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Katja Schumacher*
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Innovative energy technologies and climate policy in Germany

Berlin, August 2005

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IMPRESSUM

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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 European Union (EU) greenhouse gas emissions. Compared to the level in 1990, Germany's CO_2 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. A long-term national target is to reduce CO_2 emissions 40% by year 2020 relative to 1990. A substantial portion of 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.

At the same time, Germany is facing a major renewal and restructuring process. Around one-third of its total electric 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 wind power, 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 for 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 environmentally 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 also put into force. More stringent voluntary agreements on reducing industrial carbon emissions were established.

Trading of emissions rights is also a major theme because of its market-based approach and its economically efficient way of meeting emissions targets. The EU decided to implement a European-wide emissions trading program in 2005, while the Kyoto Protocol allows Annex I countries to begin emissions trading 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. These new technologies and their role within a future German electricity generation mix are the focus of this paper.

We simulate the introduction of advanced electricity technologies in a computable general equilibrium model for Germany, the Second Generation Model (SGM), and analyze the costs of reducing carbon emissions under different policy scenarios. SGM-Germany is a dynamic recursive, multi-sector general equilibrium model based on national 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 description 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 an estimate of the carbon price needed to meet Germany's Kyoto target.

We are also interested in calculating the carbon price at which 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 of the overall economy.

2 Energy and climate policy

Energy and environmental policies 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 at renewable energy as well as combined heat and power production. Moreover, starting in 2005, the European emissions trading program is coming into effect covering carbon dioxide emissions from electricity and 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 would be produced by renewable energy by 2010. In the medium term, by 2020, the goal is to produce at least 20% of electricity from renewable energy. In the long term, by 2050, the goal is to see the renewables share rise to at least 50% of total electricity production.

To help reach these goals, a renewable energy law was introduced. 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, compensation ranges from 5.5 to 8.7 cents per kilowatt-hour (ct/kWh) for onshore wind energy, and from 6.19 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 one of the most effective climate policy instruments in Germany (BMU 2004a). In 2003, around 53 million metric tons of carbon dioxide (Mt CO2) were displaced by using renewable energy sources for electricity, heat and motor fuels. It is expected that 85 Mt CO2 will be saved due to renewable energy use by 2010. The renewable energy law is expected to contribute about half of total savings in 2010.

*Energy Tax***:** Energy taxation in Germany consists of taxes on mineral oil (petroleum products and natural gas) 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 a phased increase in, 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 consumption, 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 program for greenhouse gas (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). The directive applies to emissions from specific energy and industrial activities as listed in Appendix I of the directive. Basically, it 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 is considered likely (Matthes et al., 2003). In Germany, allowances will be distributed free of charge to covered installations up to the year 2012.

3 German electricity sector

Currently, nuclear and fossil fuels dominate electricity production in Germany. More than 50% of electricity is produced from hard coal and lignite, and 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 1).

Figure 1 Gross electricity production by fuel (in TWh)

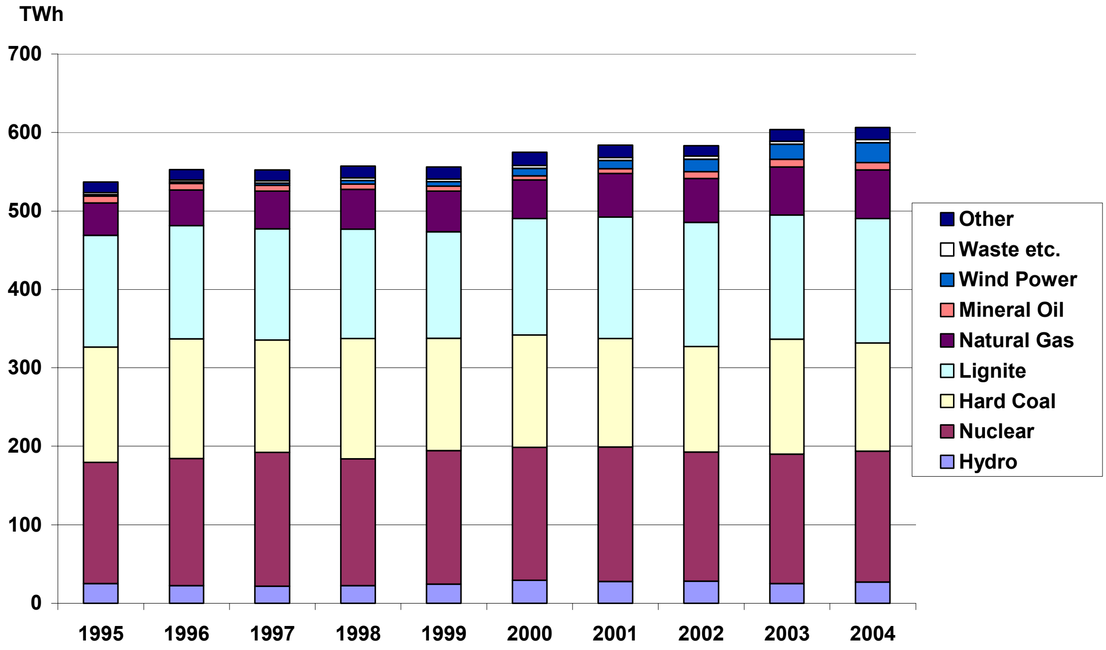
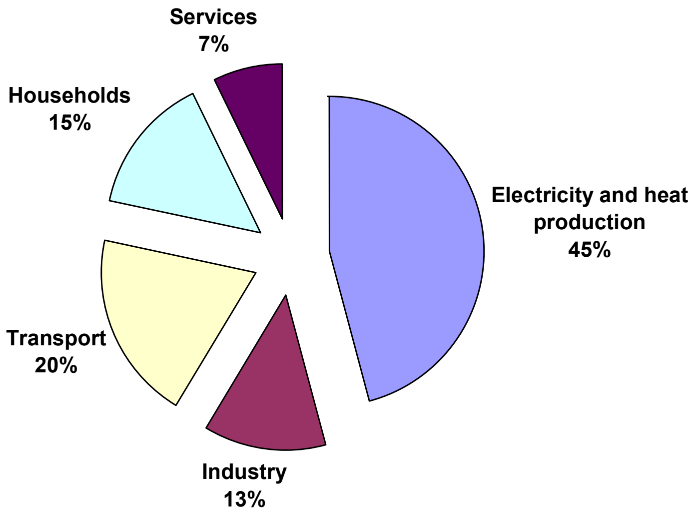


Figure 2 CO_2 emissions by sector (% share); Germany 2003



A substantial restructuring of the electricity sector will be needed within the next two decades. About 40 gigawatts (GW) 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. Some combination of new generating plants or reduced electricity demand (Enquete 2002) is needed to cover the shortfall in generation. The need for substantial (replacement) investments provides a window of opportunity for new and innovative technologies to play a role in the future electricity mix.

Among these new and innovative technologies are fossil fuel based and renewable energy based technologies. Advanced coal technologies include pulverized coal (PC) with CCS, IGCC, and IGCC with CCS. Advanced natural gas technologies include NGCC and NGCC with CCS. We also consider an advanced offshore wind technology that is expected to be available between 2010 and 2020. The technologies differ substantially in 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 a summary of cost and performance measures from various studies. In order to compare across sources, we calculate a levelized cost for each technology based on common 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 of 11 €/t CO_2 are based on assumptions provided in Enquête (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 generation (with and without CCS) with 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 a range of these 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/kWh)	0.722	0.941	0.795	0.682	0.846	0.757	0.344	0.364	0.358
Capital cost ($/kW)	1100	1490	1260	1170	1590	1380	447	690	560
COE (cent/kWh)	3.7	5.2	4.5	4.1	5.8	4.8	2.2	3.5	3.1
With capture and storage									
Emn. Rate (kg CO_2/MWh)	0.059	0.148	0.116	0.070	0.152	0.113	0.040	0.063	0.050
Capital Cost ($/kW)	1940	2580	2210	1410	2380	1880	820	2020	1190
COE (cent/kWh)	6.4	8.7	7.7	5.4	8.1	6.5	3.2	5.8	4.6
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)

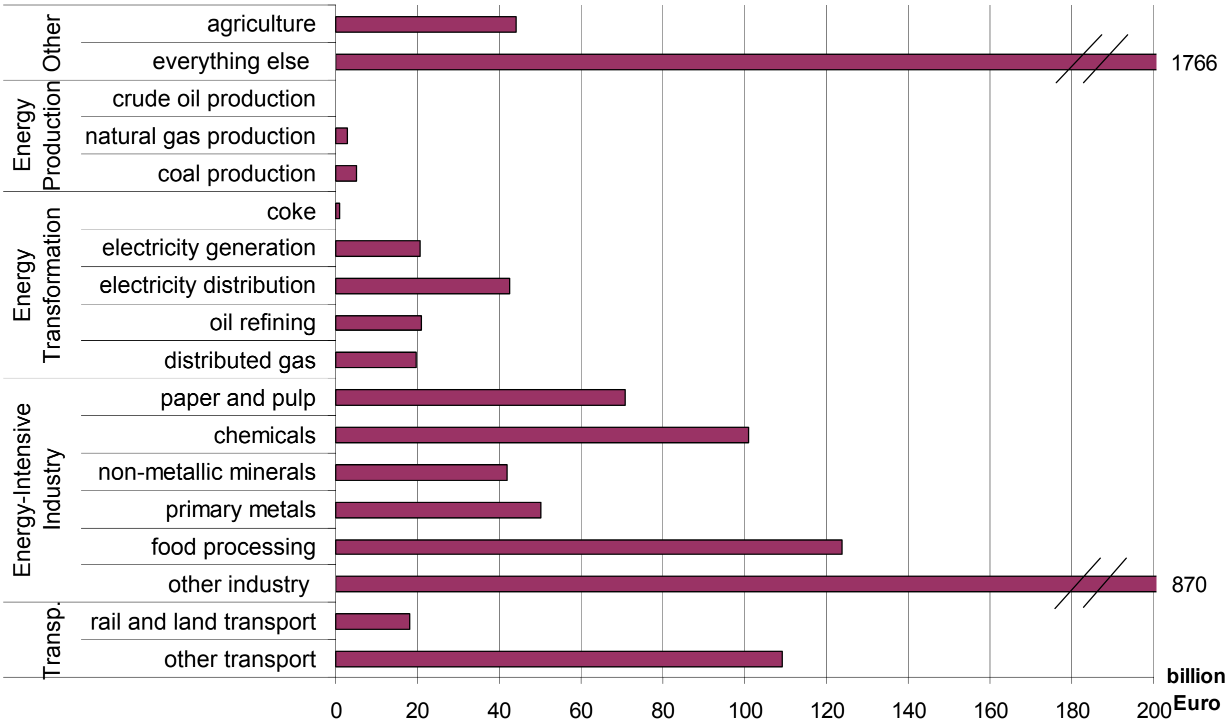
Compared to the current average levelized costs of electricity production (Liese et al., forthcoming), wind and CCS technologies would not play a major role in a business as usual scenario without further policy incentives for carbon mitigation. We will therefore examine the possible roles played by technologies in a number of alternative 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 an 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 a set of engineering costs for each electric generating technology. This is used to construct a fixed-coefficient production function for each generating technology.

Figure 3 Production in SGM-Germany 1995 (billion Euro)



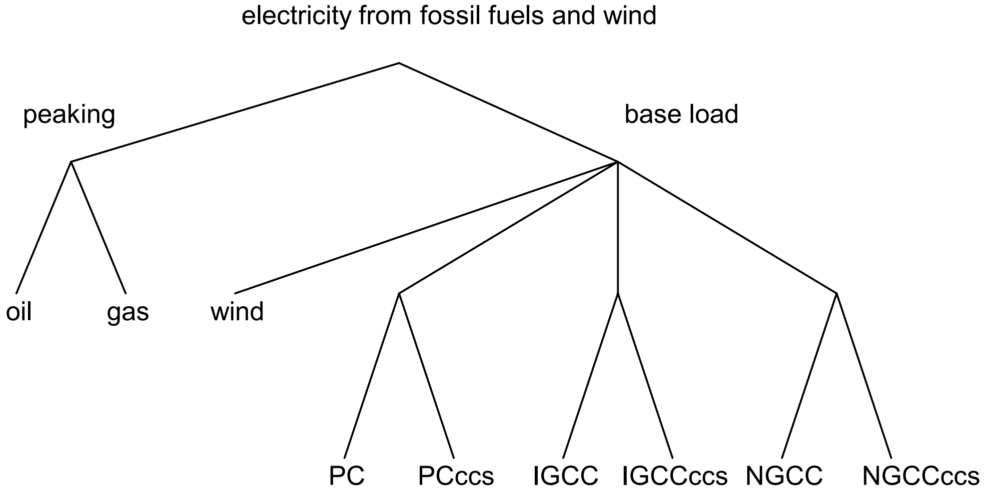
SGM-Germany is constructed with the 18 production sectors shown in Figure 3. Production sectors are organized to be useful for questions related to climate policy with an emphasis on energy production, energy transformation, and energy-intensive industries. Most services are aggregated into a single production sector, the “everything else” sector.

SGM-Germany operates in five-year time steps from 1995 through 2050 and each production activity has a capital stock segmented into five-year vintages. Capital lifetimes are typically 20 years in SGM, except for electricity generating technologies which are assigned lifetimes of 35 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.

The cost of meeting any particular carbon emissions constraint depends 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. All production sectors outside of electricity generation operate with a single technology, but the electricity sector includes many individual technologies. Each electric generating technology is represented by an individual fixed-coefficient production function; a logit algorithm determines the share of electricity generated by each technology as a function of the levelized cost per kWh. McFarland et al. (2004) use a similar approach, except that a nested CES production function is used to distinguish electric generating technologies. See Sands (2004) for a more complete description of the logit allocation procedure.

Figure 4 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.

Figure 4 Nested logit structure of electric generating technologies in SGM-Germany



Note: "NGCCccs" represents NGCC with CO_2 capture and storage, "IGCCccs" represents coal IGCC with CO_2 capture and storage, "PCccs" represents pulverized coal with CO_2 capture and storage.

Technical change in the electricity sector occurs over time as a shift across generating technologies as new technologies become available and as relative prices, especially among fossil fuels, change. Engineering characteristics of any specific generating technology remain constant over the model time horizon. A parameter of the logit allocation algorithm governs the rate that investment across generating technologies may shift in response to changes in prices. This parameter is different for each nest in Figure 4.

Technical change in production sectors outside of electricity is a combination of price-induced movement along a production function isoquant, and exogenous change over time in technical coefficients of the production function. These changes in technical coefficients are analogous to autonomous energy efficiency improvement and autonomous labor efficiency improvement and are used primarily to construct a baseline scenario of energy consumption and economic growth. Substitution elasticities govern the rate that input-output ratios can change with respect to changes in prices.

This study includes no representation of electricity generation outside of Germany and therefore treats electricity trade on a scenario basis. The scenario used here fixes trade in electricity at base-year quantities for all model time steps.

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 switch-over 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 2003). Furthermore, we use the assumptions on costs and performance of new innovative technologies as shown above (section on the German electricity sector).

We start out by analyzing levelized cost per kWh as a function of carbon price for advanced technologies: wind, IGCC, PC, NGCC, and CCS. There are two dimensions to the choice of technology. The first is whether or not to use CCS with fossil generating technologies; the second is competition across fuels. We are especially interested in understanding the 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 determine the range of carbon prices where pairs of technologies compete directly, or at what carbon price the levelized cost is the same. Pairings of interest include: pulverized coal, NGCC, and IGCC with and without CCS; wind paired with IGCC; and wind paired with IGCC+CCS.

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 carbon 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. These carbon prices are applied to all sectors of the economy. New fossil technologies (NGCC, IGCC) are introduced to the model beginning in 2015, while technologies with CCS and advanced wind are introduced after 2015.

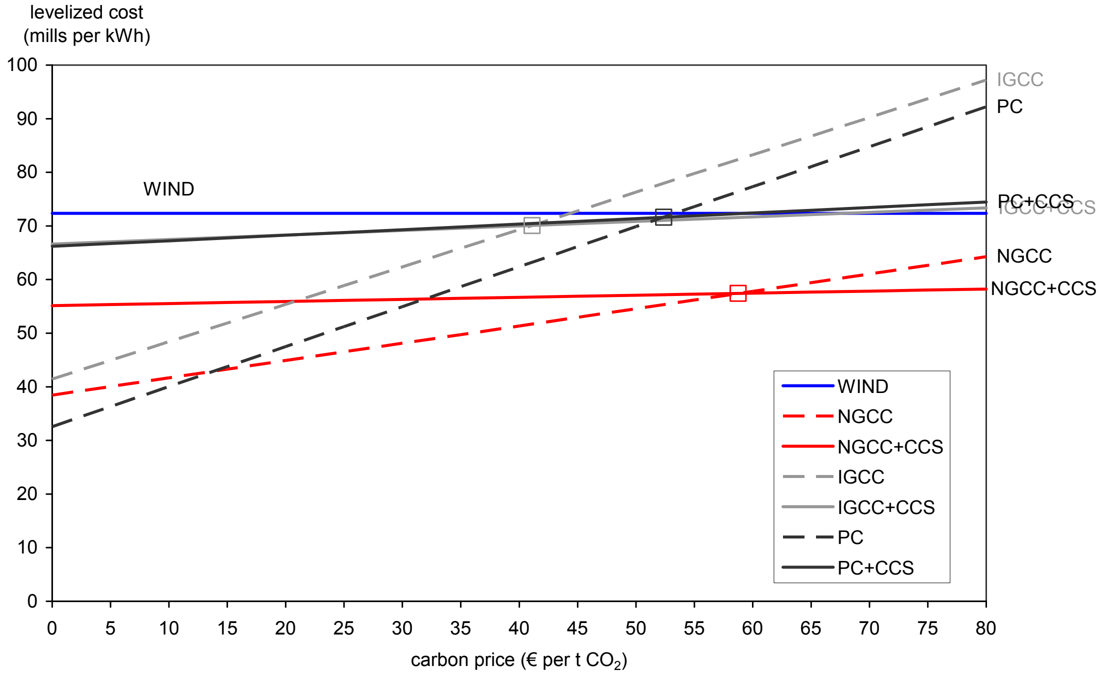
Technology Choice

Figure 5 provides plots of levelized cost per kWh as a function of carbon price for several electric generating technologies: pulverized coal with and without CCS; IGCC with and without CCS; NGCC with and without CCS; and advanced wind. Competition among these technologies occurs along two dimensions. The first dimension is the decision whether or not to use CO_2 capture. For fossil generating technologies, CCS imposes a greater capital cost, which is offset as the carbon price increases. A break-even, or crossover, carbon price exists for each fossil technology, where the levelized cost is the same with or without CCS. All of the plotted lines in Figure 5 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 (2001) projections for year 2010.

The second dimension of competition is across fuels, which is influenced by the relative prices of these fuels and the interest rate. The levelized cost per kWh of NGCC technologies is lower than IGCC technologies at all but the very low values of the carbon price in Figure 5. The pattern could reverse with higher natural gas prices because variable costs are already significantly higher for NGCC 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 these fuel prices and technology cost assumptions, the crossover price for CCS with IGCC is 41.1 €/ t CO_2, while the crossover price for CCS with NGCC 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 CCS crossover price is lower for IGCC than for NGCC because the capture process used for coal gasification technologies costs less to employ than the one for natural gas based production. Advanced wind and coal IGCC+CCS have the same levelized cost per kWh at 68 €/t CO_2. This crossover price, however, is very sensitive to technology cost assumptions because both of the corresponding lines in Figure 5 have a very low slope.

Figure 5 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 6 shows the sensitivity of the break-even carbon prices for CCS with IGCC, pulverized coal, and NGCC technologies to the interest rate. The lines show the combination of carbon prices and interest rates that would allow the CO_2 capture and storage technologies and their regular counterparts, to break even in terms of levelized costs. The break-even carbon prices increase somewhat with the interest rate, indicating that capture and storage processes are capital intensive.

Figure 6 also shows carbon price and interest rate combinations where IGCC+CCS and advanced wind have the same levelized cost. This relationship is of interest in Germany, where both wind and coal are major domestic resources and could play an important role in the development and restructuring of the electricity system. The crossover price of wind vs. IGCC+CCS is highly sensitive to changes in the interest rate. If the capital cost for advanced is increased to account for backup generating capacity, then the crossover carbon price would be even more sensitive to changes in capital markets. The lines for the fossil technologies are less steep, indicating a lower sensitivity to changes in interest rates. Lower interest rates provide an advantage for wind because wind is more capital intensive than IGCC+CCS.

Figure 6 Sensitivity of crossover price with respect to interest rate

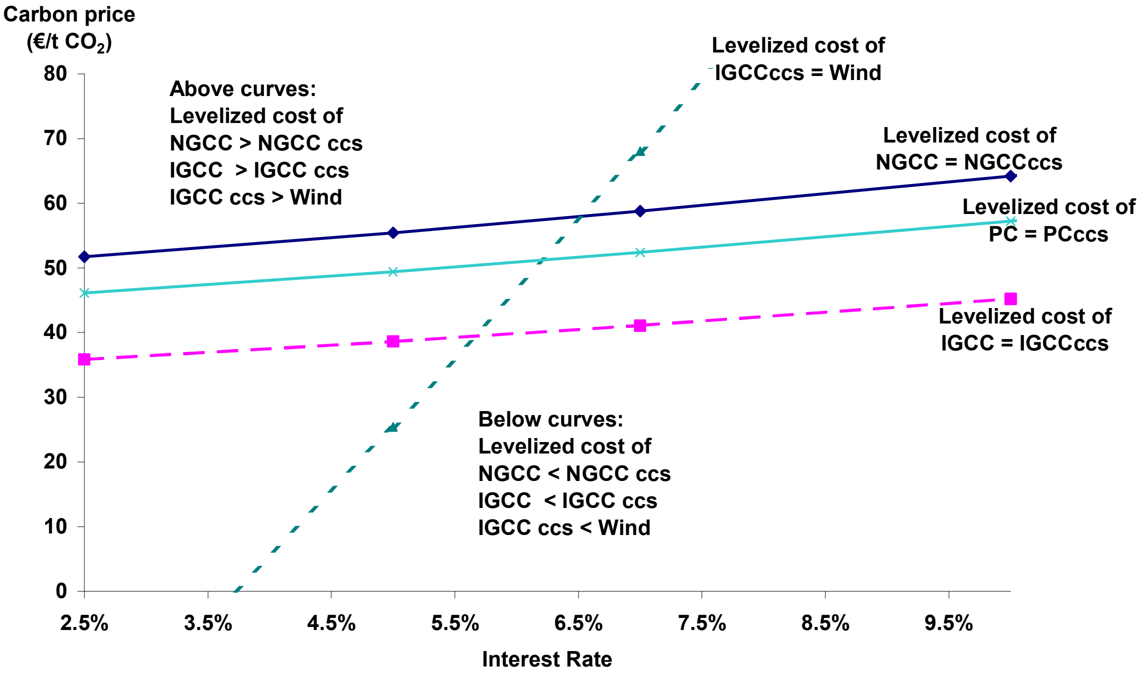
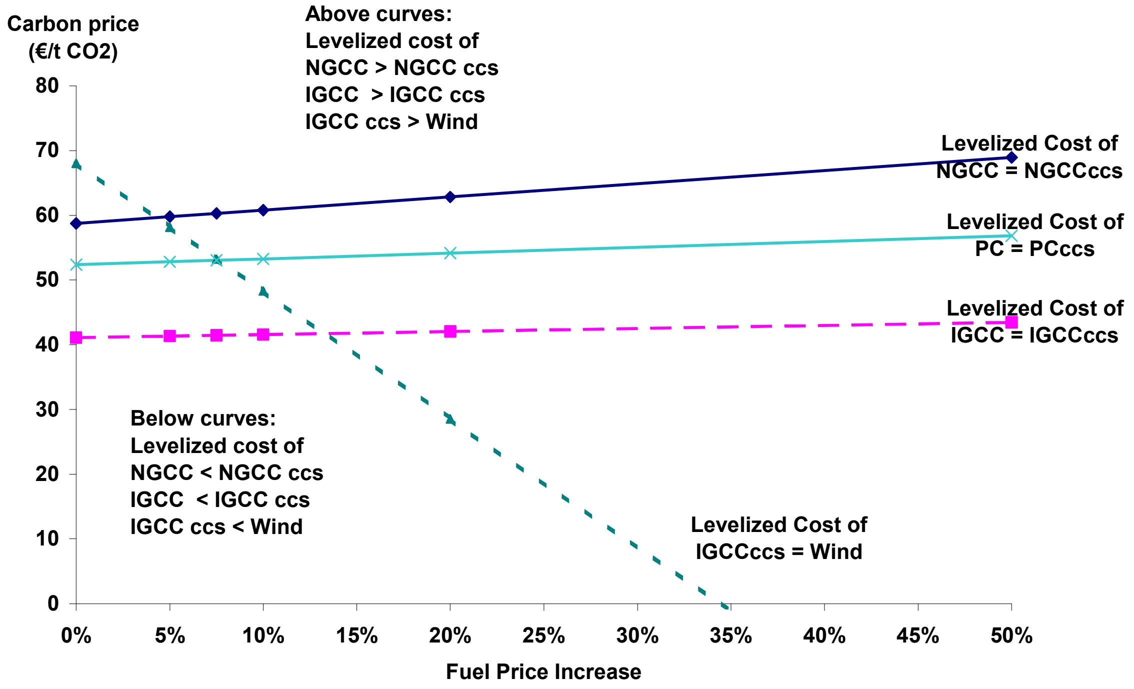


Figure 7 shows a similar sensitivity analysis, but now with respect to fuel prices. We increase prices for coal and natural gas by the same percentage and calculate the carbon price where levelized costs are equal between technology pairings of interest. CCS technologies are more fuel intensive than their counterparts, and the break-even carbon prices increase somewhat with respect to fuel prices. We see again that advanced wind vs. IGCC+CCS shows a high sensitivity to cost assumptions, including fuel costs. High fuel prices can offset the capital cost disadvantage of wind power.

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



Sensitivity analyses in Figures 5 and 6 reveal that break-even prices for CCS technologies are relatively robust with respect to interest rates and fuel prices, remaining in a price range of 35 to 55 €/t CO_2 for CCS with pulverized coal or IGCC. The ability of wind to compete with IGCC+CCS, however, is much more sensitive to interest rates and fuel prices.

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 8 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 8 Baseline electricity generation in TWh

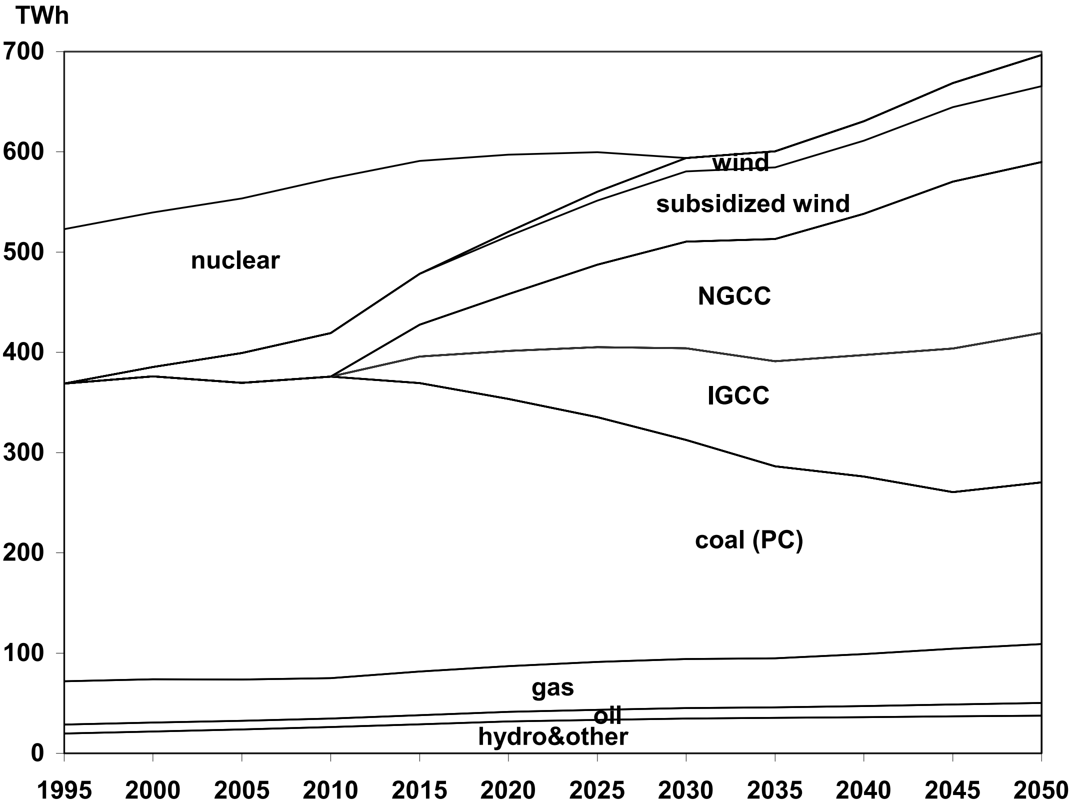
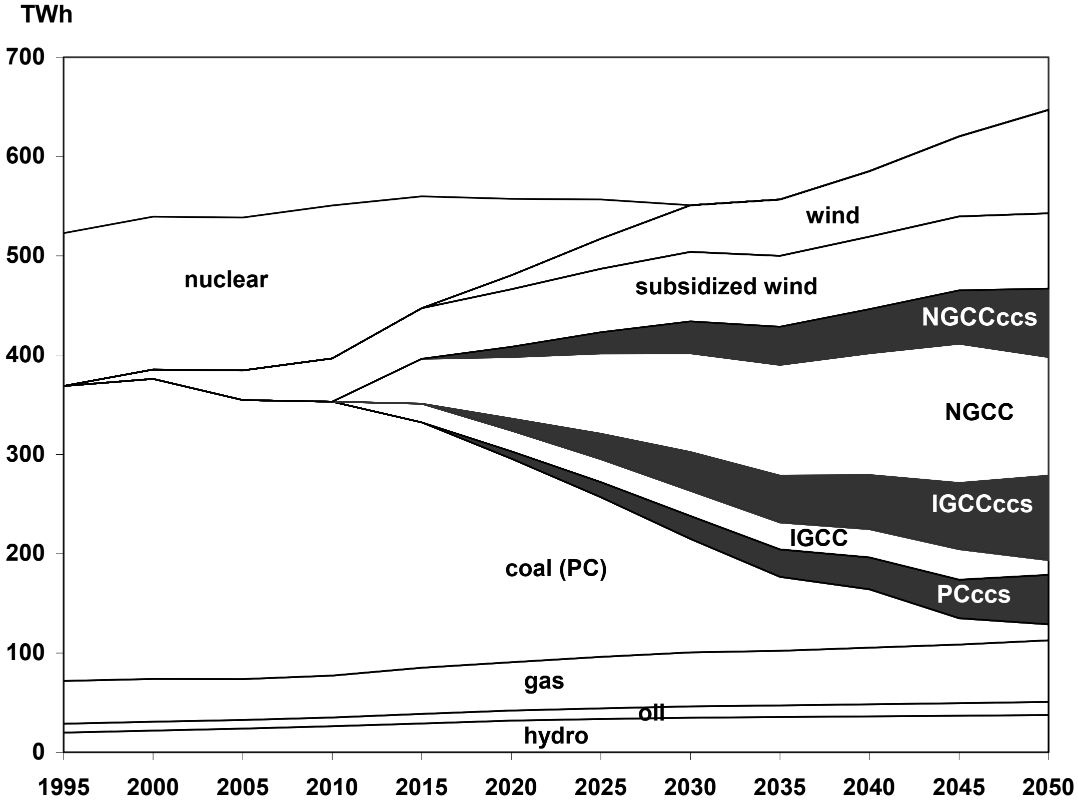


Figure 9 shows results with a carbon price of 50 € per t CO_2 introduced in year 2005 and held constant thereafter. Total electricity generation is slightly lower in the carbon price case than in the baseline. As electricity prices are already quite high in Germany, the additional costs induced by the carbon price does not have a very big impact, 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 CCS with IGCC, 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 CCS with NGCC, so less than half 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, but with a reduced share of generation.

Figure 9 Electricity generation mix with carbon price 50 €/tCO$_2$

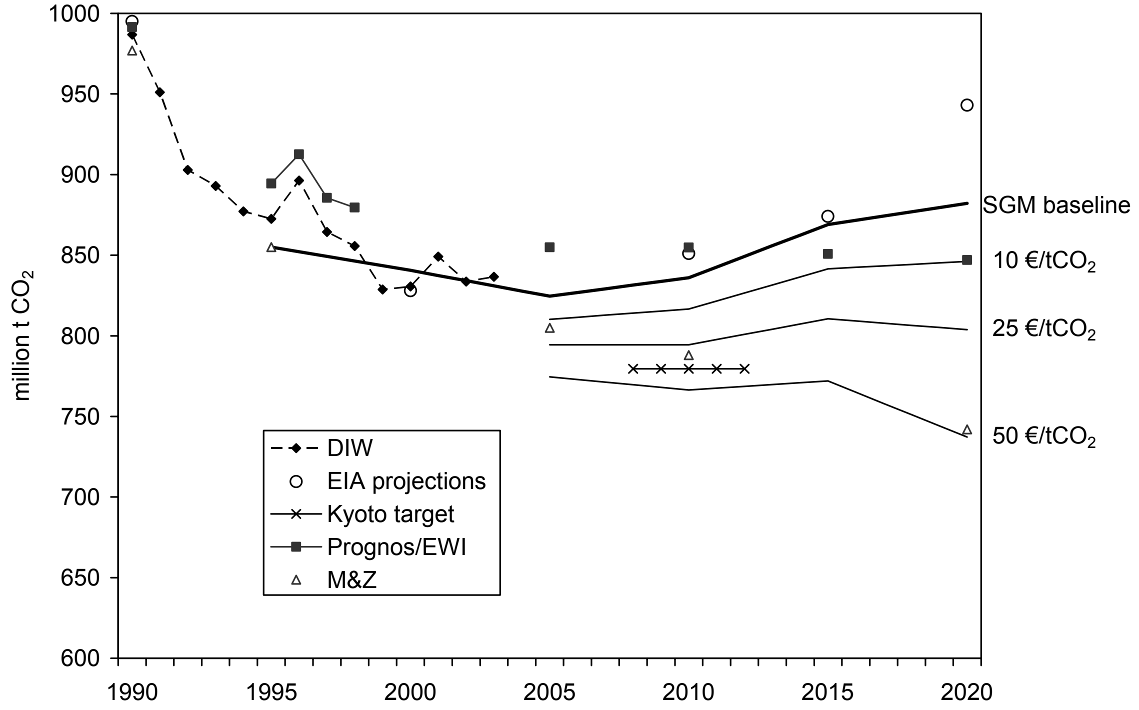


Economic and Emissions Results

Figure 10 provides a summary of several carbon emissions projections using the Second Generation Model (SGM) with the introduction of advanced electric generating technologies. Included in Figure 10 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).

Baseline emissions rise slowly again after a steady decline until the year 2005. By 2020, however, emissions are only slightly above the base year 1995 level. A carbon price of 10 € per t CO$_2$ reduces emissions by 2.3% compared to baseline emissions of 836 Mt CO$_2$ in 2010; a price of 25 € per t CO$_2$ reduces emissions 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 dioxide, the price would be approximately 30 € per t CO_2. This estimate of a carbon price needed to meet the Kyoto clearly depends on the baseline emissions scenario. If baseline emissions continue to decline after 2005, then a lower carbon price is needed.

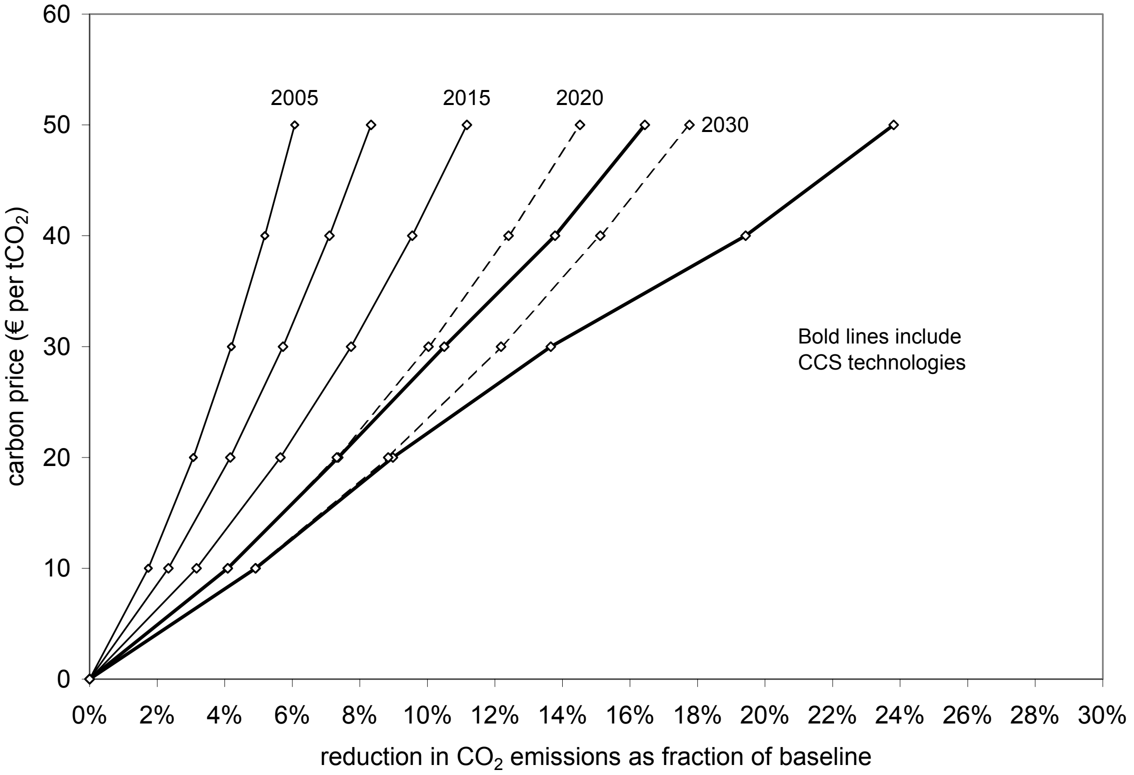
Figure 10 Projections of carbon dioxide emissions in Germany (Mt CO_2)



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 11. 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 2015, the marginal abatement cost curves with CCS differ from the others. With CCS, a lower carbon price is needed for any given emissions target after 2015. Another way to state this is that greater emissions reductions can be obtained for the same price of CO_2 when including CO_2 capture and storage technologies. The gap between marginal abatement cost curves becomes more pronounced the higher the carbon price.

Figure 11 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.

Figure 12 provides a description of the source of emissions reductions in the 50 € per t CO_2 scenario. At this price, the deviation from baseline increases over time as old capital is retired. The household sector is an exception, as the SGM household sector does not contain capital stocks. Therefore, the household sector responds more quickly to a carbon price than other sectors.

In 2005, households contribute the largest share of emissions reductions 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. By 2020, the electricity sector accounts for emissions reductions of 68 Mt CO_2, which is slightly less than 50% of the total 145 Mt CO_2 emissions reductions achieved in this policy scenario (see Figure 12).

Figure 12 Decomposition of emissions reductions with a carbon price of 50 €/t CO_2

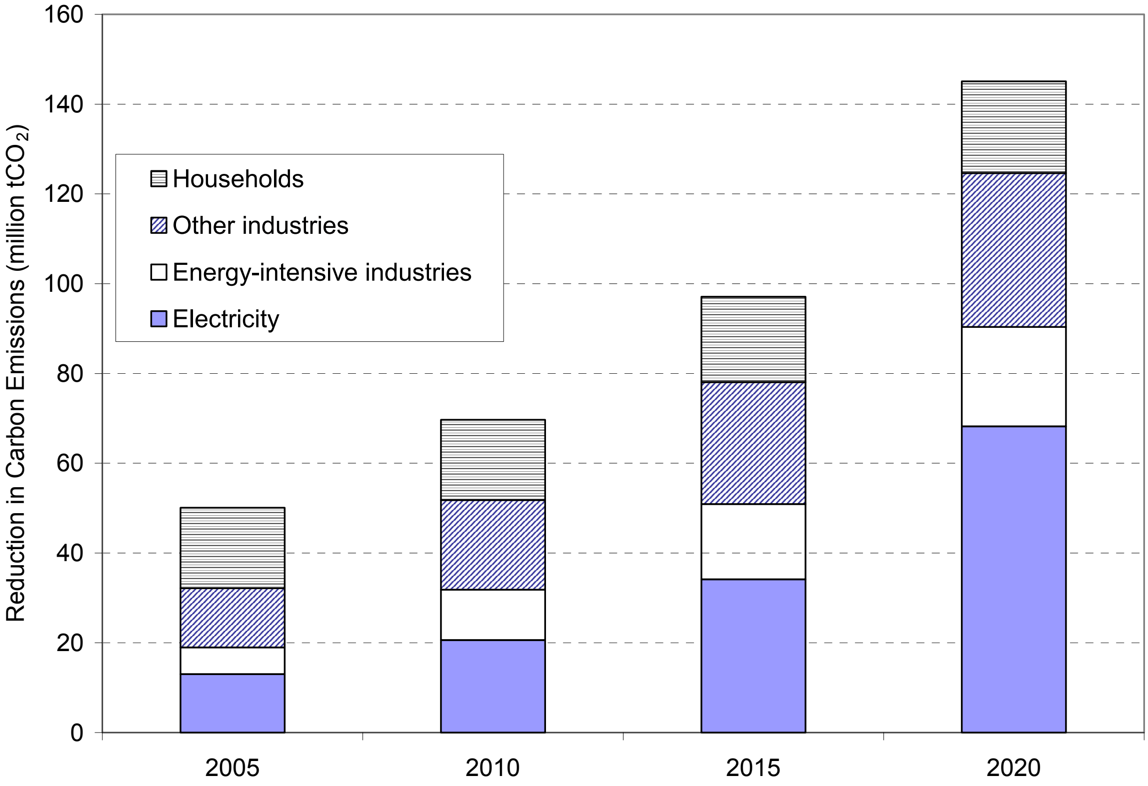
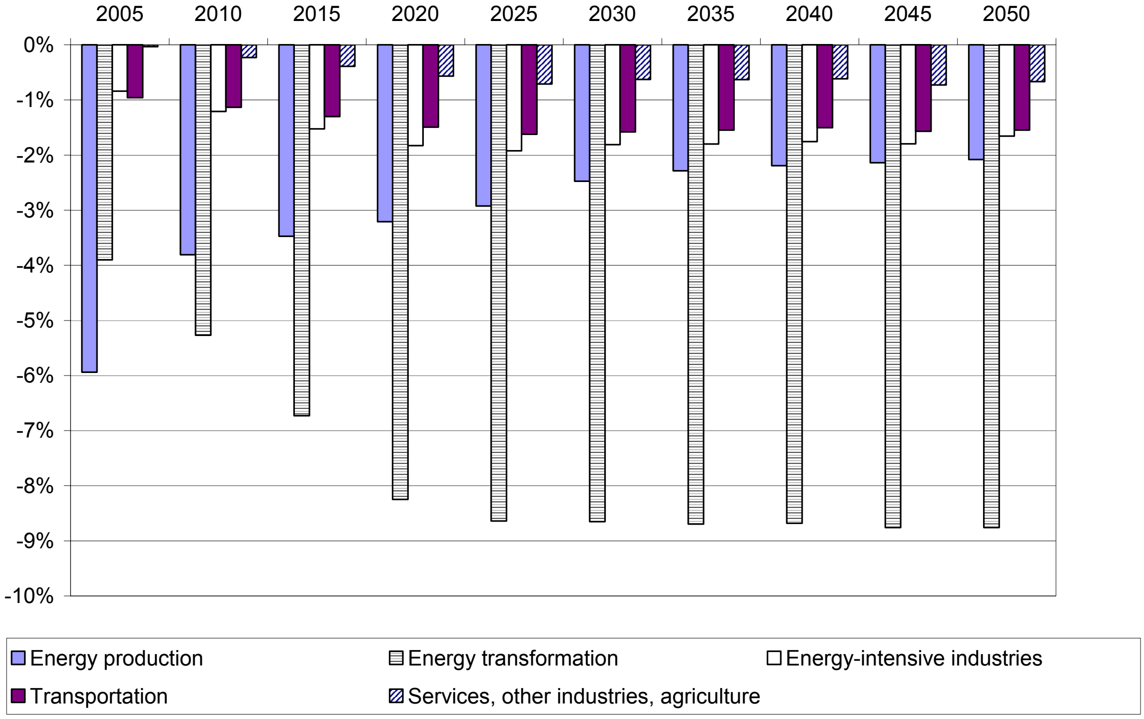


Figure 13 shows how quantity of gross output varies by sector aggregate in the 50 € per t CO_2 scenario relative to baseline. In forming sector aggregates, base year prices are used as weights. Most of the economy's output is contained in the services, other industries, and agriculture aggregate, which has a decrease in output of 0.67%. This turns out to be approximately the same as the percentage loss in real GDP. Other sectors are much smaller in terms of output, but are more sensitive to the carbon price. Energy transformation sectors have the largest percentage reduction in output, while the reduction in output across energy-intensive industries is less than 2.0%.

Figure 13 Change in sectoral output, 50 € per t CO_2 case compared to baseline



Gross Domestic Product (GDP) is measured in SGM as a Laspeyres quantity index with fixed base-year weights. GDP growth depends primarily on population growth and exogenous rates of technical change. The aggregate economy grows steadily in our baseline 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.

These carbon policy simulations apply a common carbon price to the entire economy, and revenues from the carbon policy are recycled as a lump sum to consumers. Losses in real GDP in connection with this efficient carbon mitigation scenario are less than 0.7% of GDP 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 is 0.3% in 2050 compared to the baseline.

6 Conclusions

We have two primary objectives in this paper. The first is to provide plausible scenarios of electricity generation in Germany over the next several decades, considering the anticipated phase-out of nuclear generation and the introduction of advanced generating technologies, with and without a climate policy. The second objective is to do this within a computable general equilibrium model in a way that is consistent with engineering characteristics of these technologies.

The response of electric generating technologies to a carbon policy can be represented graphically by plotting levelized cost per kWh as a function of the carbon price. The less carbon dioxide emitted per kWh generated, the lower the slope of this line. If we pair a technology with greater capital cost with a technology that emits more carbon dioxide, a crossover carbon price, where the cost per kWh is the same, is seen where the two lines cross. Technology pairings of interest include IGCC with and without CCS, pulverized coal with and without CCS, and NGCC with and without CCS. Of these, IGCC+CCS has the lowest crossover carbon price (about 41 € per t CO_2) while NGCC+CCS has the highest (59 € per t CO_2). Another pairing of interest is wind power relative to IGCC or IGCC+CCS. All of the key carbon prices vary along with fuel prices, interest rates, and technology costs. The variation is most pronounced for wind power, which is highly capital intensive and thus responsive to interest rate changes. The competitiveness of advanced wind power with the IGCC+CCS technology advances substantially as interest rates drop, fuel prices rise, or carbon prices increase. With a carbon policy, advanced technologies replace at least part of electricity generation lost from a phase-out of nuclear generation. We conclude that a carbon price range of 35 to 55 € 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.

Although much analysis can be conducted by comparing levelized cost across technologies as a function of the carbon price, we place these technologies in computable general equilibrium model of Germany. What is gained by doing this analysis within a CGE model? First, the demand for electricity is determined endogenously within the model: a carbon policy increases the cost of electricity to consumers and this is reflected in reduced demand. Second, it provides a comparison of greenhouse gas mitigation opportunities between the electric power sector and the rest of the economy. Third, estimates of the overall cost of a carbon policy can be constructed, which may be sensitive to pre-existing energy taxes.

The carbon price required to meet a near-term emissions target, such as in the Kyoto Protocol, is affected by the rate that capital stocks turn over. We model electric generating technologies with capital lifetimes of 35 years, with nuclear power phased out completely by 2030. As existing capital stock retires in each five-year time step, new investment is shared among electric generating technologies according to a nested logit allocation rule. Within each nest, the technology with the lowest cost per kWh receives the largest share of investment. The relative cost advantage of advanced wind and fossil CCS technologies increases along with the carbon price, which increases the share of electricity generation for these technologies.

One of the main uncertainties is the projection of carbon dioxide emissions in the baseline scenario. The carbon price needed to meet the Kyoto target in 2010 varies widely along with the baseline projection. Therefore, results are best described in terms of reduction from baseline. Given a range of uncertainty around baseline emissions, a corresponding range of carbon prices can be generated for any given emissions target. Other uncertainties include the evolution of technology costs over time, future fuel prices, and the amount of backup capacity required for wind power.

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References

Arbeitsgemeinschaft Energiebilanzen (AGEB). Energiebilanzen Deutschland, 1995. http://www.ag-energiebilanzen.de/; 1999.

BMU (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, 2004a) Novelle des Erneuerbare-Energien-Gesetz (EEG), Überlick über die Regelungen des neuen EEG vom 21.7.2004.

BMU (2004b) The ecological tax reform: introduction, continuation and further development to an ecological financial tax reform. http://www.bmu.de/files/oekost_en.pdf

DIW German Institute for Economic Research (2004). Economic Bulletin 10, Wochenbericht Nr. 10, März 2004. www.diw.de

David, Jeremy & H. Herzog, 2000. The cost of carbon capture In: Proceedings of the Fifth International Conference on Greenhouse Gas Control Technologies. Collingwood, Australia: CSIRO Publishing; 2000.

Edmonds JA, Pitcher HM, Barns D, Baron R, Wise MA. Modeling Future Greenhouse Gas Emissions: The Second Generation Model Description. In: Klein LR, Lo F, editors. Modelling Global Change. New York: United Nations University Press; 1993.

Edmonds, J.A., H.M. Pitcher, and R.D. Sands. October 2004. Second Generation Model 2004: An Overview. Pacific Northwest National Laboratory.

Enquete (2001). Prognos IER/WI, Szenarienerstellung Zwischenbericht: Basisdaten für die Szenarienerstellung, 21. Nov. 2001 Enquête-Kommision ‘Nachhaltige Energieversorgung’ des Deutschen Bundestages.

Enquete (2002). Endbericht „Nachhaltige Energieversorgung unter den Bedingungen er Globalisierung und der Liberalisierung“. Enquete Kommission, Deutscher Bundestag 14. Wahlperiode.

EC (European Commission, 2003a) Council Directive 2003/96/EC of 27 October 2003 restructuring the Community framework for the taxation of energy products and electricity. In: Official Journal of the European Union (L 283), 31/10/2003 P. 0051 – 0070.

EC (European Commission, 2003b) Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC. In: Official Journal of the European Union (L 275), pp 32-46.

Gilles V, Ocran GW, Gray R, and Woodbridge D (2003) German electricity wholesale market – Three shocks for the price of one. USB, London

IEA, 2004. "Prospects for CO_2 capture and storage", IEA/OECD, Paris.

Fachinformationszentrum Karlsruhe (edts.) 2003: IKARUS Data Base, Version 4.1 (CD-ROM), Karlsruhe 2003.

Kohlhaas M (2003) Energy taxation and competitiveness – Special provisions for business in Germany's environmental tax reform. DIW Berlin Discussion Paper 349, http://www.diw.de

Kohlhaas M and Mayer B (2004) Ecological Tax Reform in Germany: Economic and political analysis of an evolving policy. In: Hatch MT (ed): Environmental Policymaking: Assessing the Use of Alternative Policy Instruments. State University of New York Press, Albany New York (anticipated).

Lise, Wietze, Linderhoff, Vincent, Kuik, Onno, Kemfert, Claudia, Östling, Robert, Heinzow, Thomas: Northwestern European Electricity Market – What are the Effects of Market Power on Prices and the Environment? in: *Energy Policy*, forthcoming

MacCracken CN, Edmonds JA, Kim SH, Sands RD (1999). The Economics of the Kyoto Protocol. In: Weyant J, editor. The Costs of the Kyoto Protocol: A Multi-Model Evaluation. The Energy Journal special issue;

Matthes FC, Cames M, Deuber O, Repenning J, Koch M, Harinsch J, Kohlhaas M, Schumacher K and Ziesing HJ (2003) Auswirkungen des europäischen Emissionshandelssystems auf die deutsche Industrie. Öko-Institut, DIW, and Ecofys, Berlin Köln.

Markewitz, P. and H.-J. Ziesing (eds.) (2004). „Politikszenarien für den Umweltschutz: Langfristszenarien und Handlungsempfehlungen ab 2012". Eine Untersuchung im Auftrag des Umweltbundesamtes, Schriften des Forschungszentrum Jülich, Reihe Umwelt/Environment. Volume 50.

McFarland, J.R., J.M. Reilly, H.J. Herzog (2004). „Representing energy technologies in top-down economic models using bottom-up information". Energy Economics 26: 685-707.

Prognos/EWI (Energiewirtschaftliches Institut der Universität Köln) 1999. Energiereport III. Die längerfristige Entwicklung der Energiemärkte im Zeichen von Wettbewerb und Umwelt. Stuttgart.

Sands, R.D. (2004). "Dynamics of Carbon Abatement in the Second Generation Model." Energy Economics 26 (4): 721-738.

Statistisches Bundesamt (1995). Volkswirtschaftliche Gesamtrechnung, Input-Output Tabellen 1995. Wiesbaden: Statistisches Bundesamt.

Rubin, Edward S.; Raeo, Anand B. and Chen, Chao (2004) "Comparative Assessments of Fossil Fuel Power Plants with CO_2 Capture and Storage" 7th Conference of Greenhouse Gas Control Technologies. Vancouver. Canada.

U.S. Energy Information Administration (EIA) (2002). Annual Energy Outlook. http://www.eia.doe.gov/oiaf/aeo; 2002.