits and recent flood events and heat spells have heightened public attention. In parallel, CCS technology is making progress and is being recognized on an international level by the climate policy community, as shown by the IPCC report on CCS (IPCC 2005). In this vein, political interest in CCS is beginning to increase and the debate has been gaining considerable momentum lately. This is especially so in the case of electricity and power plant industry – and of environmental NGOs, which are now forming up to develop and demand a clear legal framework and registration rules for CCS, similar to the "Golden Standard" for projects in the Clean Development Mechanism. Altogether, however, there is no fierce opposition to CCS in Germany yet.

THE INTERFACE OF ENERGY EFFICIENCY AND CCS

In comparison to CCS, energy efficiency has a long-standing tradition in Germany which finds its reflection in a number of established policies such as standards for all kind of technologies, appliances and heating, and tax advantages for highly efficient energy generation technologies, for example cogeneration plants or combined cycle gas technology stations (CCGT). Energy efficiency has been an area of concern and action in European and German energy policies since the early 1970's oil price increases and the related debates about security of energy supply. Fuelled by actual fears or expected rises in energy prices, and supported by efficiency standards, informational measures, energy audits and investment subsidies, energy efficiency improved in Germany on all levels. Since 1990, primary and final energy intensities in Europe (EU-15) declined by 1.1 % per year or 14 %, while the growth in energy consumption has been 40 % below economic growth (Odyssee 2007). Until 2000, primary energy intensities decreased faster than after 2000, because of the parallel increase in the deployment of cogeneration and gas combined cycles. In Germany, the total energy efficiency increased even faster (Odyssee 2006), but large energy efficiency potentials still remain untapped (WI 2006).

Energy efficiency and CCS are potentially interlinked in both directions, positively and negatively. A major drawback of CCS is that it requires additional energy input and implies a so-called energy penalty. The negative impact of CCS on power plant efficiency is substantial: 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). This figure increases even more when a life cycle analysis (LCA) of all up- and downstream processes is conducted (Idrissova 2004; Pehnt 2005). These efficiency losses increase fuel consumption and associated environmental damage such as landscape destruction and pollutant emissions. This also means that CO_2 and other emissions are still being produced, i.e. they physically exist. In fact, CCS related CO_2 mitigation takes place in form of capture and storage as opposed to CO_2 production being actually and physically reduced through efficiency improvement. Successful mitigation is thus dependent on the availability of non-leaking storage capacity. However, a risk of leakage always remains, which may offset mitigation efforts. Both – leakage and conversion efficiency – are significant parameters for the global warming balance of CCS.

A second – potential – drawback could emerge on the level of R&D policies. When politicians consider CCS to be a "magic bullet" to the mitigation of climate change, they may refocus (public) R&D expenditures towards CCS and disregard R&D efforts to further improve energy efficiency. Currently, the shares dedicated for the different technology areas within the German federal R&D budget still prioritize other mitigation options: R&D on renewable technologies enjoys about 130 Mill. EUR annually, energy efficiency receives about 80 Mill. EUR, while CCS has been fostered with 18 Mill. EUR per year (BMWI 2006; UBA 2006). However, this picture may change.

Conversely, both CCS and energy efficiency could also be considered to belong to the same trajectory towards a sustainable energy system: Given an appropriate price for CO_2 allowances and a related increase in final energy prices, both energy utilities and consumers will choose a portfolio of economical options to reduce their CO_2 emissions, including both CCS and energy efficiency measures (and others). This line of thinking finds its reflection in the draft Energy Policy for Europe published in early January 2007. Therein, the EU Commission commits itself to installing CO_2 capture and storage in a substantial number of fossil fuel power stations by 2015, and to phase out plants without it. At the same time, the EU Commission also targets energy efficiency improvements of 20 % compared to energy consumption in a reference scenario. The ultimate aim is to cut CO_2 emissions by at least 20 % compared to 1990 until 2020 by means of a mix of measures, including efficiency improvements, CCS and renewable energy (EU 2007).

A pressing concern is therefore whether CCS might be implemented in such a way that it functions as a "bridge" towards implementation of sustainable technologies, such as energy efficiency or renewable technologies, rather than hindering these technologies from diffusion into the existing system. 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 2020. Until this – speculative – point of time of market introduction, other means of mitigation would need to be explored. Observers expect that by this time some 40 GW of capacity will already have been replaced in Germany, due to the phasing-out of nuclear energy and the decommissioning of further plants (Matthes and Ziesing 2003; UBA 2003). This significantly reduces future opportunities for the deployment of CCS. As CCS retrofit is much more expensive than integrated CCS, the question is whether CCS will simply come too late.

To summarize, CCS is a mitigation option economical for large point sources, such as large power generation units. This leaves scope (and the need) for other mitigation options, including energy efficiency and renewable technologies. In fact, as we will discuss below, instead of discussing "competing options", CCS and the other mitigation options could also be complements within a mix of mitigation options, including energy efficiency.

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.

ECONOMICS OF CCS AND MITIGATION SCENARIOS

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 coal-based electricity generation because of the additional plant equipment and the "energy penalty". 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, future 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 2006).

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 2005).

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 the share of 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). 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.

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 (1) 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 (2) 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 relative 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.[2] 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.[3] 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.

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 CO_2 allowances allocated to the covered industries.[4] It would imply that power stations with CCS require CO_2 allowances corresponding to their CO_2 emission.[5]

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 in the form of marginal abatement cost curves. This is done in Figure 1 and Figure 2 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).[6] 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 for a national emissions trading system with a given target. 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 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 Figure 1 and even more pronounced for the year 2040 in Figure 2, 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 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.

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, one can calculate 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

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[2] 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).

[3] 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.

[4] 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.

[5] 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).

[6] 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).

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. Figure 2 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.

Figure 3 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 with 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.

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 re-

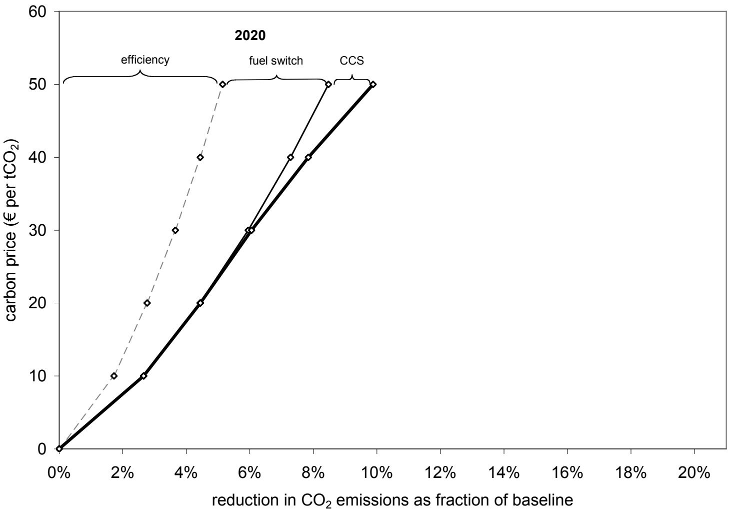

Figure 1 - Simulated economy wide emissions reductions over a range of CO_2 prices, Germany 2020

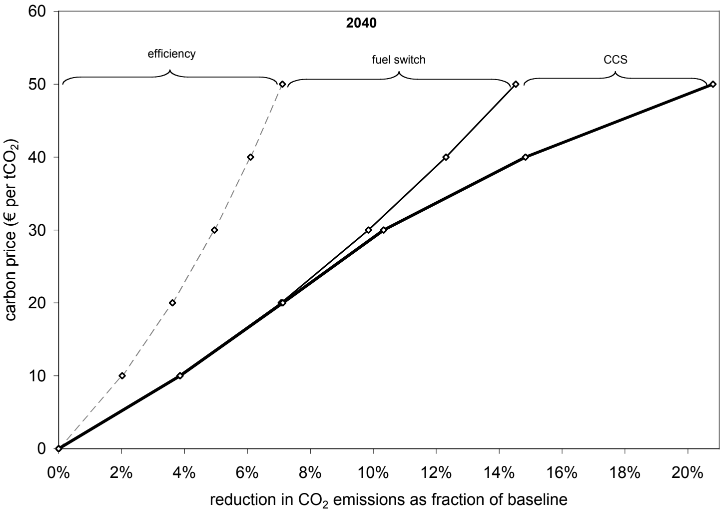

Figure 2 - Simulated economy wide emissions reductions over a range of CO_2 prices, Germany 2040

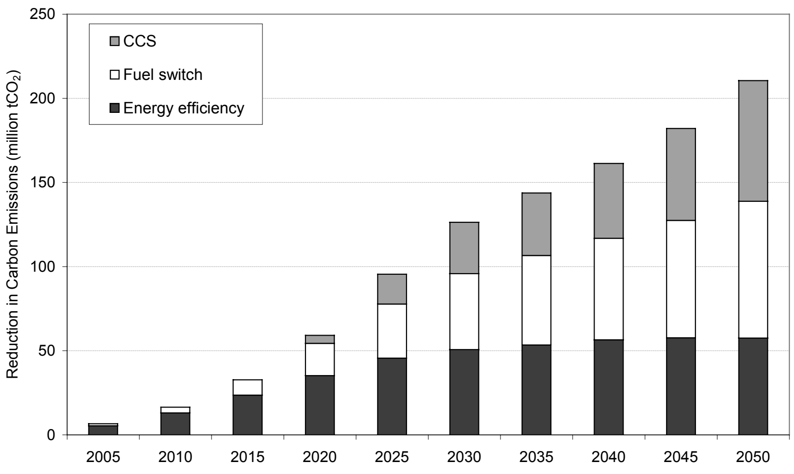

Figure 3 Decomposition of economy wide emissions reductions at stepwise increase of CO_2 price

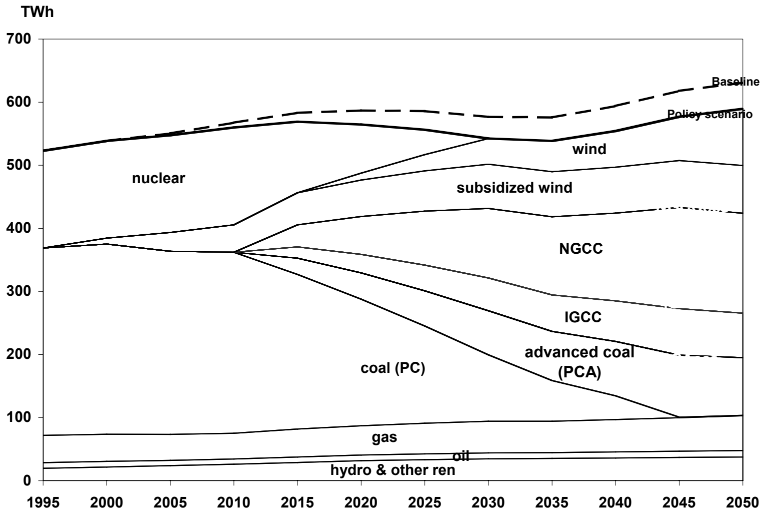

Figure 4 - Electricity generation mix without CCS technologies at stepwise increase of CO_2 price (policy scenario) vs. baseline total electricity generation

ductions as shown in Figure 3. 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 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.

ELECTRICITY SECTOR RESULTS

This section provides more detailed results for the electricity sector. Figure 4 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.

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.

Figure 5 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.

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 Figure 4). 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 efficiency increase in sectors and processes that use electricity.[7]

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

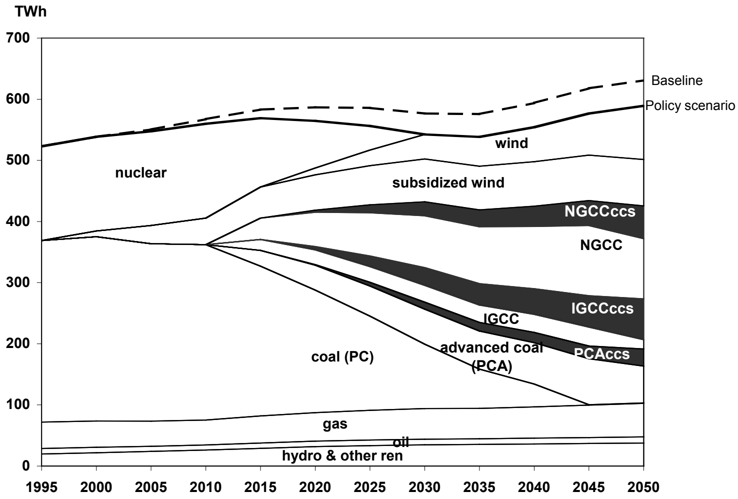

Figure 5 - Electricity generation mix with CCS technologies at stepwise increase of CO$_{2,}$ price and baseline total electricity generation

Discussion

Our paper assessed the potential for a future deployment of CCS in Germany and asked for the interaction with energy efficiency. In the following, we will discuss main aspects with regard to the expected future of CCS and close with a summary of preconditions for a sustainable transition of the electricity system –with or without CCS.

It is likely that CCS will come, most probably as an integrated process (no retrofit). Indicators are increasing R&D activities – both nationally and internationally, by governments and by industry – and the fact that there are only few principally opposed actors. Activities to develop the necessary regulatory framework are already underway on an international level, although they are not so much recognized in the German debate. For example, the IPCC is currently issuing new guidelines for including CCS into national greenhouse gas inventories (Eggleston 2006; IPCC 2006). Also, in an October 2006 workshop, the International Energy Agency has done intensive work on legal aspects (IEA 2006). As recommended by the Working Group on CCS under the Second European Climate Change Programme (ECCP II), the European Commission is planning to issue a Communication on CCS for the second half of 2007 and to develop draft legislation for the topics of risk, liability, legal barriers and incentives (CCS 2006; Levefre 2006; Dimas 2006b).

Our scenario analysis shows that CCS and energy efficiency could both contribute to higher emission reductions, given a significant level of the CO$_2$ price. We conclude that, given an unchanged level of other energy policy and research activities, a high enough climate target would stimulate both efficiency improvement and deployment of CCS. Given such a target, over time emissions reductions can be achieved at lower marginal costs when CCS is included in the analysis. From this perspective, despite the loss of conversion efficiency in electricity generation induced by CCS, we consider overall energy efficiency and CCS as complementary or "natural allies". This presumes, however, a sensitive R&D policy which does not significantly shift its current focus. In case that CCS diverts too much funding from energy efficiency and renewable technologies, the result could differ considerably.

CCS endorses the idea of fossil fuels – including coal – as transitional fuels. CCS may prolong the dominance of the current coal-to-electricity path to some 100 years – instead of about 40 years as maintained by environmentalists. As CO$_2$ separation is only viable for large point sources, the current structure of centralized coal-fired power plants will be partly conserved. Not all investment is likely to flow into such plants. How far a mix of central and decentralized options based on different fuels is likely to result remains to be investigated.

Timing is another important issue. With their "three-step" concept, industry gives priority to the installation of current state-of-the-art plants, so that a large number of conventional coal plants will have been installed by 2020, thus reducing future CCS potential. Hence, coal has a future in Germany even without deployment of CCS. However, contrary to public perceptions, 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 allows for a step-by-step implementation of CCS after 2020. This is underlined by our scenario analysis given appropriate climate policy measures. It will be followed by a slow but steady decommissioning of CCS plants towards the depletion of CO$_2$ storage capacities.

Aside from this, CCS is relevant not only for Germany. In fact, emerging economies like China and India (and other developing countries) have even more potential as addressees for the deployment of CCS (Watson 2005; Stern 2006; Unruh and Carrillo-Hermosilla 2006). Stern (2006) also points out that "…CCS is a technology expected to deliver a significant portion of the emission reductions. The forecast growth in emissions from coal, especially in China and India, means CCS technology has particular importance. Failure to develop viable CCS technology, while traditional fossil fuel generation is deployed across the globe, risks locking-in a high emissions trajectory." For Germany, this opens up new perspectives for power plant industry – a new export market can be developed. To this end, technology development and implementation in Germany is an important step. However, whether CCS will take off in emerging economies ultimately depends on the climate regime.

To summarize, the somewhat provocative title of this paper turns out to be exaggerated in both directions. There is no economic reason to exclude CCS from mitigation strategies. Given the speculative nature of technology forecasts, a sensitive research and mitigation policy strategy must include all other options. More R&D on geological and other environmental risks is required, in order to gain a realistic idea about its potential. For example, EOR and EGR appear to be well-researched, but saline aquifers leave a number of open questions with respect to underground chemical impacts and leakage. In any case, CCS should not be considered a magic bullet but as one option within a broad portfolio of climate protection measures, competing for their implementation. Such a broad portfolio allows to choose those options with lowest CO_2 mitigation cost. CCS can assume a specific role within that portfolio as a bridging technology during a transition from a carbon-based towards a carbon-free electricity system. In Germany, but also elsewhere, CCS is only likely to start playing a more significant role after the year 2020 or even later, mainly depending on the CO_2 price.

For this to come, a clear and reliable 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. Such a framework consists of four core elements. First and foremost, electricity and energy prices 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. This stimulates the development of efficiency and renewable technologies, and also of CCS. In case that the economic incentives do not trigger the desired outcome, it needs to be discussed whether, similarly to the case of SO_2, new coal-based power plants could be obliged to include CCS. Secondly and respectively, 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. Thirdly, public funding for CCS is needed to explore its potential. It is important, though, that CCS should not crowd out research on and investment in 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. An appropriate funding policy must also ensure the development of technologies that are not yet economic today, but may be needed in the future to combat climate change or replace scarce and environmentally problematic fossil fuels. Last but not least, aspublic acceptance is an important aspect of a future deployment of CCS, any strategy to implement CCS needs active and open public outreach activities, combined with a well-developed regulatory framework.

This paper could only touch upon a number of issues that deserve to be treated in more detail in future research. In particular, likely investment decisions up to 2020 and their dependence on climate and energy policy are major issues to be investigated in more depth. Also, such policies may trigger innovation and learning effects within industry and business that are not captured in conventional (economic) indicators. The scenario analysis does not investigate research and development efforts and the potential diversion of R&D investment in response to climate policies. Moreover, it does not allow any conclusion about the desirability of CCS. Also, leakage, in form of production and inherent emissions lost to other countries, and energy efficiency, in particular in private households, would deserve to be modeled in a more detailed form.

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