Innovative energy technologies and climate policy in Germany

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Abstract

Due to the size and structure of its economy, Germany is one of the largest carbon emitters in the European Union. Substantial mitigation possibilities exist in the electricity generation sector through advanced generating technologies or substitution of less carbon-intensive fuels. Various climate policies are considered to reduce emissions and enhance the share of climate friendly technologies. At the same time, Germany is facing a major renewal and restructuring process in the energy sector. Within the next two decades up to 50% of the current electricity generation capacity is likely to retire because of end of plant lifetime and the nuclear phase-out pact of 1998. This may provide a window of opportunity for new and innovative technologies to play an even more substantial role in the future electricity mix. Those new technologies and their role within a future German electricity system are the focus of this paper. We introduce advanced electricity technologies such as integrated gasification combined cycle (IGCC), natural gas combined cycle (NGCC), wind power, and CO_2 capture and storage into a computable general equilibrium model for Germany, the Second Generation Model (SGM). We simulate the response of greenhouse gas emissions in Germany to various technology and carbon policy assumptions over the next few decades. This provides an estimate of the cost of meeting an emissions target, such as that from the Kyoto Protocol, and the share of emissions reductions available from the electricity generation sector.

1. Introduction

Due to the size and structure of its economy, Germany is one of the largest carbon emitters in the European Union. It is responsible for approximately 800 million tons of carbon dioxide (CO_2) emissions annually, accounting for about one-fourth of EU greenhouse gas emissions. Compared to the level in 1990, Germany's emissions are now 19% lower. Within the burden sharing agreement under the Kyoto Protocol, Germany is committed to reduce carbon emissions by 21% in 2008-2012 compared to 1990. Another long-term national target is to reduce CO_2 emissions 40% by the year 2020 relative to 1990. A substantial part of global greenhouse gas emissions is produced by the electricity system. CO_2 emissions due to fossil fuel combustion for electricity production amount to more than 40% of total CO_2 emissions in Germany, as they do in many other industrialized countries.

At the same time, Germany is facing a major renewal and restructuring process. Around one-third of its total electricity generating capacity, in the form of fossil-fuel based generation, may retire within the next twenty years; another one-sixth of capacity, in the form of nuclear power plants, is scheduled to be phased out. With a projected stable electricity demand, this means that almost fifty percent of German electric power capacity could be replaced within the next twenty years. This provides a substantial window of opportunity for new and innovative technologies such as renewables, coal integrated gasification combined cycle (IGCC), natural gas combined cycle (NGCC), and CO_2 capture and storage (CCS) combined with either coal IGCC or NGCC. Substantial mitigation possibilities in the electricity sector exist in the form of reducing demand through more efficient end-use technologies, or on the generation side through advanced generating technologies or substitution of less carbon-intensive fuels. CCS has received much attention recently as it allows continued use of fossil fuels while emitting much less CO_2 to the atmosphere. CCS has the potential to reduce global emissions up to 50% by 2050 (IEA 2004). A recent study by the International Energy Agency calls governments to step up their support for CCS and increase research on these technologies (IEA 2004).

Various environmental and energy policy efforts are in place to reduce emissions and increase the share of environmental friendly technologies in Germany. For example, an ecological tax reform was introduced in 1999. A renewable energy law to increase the share of renewable energy, and a combined heat and power (CHP) law to increase the share of CHP based electricity production, were put into force. More stringent voluntary agreements on reducing industrial carbon emissions were established.

At the same time, trading of emissions rights is a major topic because of its market-based approach and its economically efficient way of meeting emissions targets. The European Union decided on implementing a European-wide emissions trading scheme in 2005, while it is foreseen for Annex I countries in the Kyoto Protocol to start in 2008. Additional policies are in place to enhance the share of advanced technologies and to promote efficient transformation and consumption of energy.

It is expected that advanced and innovative generating technologies will play an increasingly important role in electric power production in Germany. Those new technologies and their role within a future German electricity mix are the focus of this paper.

We simulate the introduction of advanced electricity technologies such as IGCC, NGCC, wind power, and CCS in a computable general equilibrium model for Germany, the Second Generation Model (SGM), and analyze the costs of mitigating carbon emissions with and without these technologies under different policy scenarios. SGM-Germany is a dynamic recursive, multi-sector general equilibrium model based on national economic input-output data, national energy balances and country-specific engineering cost information for each electric generating technology. These data are combined in the general equilibrium model to maintain the technological richness of a market-based energy system comprised of conventional and advanced electric generating technologies.

We first develop a baseline simulation of the German economy and energy system from 1995 through 2050 in five-year time steps, including a scenario of electricity generation by technology. Next, the model is exercised at various carbon prices to estimate the cost of reducing carbon emissions below the baseline. We consider a wide enough range of carbon prices to provide some idea about the carbon price needed to meet Germany's Kyoto target.

We are also interested in analyzing at what carbon prices new electric generating technologies, both with and without CCS, become economically competitive. Simulation results are sensitive to engineering cost assumptions on the generating technologies, and we have collected a range of such data from various sources. One important characteristic is the break-even carbon price for introducing CCS, either with IGCC or NGCC technologies. In addition, we consider the role of renewable energy and conduct a similar break-even analysis for wind technologies.

Section 2 provides an overview of energy and climate policy in Germany. Section 3 gives a brief overview of the current structure of the German electricity system. It highlights important features with respect to the electricity generation mix, emissions trends, past and future technologies, and costs. We introduce the SGM model in Section 4 and describe how it can be used to analyze the costs of carbon mitigation under different policy and technology assumptions. In Section 5, we discuss results for the electricity sector and then place them in context with the overall economy.

2. Energy and climate policy

Energy and environmental policies and measures in Germany consist of efforts that originate at the national, European and international levels. An ecological tax on fossil fuel and electricity use was introduced in 1999 on top of existing mineral oil taxes. Currently, policies are targeted to renewable energy as well as combined heat and power production. Moreover, starting this year, the European emissions trading program is coming into effect covering carbon emissions from energy as well as industrial sectors.

Renewable energy: The German government aims to double the share of renewable energy production by the year 2010 compared to 2000. This means that at least 12.5% of electricity should be produced by renewable energy by 2010. In the medium term, the goal is even higher. By 2020, the goal is to produce at least 20% of the electricity by renewable energy. In the long term, by 2050, the goal is to see renewables share rise to at least 50% in total energy production.

To help reach these goals, a renewable energy law was introduced to support production of renewable energy. The law was originally passed in 2000 and replaced the electric power feed in law of 1991. The law supports renewable energies (wind power, hydropower, solar energy, biomass) through two main features: a legally fixed compensation for renewable-based power fed into the grid, and a priority purchase requirement for renewable power imposed upon transmission system operators.

To give an example, the compensation ranges from 5.5 ct/kWh to 8.7 ct/kWh for onshore wind energy, from 6.19 ct/kWh to 9.1 ct/kWh for offshore wind power. Solar energy receives a payment of up to 62 ct/kWh depending on the kind and size of installation. The law is considered by some to be an effective climate policy instruments in Germany (BMU 2004a). In 2003, around 53 Mt CO_2 were mitigated by using renewable energy sources for electricity, heat and gasoline. It is expected that 85 Mt CO_2 will be saved due to renewable energy use by 2010. The renewable energy law is anticipated to reduce emissions by 42 Mt CO_2, about half of total savings.

*Energy Tax***:** Energy taxation in Germany consists of taxes on mineral oil (petroleum products) and electricity aimed at reducing energy-related emissions. In 1999, Germany introduced an ecological tax reform (ETR), which increases taxes on energy in a complex way. On one hand, the ETR raises existing taxes on petroleum products (gasoline, diesel fuel, heating oil, and natural gas); it also introduces, and provides for the increase of a tax on electricity (BMU 2004b). Eco-taxes are levied on final energy consumption (Kohlhaas 2003, Kohlhaas and Mayer 2004).

A significant feature of the ETR is that coal use is generally exempt from taxation, while gas input to electricity production is still taxed via the pre-existing mineral oil tax. This makes for an imbalance within fossil fuel use. In particular, it presents a disadvantage for natural gas use, which is less carbon intensive than coal. This imbalance will be alleviated soon, due to a recent EU Directive on Energy Taxation (EC 2003a) that requires the general exemption from energy taxation of fuel inputs to electricity production. The required exemption of gas inputs to electricity production has yet to be put into national force. Special provisions, e.g. lower tax rates or tax exemptions, are given so to not excessively burden some sectors compared to others.

Emissions trading: In October 2003, the EU adopted Directive 2003/87/EG, establishing a scheme for GHG emission-allowance trading within the Community: “This directive aims to contribute to fulfilling the commitments of the European Community and its Member States to reduce greenhouse gas emissions more effectively, through an efficient European market in allowances, with the least possible diminution of economic development and employment," (EC 2003b). Basically, the directive controls all greenhouse gases covered by the Kyoto Protocol, although in the first three-year period from 2005 to 2007, only CO_2 will be covered. Estimates of the price of CO_2 allowances range from 5 to 30 €/t CO_2, but a level of slightly less than 10 €/t CO_2 seems to be most likely (Matthes et al. 2003). In Germany, allowances will be distributed free of charge to the covered installations up to the year 2012.

3. German electricity sector

Currently, electricity production in Germany is dominated by nuclear and fossil fuels. More than fifty percent of the electricity is produced from hard coal and lignite, another 28% from nuclear fuels. Renewable energy sources, so far, account for only a small share (7.4%). Over the last decade, however, production from renewables, in particular wind, has substantially increased (see Figure 1). The electricity sector is responsible for more than 40% of German CO_2 emissions (see Figure 2).

A substantial restructuring of the electricity sector will be needed within the next two decades. About 40 GW worth of fossil fuel based power capacity may retire within this period and another 18 GW of nuclear power capacity could go off-line in accordance with the German nuclear phase out pact of 1998. These plants either have to be replaced by new plants or compensated by reductions in electricity demand (Enquete 2002). In any case, it calls for substantial (replacement) investments and may provide a window of opportunity for new and innovative technologies to play a role in the future electricity mix.

Figure 1 Gross electricity production by fuel (in TWh)

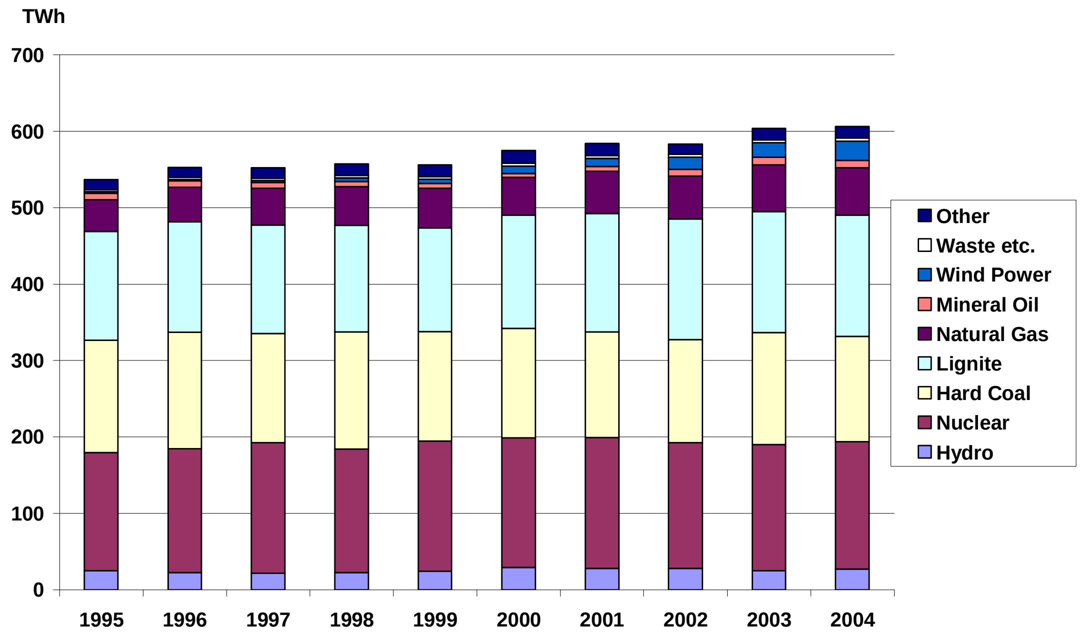
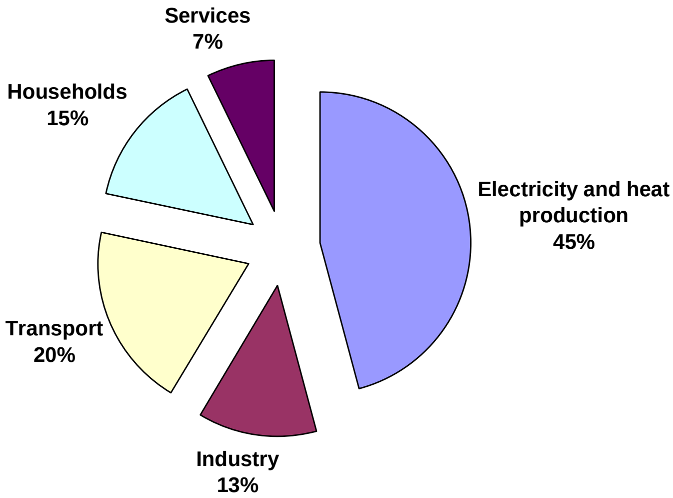


Figure 2 CO_2 emissions by sector (% share); Germany 2003



Among those new and innovative technologies are fossil fuel based as well as renewable energy based technologies. For coal we consider IGCC with and without CCS to be a significant advance in the future; for natural gas based technologies it is NGCC with and without CCS. For wind we consider an advanced offshore technology that is expected to be available between 2010 and 2020. The technologies differ substantially in their costs and performance. Since our analysis is focused on Germany, we aim at including as much country-specific information as possible.

Table 1 Cost and performance measures of new electricity technologies with and without CO_2 capture and storage

Cost and Performance Measures	**Wind**	**PC Plant**			**IGCC Plant**			**NGCC Plant**		
	Ikarus	**Enquete**	**David/ Herzog**	**IEA**	**Enquete**	**David/ Herzog**	**IEA**	**Enquete**	**David/ Herzog**	**IEA**
Without capture & storage										
Conversion Efficiency (%)		51	42	43	54	48	46	62	60	56
Emn. Rate (kg CO_2/kWh)		0.629	0.756	0.746	0.594	0.671	0.697	0.294	0.301	0.323
Capital cost (cent/kWh)	5.71	1.28	1.29	1.26	1.72	1.4	1.78	0.54	0.64	0.49
Labor cost (cent/kWh)	1.52	0.80	0.61	0.52	1.55	0.61	0.98	0.39	0.24	0.33
Fuel cost (cent/kWh)		1.24	1.49	1.47	1.17	1.32	1.38	2.76	2.82	3.03
COE (cent/kWh)	7.23	3.32	3.39	3.26	4.44	3.34	4.14	3.69	3.7	3.84
With capture & storage										
Conversion Efficiency (%)			36	31	48	43	38		55	47
Emn. Rate (kg CO_2/kWh)			0.089	0.103	0.067	0.074	0.084		0.033	0.038
Investment cost (Euro/kW)			1708	1850	2033	1462	2100		850	800
Capital cost (cent/kWh)			2.01	2.17	2.49	1.79	2.58		1.04	0.98
Labor cost (cent/kWh)			1.16	1.39	2.07	0.85	1.59		0.42	0.55
Fuel cost (cent/kWh)			1.66	2.04	1.32	1.38	1.67		3.22	3.61
Storage cost (cent/kWh)			0.87	1.02	0.66	0.72	0.83		0.32	0.38
COE (cent/kWh)			5.70	6.62	6.54	4.75	6.66		5.01	5.51
Cost penalty (cent/kWh)			2.31	3.36	2.10	1.41	2.52		1.31	1.67
Difference in emissions (kg CO2/kWh)			0.67	0.64	0.53	0.60	0.61		0.27	0.28
Cost of CO_2 avoided (€/t CO_2)			35	52	40	24	41		49	59

Source: Fachinformationszentrum Karlsruhe 2003, Enquete 2001, David & Herzog 2000, IEA 2004.
Note: Levelized costs are calculated at a 7% interest rate, a projected 2010 gas price of 4.71 $€_{2000}$/GJ, and coal price of 1.76 $€_{2000}$/GJ. CO_2 capture for pulverized coal plant via chemical absorption. Wind plant is hypothetical off-shore plant (30km distance from the coast).

Table 1 provides detailed information on the costs and performance measures resulting from various studies. In order to compare the different sources, we calculate the levelized costs for each technology and data source based on the same economic assumptions with respect to interest rates (7%) and fuel prices (4.71 €/GJ for gas, 1.76 €/GJ for coal). The levelized costs of electricity production (COE) for each technology consist of

COE = capital cost + labor cost + fuel cost + (capture costs + storage costs)

Capture costs include incremental fuel, capital and labor costs for capturing the carbon emissions. We assume that 90% of total carbon emissions can be captured. Transport and storage costs are estimated at 11 €/t CO_2 based on assumptions provided in Enquete (2002).

Interestingly, levelized costs of electricity production do not differ much among the three data sources, with the exception of the David and Herzog assumptions on IGCC production (with and without CCS) who assume substantially lower capital and labor costs. The numbers we employ are well in the range of technology characteristics shown in the literature. Rubin et al. (2004) provide an overview of those characteristics, indicating the low and high numbers for each technology (see Table 2).

Table 2 Overview of cost and performance of new fossil technologies with and without carbon dioxide capture and storage

Cost and Performance Measures	PC Plant			IGCC Plant			NGCC Plant		
	Range		Rep.	Range		Rep.	Range		Rep.
	low	high	Value	low	high	Value	low	high	Value
Without capture & storage									
Emn. Rate (kg CO_2/MWh)	722	941	795	682	846	757	344	364	358
Capital cost ($/kW)	1100	1490	1260	1170	1590	1380	447	690	560
COE ($/MWh)	37	52	45	41	58	48	22	35	31
With capture and storage									
Emn. Rate (kg CO_2/MWh)	59	148	116	70	152	113	40	63	50
Capital Cost ($/kW)	1940	2580	2210	1410	2380	1880	820	2020	1190
COE ($/MWh)	64	87	77	54	81	65	32	58	46
Cost of CO_2 avoided ($/t CO_2)	42	55	47	13	37	26	35	74	47
Cost of CO_2 captured ($/t CO_2)	29	44	34	11	32	22	28	57	41
Energy penalty for capture (% Mw_{ref})	22	29	27	12	20	16	14	16	15
changes									
Percent CO_2 reduction per kWh (%)	80	93	85	81	91	85	83	88	87
Percent increase in Capital Cost (%)	67	87	77	19	66	36	37	190	110
Percent increase in COE (%)	61	84	73	20	55	35	32	69	48

Source: Rubin, E. et al. (2004)

Compared to the current average levelized costs of electricity production, wind as well as CCS technologies would not come to play a major role in a business as usual scenario without further policy incentives for carbon mitigation. We will therefore examine the possible roles played by technologies in a number of potential climate policy scenarios.

4. SGM-Germany

We now present an analysis of electricity generating technologies, and their relative roles over time, in the context of German climate policy. The analysis brings together historical data on the German economy and energy system, parameters of advanced generating technologies, policies governing nuclear and renewable energy, and population projections. We use a computable general equilibrium model, the Second Generation Model (SGM), as an integrating tool.

References for SGM include Edmonds et al. (1993), MacCracken et al. (1999), Edmonds et al. (2004), and Sands (2004). Three basic types of data are used to construct SGM-Germany. The first is the 1995 input-output table for Germany that provides the overall economic framework (Statistisches Bundesamt 1996). The second is a 1995 energy balance table for Germany, which is essentially an energy input-output table (AGEB 1999). These two tables are combined into a hybrid input-output table with units of joules for energy inputs, and units of 1995 DM for other inputs. Use of the hybrid input-output table ensures calibration to 1995 energy flows, and ensures that energy balance is maintained throughout all model time steps. The third basic data set is the engineering costs for each electric generating technology. This is used to construct a fixed-coefficient production function for each technology.

SGM-Germany is constructed with the 18 production sectors shown in Table 3. Production sectors in SGM are organized to be useful for questions related to climate policy and they emphasize energy production, energy transformation, and energy-intensive industries. Most services are aggregated into a single production sector. SGM-Germany operates in five-year time steps from 1995 through 2050 and each production activity has a capital stock separated into five-year vintages. Capital lifetimes are typically 20 years in SGM, except for the electricity generating technologies that have lifetimes up to 40 years. Old vintages of capital operate as a fixed-coefficient technology, while new vintages can be fixed-coefficient (in the energy transformation sectors) or constant-elasticity-of-substitution (CES). Therefore, new vintages of capital have a greater response to changes in relative prices, including carbon prices, than do old vintages of capital

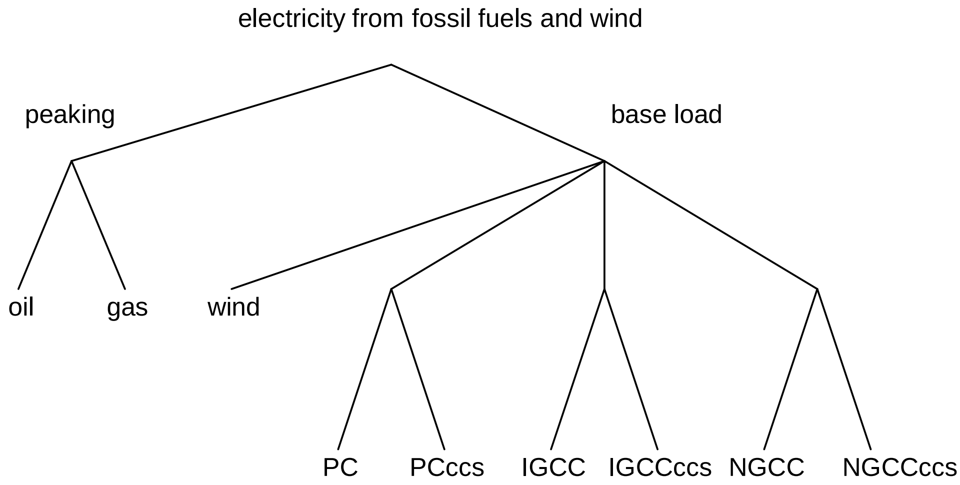
Table 3 Production sectors in SGM-Germany

	Production Sector	Value of production in 1995 (billion DM)
1	agriculture (including fishery, forestry)	86.3
2	everything else (including services)	3,454.0
Energy Production		
3	crude oil production	0.5
4	natural gas production	5.5
5	coal production	10.1
Energy Transformation		
6	coke	2.0
7	electricity generation	40.2
8	electricity distribution	83.3
9	oil refining	41.1
10	distributed gas	38.4
Energy-Intensive Industry		
11	paper and pulp	138.7
12	chemicals	197.7
13	non-metallic minerals	81.7
14	primary metals	98.3
15	food processing	242.4
16	other industry and construction	1,701.8
Transportation		
17	rail and land transport	35.3
18	other transport	213.7

The cost of meeting any particular carbon emissions constraint depends crucially on the set of technologies and the amount of time available for capital stocks to adjust to a new set of equilibrium energy and carbon prices. Each electric generating technology is represented by an individual fixed-coefficient production function, and a logit algorithm to determine the share of electricity generated by each technology as a function of the levelized cost per kilowatt-hour (kWh). McFarland et al. (2004) use a similar approach, except that a nested CES production function is used to distinguish electric generating technologies.

Figure 3 provides the nested logit structure of electricity technologies employed in SGM-Germany. At each nest, technologies compete on levelized cost per kWh. If the cost per kWh is equal among competing technologies in a nest, then each technology receives an equal share of new investment. A parameter at each nest determines the rate that investment shifts among technologies as levelized costs diverge. As a carbon price is introduced, the levelized cost per kWh increases for all generating technologies that emit CO_2. Technologies that are less carbon intensive receive a larger share of new investment than before the carbon price was introduced. Capital stock for each technology is grouped into five-year vintages and old capital cannot move across technologies. The logit investment structure determines the share of new electric generating capital that goes to each technology.

Figure 3 Nested logit structure of electric generating technologies in SGM-Germany



Note: "NGCC ccs" represents NGCC with CO_2 capture and storage, "IGCC ccs" represents coal IGCC with CO_2 capture and storage, "PC ccs" represents pulverized coal with CO_2 capture and storage.

5. Analysis and results

As outlined above, a current energy policy focus in Germany is on renewable energy polices and on emission trading. Therefore, our analysis emphasizes those issues, while at the same time accounting for the eco tax and other German-specific features. We introduce two kinds of wind: one is subsidized wind according to the renewable energy law; the other wind category (advanced wind) competes in the open market. Additional baseline assumptions relate to prices of imported fuels, nuclear phase out, minimum use of coal, a constraint in the switchover possibilities to gas for reasons of supply security and to account for inertia of the system. For renewable energy other than wind, we assume hydro capacity is stable over time, as resources are limited, and allow for an increase in biomass and waste based electricity production. The baseline assumptions are in accordance with widely accepted German projections that are outlined in detail in a report for the German government on sustainable energy supply under liberalization and globalization of the energy market (Enquete 2002). Furthermore, we use the assumptions on costs and performance of new innovative technologies as shown above (section on the German electricity sector). We realize that carbon prices play an important role for the development of the electricity system.

We start out with analyzing the levelized costs per kWh as a function of carbon price for three advanced technologies (wind, IGCC, PC and NGCC), with and without CCS. There are two decisions involved. The first is whether or not to use CCS for each technology, the second is whether wind can compete with those new technologies, in particular those with CCS. We are specifically interested in understanding what role wind can play in the future system and at what carbon price it can compete with clean coal technologies. Since wind technology is highly capital intensive (compare Table 1), we first conduct sensitivity analyses for the four technologies with respect to the interest rate and fuel prices. This helps us to find at what level of carbon price competition between the new fossil technologies with and without CCS and more importantly between IGCC with CCS and wind power would be initiated.

We then use a general equilibrium framework, SGM-Germany, to conduct a baseline analysis and alternative policy scenarios in order to yield information on the future electricity mix, the role of CO_2 capture and storage technologies within this mix, projections of carbon emissions, and economic growth and costs. Our policy analysis consists of three carbon price scenarios at 10, 25, and 50 € per t of CO_2 starting in 2005. The new fossil technologies (NGCC, IGCC) are introduced to the model beginning in 2015, while the technologies with CCS and advanced wind are introduced in 2020.

Technology Choice

Figure 4 provides plots of levelized cost per kWh as a function of carbon price for advanced wind and the two advanced fossil technologies (IGCC and NGCC), with and without CCS. Competition among these technologies occurs along two dimensions. The first dimension is the decision whether or not to use carbon capture. For either IGCC or NGCC, CCS imposes a greater capital cost, which is offset as the carbon price increases. A crossover carbon price exists for each technology, where the levelized cost is the same with or without CCS.

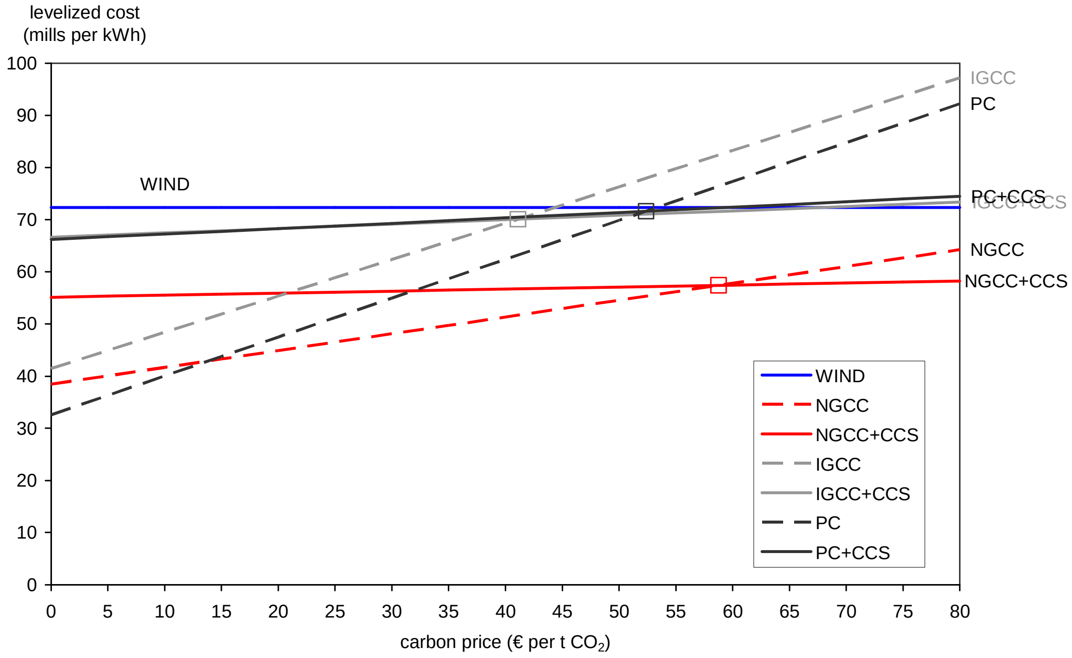
All of the plotted lines in Figure 4 are conditional on the interest rate and fuel prices. We use an interest rate of 7%, a gas price of 4.71 €/GJ, and a coal price of 1.76 €/GJ. Fuel prices are taken from Enquete (2002) projections for year 2010.

At these fuel prices and technology cost assumptions, the crossover carbon price for IGCC vs. IGCC+CCS is at 41.1 €/ t CO_2, while the crossover point NGCC vs. NGCC+CCS is 58.8 €/t CO_2. The crossover price for each technology includes a constant 11 € per ton of CO_2 transport and storage cost. The crossover price for IGCC is lower than for NGCC because the capture process used for coal technologies costs less to employ than the one for gas based production.

The second dimension of competition is between wind, and coal and natural gas as a fuel, which is influenced by the relative prices of these fuels and the interest rate. The levelized cost per kWh of NGCC vs. NGCC+CCS is lower than IGCC vs. IGCC+CCS at all but the very low values of the carbon price in Figure 4. The pattern could reverse with higher natural gas prices because variable costs are already significantly higher for NGCC and NGCC+CCS than for IGCC technologies. Wind is highly sensitive to the interest rate because its main cost component is capital costs. The cost disadvantage of wind may be offset as the carbon price increases, fuel prices increase or interest rates decrease.

At an interest rate of 7% with fuel prices for 2010, advanced wind and clean coal IGCC (i.e. with CO_2 capture and storage) break even at a carbon price of 68 €/t CO_2.

Figure 4 Levelized cost as a function of carbon price



Notes: "NGCC+CCS" represents NGCC with CO_2 capture and storage, "IGCC+CCS" represents coal IGCC with CO_2 capture and storage, "PC+CCS" represents pulverized coal with CO_2 capture and storage. Crossover prices where CCS breaks even are marked with a square for each fossil generating technology.

Figure 5 shows the sensitivity of the crossover carbon prices of NGCC vs. NGCC+CCS, of IGCC vs. IGCC+CCS, and of IGCC+CCS vs. advanced wind with respect to the interest rate. The lines show the combination of carbon price and interest rate that would allow the CO_2 capture and storage technologies and their regular counterparts, as well as advanced wind vs. IGCC+CCS, to break even in terms of levelized costs. The relationship between the latter two (IGCC+CCS vs. wind) is of high interest in Germany, where both wind and coal are major domestic resources and play a major role in the development and restructuring of the electricity system.

The crossover price of wind vs. IGCC+CCS is sensitive to the interest rate, but also to cost assumptions for these technologies. If the capital cost for advanced wind is increased to account for backup generating capacity, then the crossover price would occur at a lower interest rate, for any given carbon price. The lines for the two fossil technologies are much less steep, indicating a lower sensitivity to changes in interest rates.

Figure 5 Sensitivity of crossover price with respect to interest rate

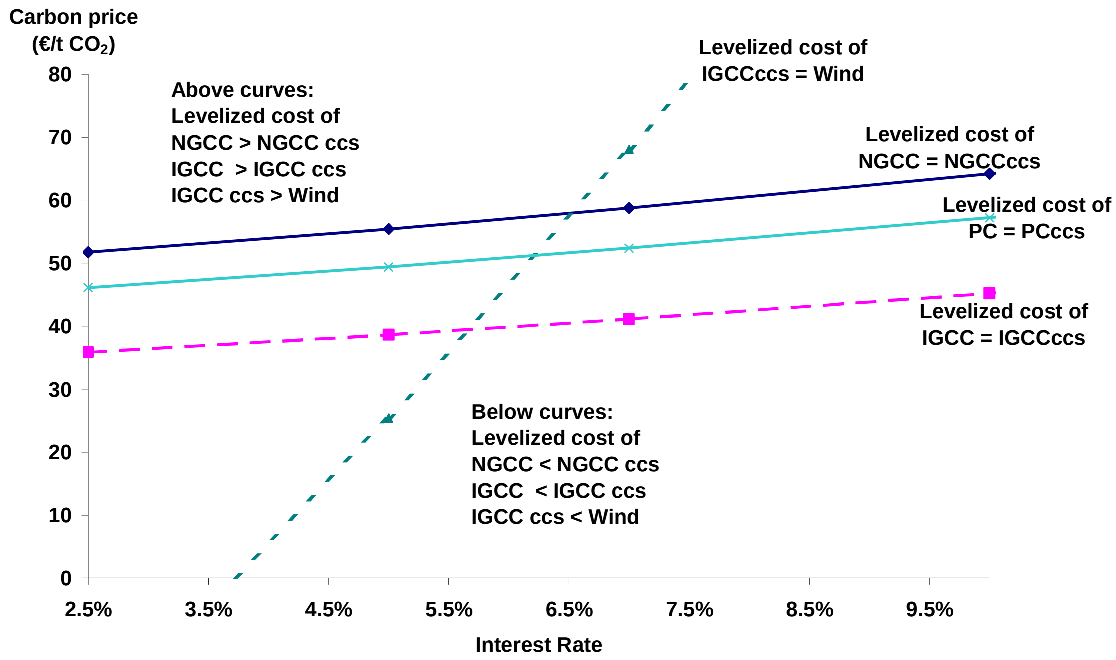
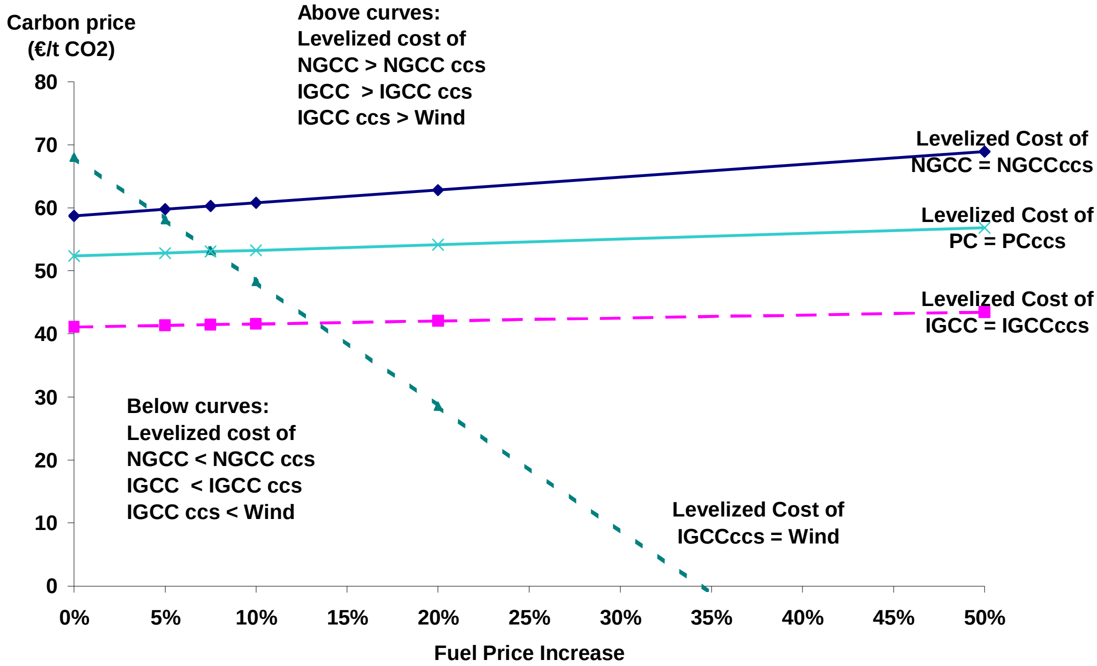


Figure 6 shows a similar approach for the sensitivity with respect to fuel prices. We increase prices for coal and gas at the same percentage and calculate the crossover carbon price that equalizes levelized electricity costs for each pair of technologies. We see again that advanced wind shows a high sensitivity. High fuel prices can offset the capital cost disadvantage of wind power. The break-even carbon price falls rapidly with increasing fuel prices. For example, a 15% increase in coal prices would be sufficient to bring the crossover price of wind vs. IGCC+CCS below the crossover price for IGCC vs. IGCC+CCS (about 40 €/t CO_2). At the same time, as CCS technologies are more fuel intensive than their counterparts, their break even points are also sensitive, if much less though, to changes in fuel prices.

Figure 6 Sensitivity of crossover price with respect to fuel price increase (at fixed 7% interest rate and starting with 2010 fuel prices)



The sensitivity analysis reveals that a price range of 30 to 50 €/t CO_2 is a critical range for CO_2 capture and storage as well as advanced wind technologies to play a major role. Depending on the development of the interest rate and fuel prices, the critical range changes, in particular for wind based technology.

Electricity Sector Results

We use a general equilibrium model, SGM-Germany, that allows the introduction of advanced electric generating technologies and the projection of the future electricity mix with these technologies in a base case and under different carbon price assumptions.

Figure 7 shows the share of electricity generation by technology for an SGM-Germany baseline through year 2050, with total generation rising gradually over time. The share of nuclear power is exogenously reduced to zero by 2030. Wind power subsidized by the 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 competes apart 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.

CO_2 capture and storage is introduced after 2015, but has no market share in the baseline; its share increases with the carbon 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 carbon prices but old capital does not. Therefore, the full impact of a carbon price is delayed until all old capital retires. Outside the electricity sector, SGM-Germany uses a capital lifetime of 20 years.

Figure 7 Baseline electricity generation in TWh

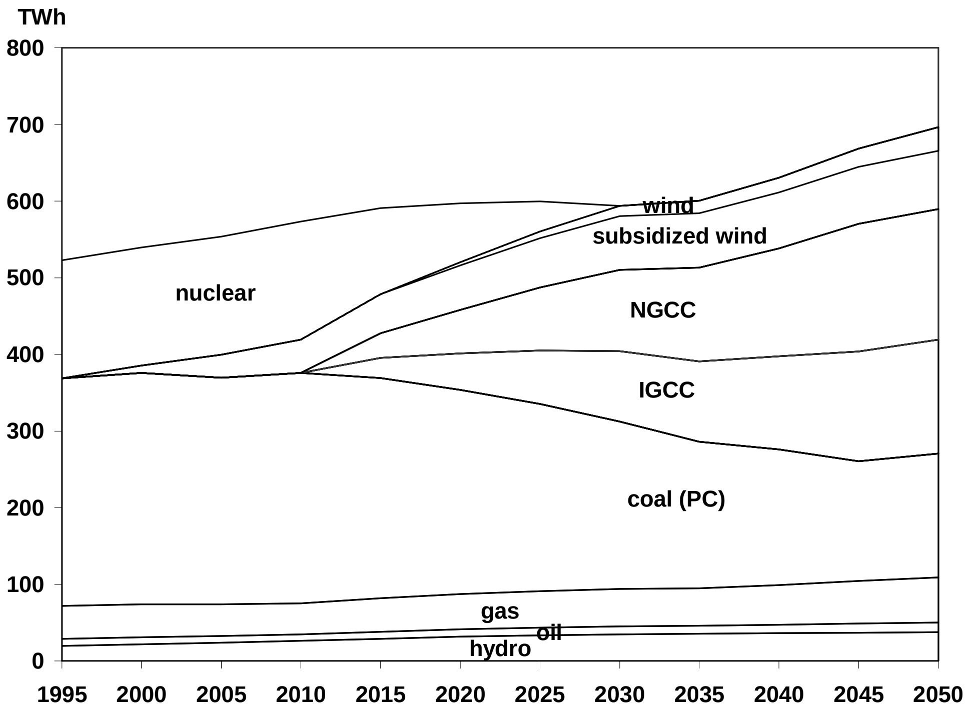
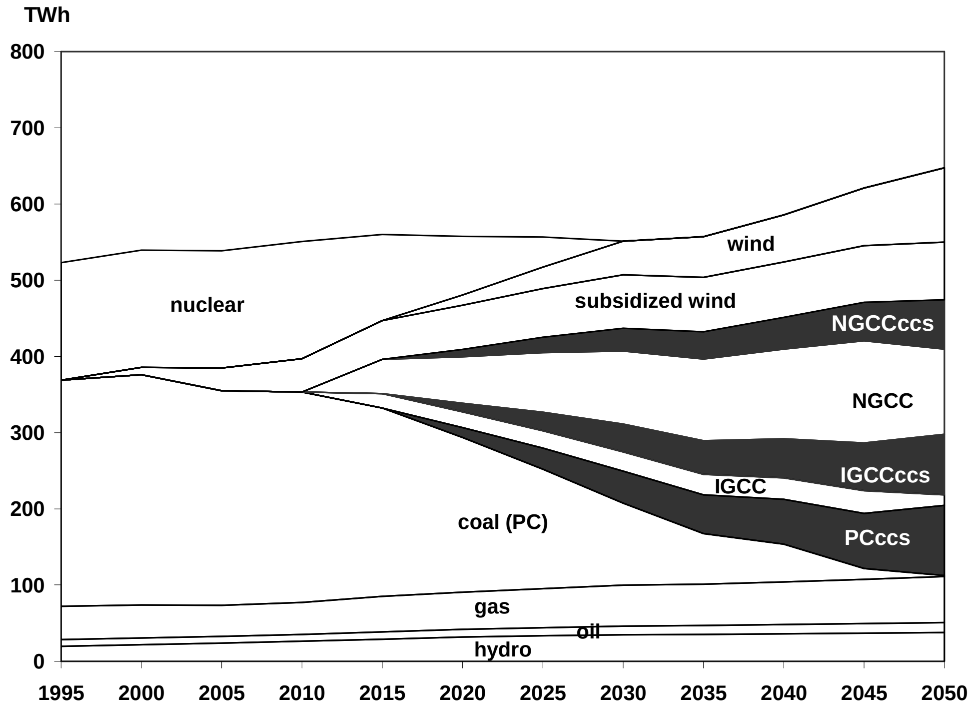


Figure 8 shows the results of a carbon price as high as 50 € per t CO_2 introduced in year 2005 and held constant thereafter. Total electricity generation is slightly lower in the carbon price case than in the baseline. As electricity prices are already quite high in Germany, the additional costs induced by the carbon price does not have a very big weight, thus affecting electricity demand only slightly. The shares of wind and gas based production increase in the carbon price case, while the share of pulverized coal decreases. The carbon price is well beyond the crossover price for IGCC, as shown in Figure 4, so a large share of IGCC capacity includes CCS by 2050. A carbon price of 50 € per t CO_2 is below the crossover price for NGCC, so approximately one third of 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 carbon price, energy technologies that are less carbon-intensive increase their share of electricity generation. At lower levels of carbon prices (20 to 50 € per t CO_2), CO_2 capture and storage technologies as well as advanced wind still come into place, however, they take up a lower share.

Figure 8 Electricity generation mix with carbon price 50 €/tCO$_2$

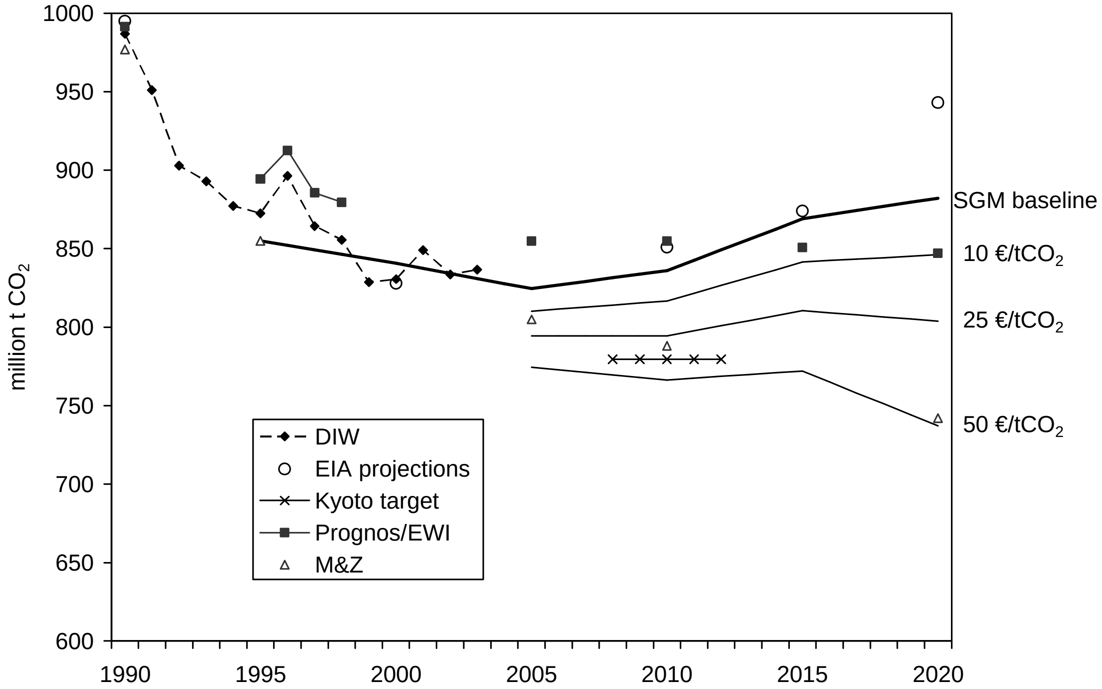


Economic and Emissions results

Figure 9 provides a summary of several carbon emissions projections using the Second Generation Model (SGM) that allows the introduction of advanced electric generating technologies. Included in Figure 9 are baseline scenarios to the year 2020. Also included are projections of carbon emissions at carbon prices of 10, 25, 50 € per t CO_2. All of these scenarios are shown relative to historical carbon emissions (DIW 2004) and Germany's Kyoto emissions target. The figure also includes projections of carbon emissions from Markewitz and Ziesing (M&Z 2004), Prognos/EWI (1999) and the U.S. Energy Information Administration (2002). The carbon price can be interpreted as either a carbon tax or as the market price of emissions rights in an emissions trading system.

Baseline emissions are projected to pick up again after a steady decline until the year 2005. By 2020, however, there are only slightly above the base year 1995 level. A carbon price of 10 € per t CO_2 brings down emissions by 2.3% compared to baseline emissions of 836 Mt CO_2 in 2010, a 25 € per t CO_2 brings emissions down by 5% and a 50 € per t CO_2 price by 8.3%. If the Kyoto target of reducing CO_2 emissions by 21 % to 780 Mt CO_2 was solely to be met by adding a price on carbon, the price would need to be in the order of around 30 € per t CO_2.

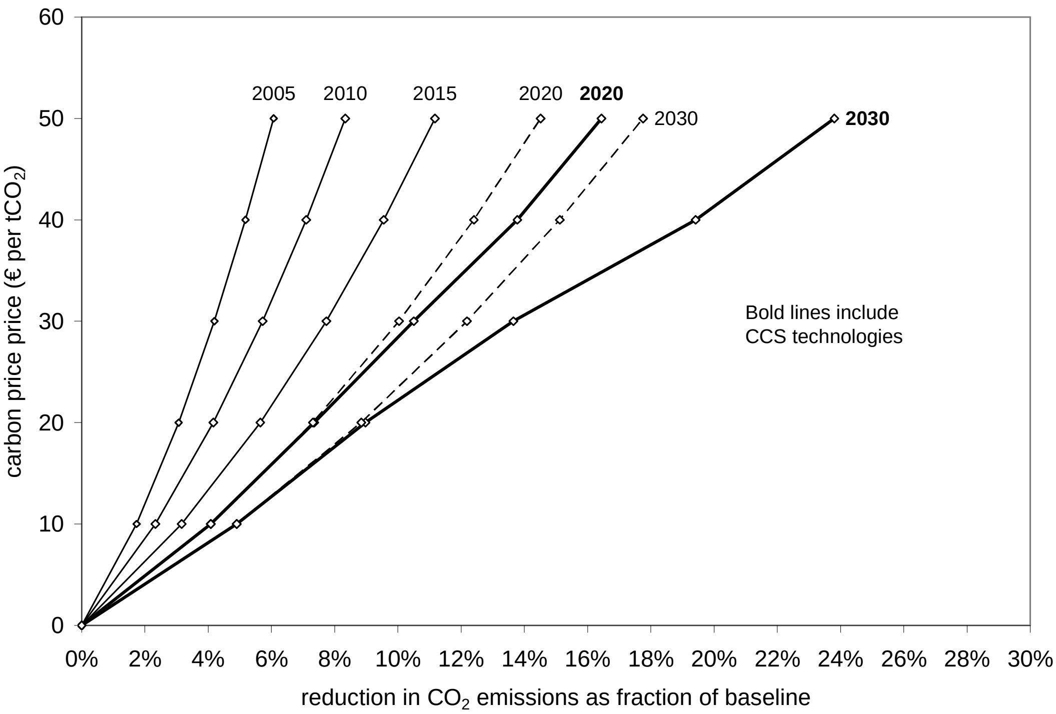
Figure 9 Projections of carbon dioxide emissions in Germany (Mt CO_2)



Note: Advanced electric generating technologies in these scenarios include integrated gasification combined cycle (IGCC), natural gas combined cycle (NGCC), and wind. CO_2 capture and storage is introduced after 2010 in new generating plants.

The importance of CCS technologies in reducing CO_2 emissions is depicted in Figure 10. The marginal abatement cost curves show the level of carbon price needed to achieve a specific emissions reduction target compared to the baseline. A marginal abatement cost curve is plotted for each target year. Since CCS technologies are introduced after 2010, the marginal abatement cost curves including CO_2 capture and storage differ from the ones without CO_2 capture and storage thereafter. The curves including CO_2 capture and storage rise more gently. This means, lower marginal abatement costs occur to reach a given emissions reduction target when including CCS technologies. Another way to state this is that higher emissions reductions can be obtained for the same price of CO_2 when including CO_2 capture and storage technologies. The gap between the marginal abatement costs becomes more pronounced the higher the emissions reductions target is.

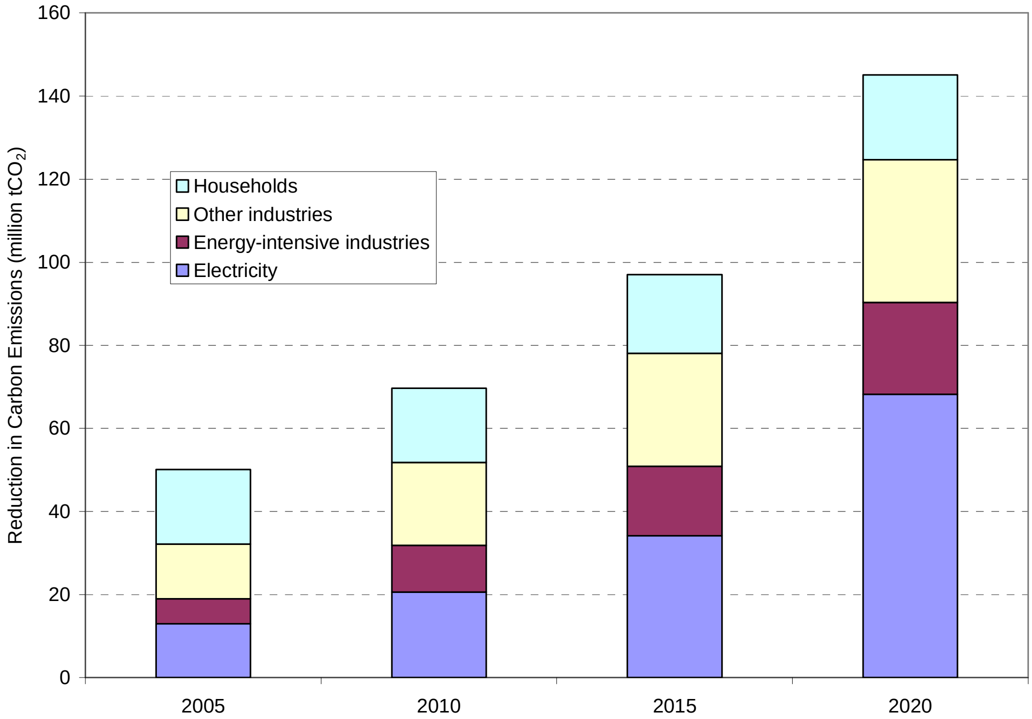
Figure 10 Marginal abatement cost curves with and without carbon dioxide capture and storage (CCS)



Note: Carbon dioxide capture and storage is introduced after 2015 in new generating plants.

While in 2005, the largest share of emissions reductions is taken on by households followed by slightly lower and almost equal shares of the electricity sector and other non-energy-intensive industries, the picture changes over time and with higher carbon prices as new and advanced electricity generating technologies come into place. A carbon price of 50 € per t CO_2 induces the electricity sector to install wind and CO_2 capture and storage technologies so that substantial emissions reductions can be achieved in the sector. In 2020, the electricity sector accounts for emissions reductions of 68.2 Mt CO_2, which equals slightly less than 50% of the total 145.1 Mt CO_2 emissions reductions achieved in this policy scenario (see Figure 11).

Figure 11 Decomposition of emissions reductions with a carbon price of 50 €/t CO_2



The aggregate economy grows steadily at 1% to 1.4% (in terms of changes in real GDP) per year between 2000 and 2035. Annual growth then picks up in 2035 as the working-age population stabilizes and is no longer falling over time.

The losses in real GDP that arise in connection with efficient carbon mitigation policies are small relative to the level of GDP. Losses are below 0.7% in 2050 even for a carbon price as high as 50 € per t CO_2. For a carbon price of 25 € per t CO_2, the GDP loss amounts to 0.3% in 2050 compared to the baseline.

Conclusions

This paper demonstrates the introduction of advanced electricity technologies, such as IGCC, NGCC, wind power, and CO_2 capture and storage, in a computable general equilibrium model for Germany, the Second Generation Model. We embed an electricity sector built up from engineering data, using a logit algorithm to determine investment shares, in the CGE model. In doing this, we keep the technological richness of existing and advanced electric generating technologies. Along the lines of German climate policy goals, and in times of a substantial restructuring and renewal process of the German electricity sector, we focus on innovative advanced technologies, in particular renewable energy and CO_2 capture and storage, and their role within a future energy system. We evaluate alternative carbon polices to analyzes the costs of mitigating carbon emissions in Germany with and without these technologies. We also analyze at what carbon prices these new technologies with and without CO_2 capture and storage become economically competitive. Simulation results are highly sensitive to engineering cost assumptions. Therefore, we conduct a sensitivity analysis with respect to these assumptions.

Our findings can be summarized as follows. The crossover carbon price, that is the carbon price at which CO_2 capture and storage, either with IGCC or NGCC technologies, or wind break-even, is sensitive to the interest rate and fuel price changes. The sensitivity is most pronounced for wind power, which is highly capital intensive and thus very responsive to interest rate changes. The competitiveness of advanced wind power with the IGCC+CCS technology, in particular, advances substantially as interest rates drop, fuel prices rise, or carbon prices increase. Given our engineering cost and performance assumptions, an interest rate below 3% or a 15% increase in coal prices would be sufficient for advanced wind power to be more cost efficient no matter what level of carbon price assumed. On the contrary, high interest rates and low fuel prices always put wind power at an economic disadvantage. Our analysis reveals that the crossover price for NGCC vs. NGCC+CCS (about 58 € per t CO_2) is higher than the crossover point for IGCC vs. IGCC+CCS (41 € per t CO_2).[1] The levelized cost per kWh of NGCC and NGCC+CCS is lower than IGCC and IGCC+CCS at all levels of the carbon price. This pattern could reverse with higher natural gas prices. We conclude that a carbon price range of 30 to 50 € per t CO_2 is a critical range for CO_2 capture and storage as well as advanced wind technologies to play a major role.

We introduce CO_2 capture and storage as well as advanced wind technology into the SGM model in 2020. The CCS technologies receive no market share in the baseline analysis where no climate policy is introduced. Starting at a carbon price of about 30 € per t CO_2, however, CCS technologies set in and receive more substantial shares with increasing carbon prices in the policy scenarios. At a carbon price of 50 € per t CO_2 almost all of the IGCC produced electricity is supplied with CO_2 capture and storage and approximately one-third of NGCC uses CO_2 capture and storage. The share of wind together with hydro and other renewables is beyond the German government's goal of 12.5% renewable based electricity production by 2010 and 20% by 2020. If the Kyoto reduction target of 21% for Germany were to be reached by means of a carbon price alone (no additional policies), the Kyoto target could be reached with a carbon price of about 30 € per t CO_2.

The importance of CCS technologies becomes evident when looking at the marginal abatement cost curves. An emissions reductions target can be achieved at equal or lower marginal costs when CO_2 capture and storage technologies are included. In particular in the long run, marginal abatement costs are substantially lower with new advanced electricity generating technologies in place. With these technologies the share of emissions reductions achieved in the electricity sector increases over time and with higher carbon prices. GDP losses in the economic model are less than 1% relative to baseline for all policy scenarios.

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[1] We assume a 7% interest rate and fuel prices for the year 2010 of 4.71 $€_{2000}$/GJ for gas, 1.76 $€_{2000}$/GJ for coal.

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