Advanced electric generating technologies in a CGE model of Germany

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Abstract

Electricity generation is important for analysis of climate policy because of the large point sources of carbon emissions, the potential for fuel switching, and the potential for advanced generating technologies. One of the challenges facing developers of computable general equilibrium (CGE) models is representing advanced energy technologies in a way that is consistent with engineering cost models. We report on progress to introduce advanced electricity technologies such as integrated gasification combined cycle (IGCC), natural gas combined cycle (NGCC), wind power, and carbon capture into SGM-Germany, a computable general equilibrium (CGE) model used to analyze the cost of reducing carbon emissions.

1. Introduction

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 required to meet the constraint. This suggests that top-down economic models should consider the composition of the capital stock carefully and account for advanced technologies to the extent possible. Model developers thereby face the challenge of representing advanced technologies in a way that is consistent with engineering cost models. A few model developers have tried to reconcile the gap in linking top-down representations of the economy with bottom-up descriptions of technologies in energy markets through hard links, that is, through integrating both models in a consistent modeling framework (Kemfert [1]). A good example is Böhringer [2], where electric generating technologies are modeled as specific activities within a mathematical-programming representation of the electricity sector, which is embedded directly in a computable general equilibrium model. Our approach is similar in that each electric generating technology is represented by an individual fixed-coefficient production function, but we use a logit algorithm to determine the share of electricity generated by each technology as a function of the levelized cost per kilowatt-hour (kWh). Other attempts use so-called soft links where bottom-up and top-down models are run independently of each other. Results from one model feed into the other, and vice versa.

A substantial part of global greenhouse gas emissions is produced by the electricity system. Carbon dioxide emissions due to fossil fuel combustion for electricity production amount to more than 40% of total carbon dioxide emissions in Germany, as they do in many other industrialized countries. 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. In Germany as in many other countries, environmental policies are in place to enhance the share of advanced technologies such as renewable energy, and to promote efficient transformation and consumption of energy. It is expected that advanced generating technologies will play an increasingly important role in electric power production.

In this paper, we develop a baseline simulation for estimating the costs to Germany of complying with the Kyoto target and the national emissions reductions target. Currently, Germany is one of the largest carbon emitters in the European Union. Within the burden sharing agreement under the Kyoto Protocol, Germany has committed to reduce its carbon emissions by 21% in 2008-2012 compared to 1990. The national target of reducing emissions by 25% by the year 2005 compared to 1990 is even stricter. Another long-term national target is to reduce carbon dioxide emissions 40% by the year 2020 relative to 1990.

Traditionally, environmental policy in Germany focused on command and control options. Recently, however, an ecological tax was introduced and 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.

This paper reports on progress to introduce advanced electricity technologies such as integrated gasification combined cycle (IGCC), natural gas combined cycle (NGCC), wind power, and carbon capture into a computable general equilibrium model for Germany. The impact of a carbon policy depends on the pre-existing tax structure, and the following section describes the energy tax system in Germany. The next section provides a baseline projection of carbon emissions using SGM-Germany along with emissions projections at carbon prices of 200 euros and 400 euros per metric ton of carbon (tC). Next, individual technologies that make up the electricity sector are described. The share of each technology in electricity generation is plotted over time in the baseline and carbon price cases. The final simulation allows for carbon capture and disposal from electric power.

2. Energy Taxes in Germany

In 1999, Germany introduced an ecological tax ('eco tax') on fossil fuel and electricity consumption to support two goals: (1) to help achieve environmental targets, and (2) to reduce the rate of unemployment. The tax was additional to any pre-existing energy taxes, and increased in five stepwise intervals from 1999 to the year 2003. The energy carriers taxed under the 'eco tax' are fuel oils (heavy and light), electricity, natural gas, diesel, and gasoline; coal consumption is exempt from the 'eco tax'. Fig. 1 provides an overview of the pre-existing tax rates, the cumulative increase and the total tax burden in 2003 by energy carrier. It can be seen that the tax rate increase is highest, in absolute numbers, for electricity, gasoline, and diesel. More detailed information on ecological tax rates is given in the appendix.

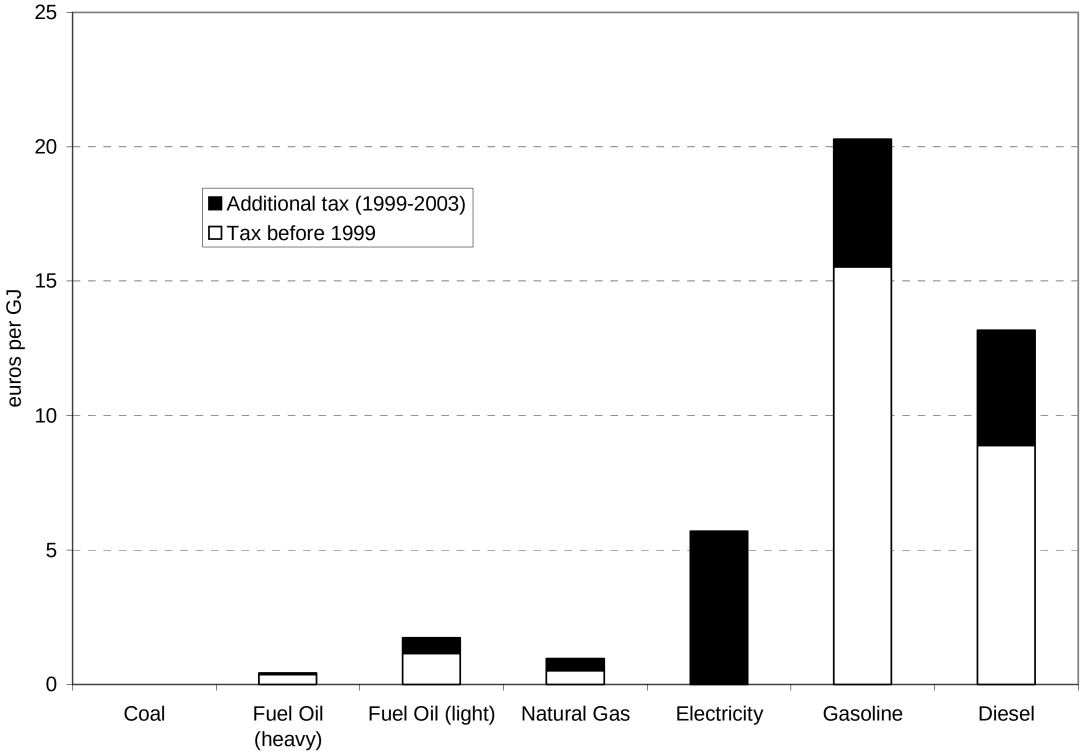

Fig. 1. Energy taxes and ecological taxes in Germany.

The collected tax revenue was recycled as a decrease of the cost of labor in order to stimulate employment. Several special provisions and exemptions to the ecological tax were introduced so to not excessively burden some sectors compared to others. For example, industries (mining, utilities, manufacturing and construction industries) can claim a 'balance of net burden': Should the tax burden exceed the associated reduction in social security payments (more specifically, the reduction of industry's contribution to employee's pension plan payments) by more than 20%, the exceeding electricity and gas and fuel oil tax will be reimbursed. More details on special provisions and exemptions to the ecological tax are provided in the appendix.

In order to incorporate the ecological tax in the SGM, an effective tax rate by sector accounting for these provisions and exemptions was derived. This was done based on the mix of energy inputs, the average size of enterprises in the sector, the reduction in costs of labor through tax revenue recycling, etc. (Bach et al. [3]). Results are shown in Table 1 for the production sectors in SGM-Germany.

Table 1
Effective ecological tax rate for economic sectors in SGM (euro/GJ)

	Electricity		Ref. Petr. Prod.		N. Gas	
	Tax before 1999	Cumulative Tax 2003	Tax before 1999	Cumulative Tax 2003	Tax before 1999	Cumulative Tax 2003
Agr.	0	3.68	9.94	13.54	0.5	0.84
ETE	0	5.68	8.34	11.11	0.5	0.97
Crude Oil	0	1.12	0	3.04	0	0.18
N. Gas	0	1.12	0	3.04	0	0.18
Coal	0	0.56	0	1.78	0	0.09
Coke	0	0	0	0.00	0	0.00
Elec.	0	0.01	0	0.59	0	0.09
Ref. Petr.	0	0.00	0	0.92	0	0.09
City Gas	0	1.14	0	0.11	0	0.09
Paper	0	0	0	0.95	0	0.10
Chemicals	0	0.10	3.89	3.96	0.5	0.60
NM Min.	0	1.05	0.46	1.44	0.5	0.62
Metals	0	0	3.78	4.15	0.5	0.60
Food	0	1.14	3.63	5.45	0.5	0.63
Other Ind.	0	3.82	5.79	7.77	0.5	0.82
Land+Rail Transp.	0	5.68	6.12	10.31	0.5	0.97
Other Transp.	0	5.68	0.46	1.72	0.5	0.97
Consumer	0	5.68	8.84	11.75	0.5	0.97

3. National projections of carbon emissions

Fig. 2 provides a summary of several carbon emissions projections using a recent object-based version of the Second Generation Model (SGM) that allows the introduction of advanced electric generating technologies. Included in Fig. 1 are baseline scenarios to the year 2020 with and without the ecological tax. Also included are projections of carbon emissions at carbon prices of 200 and 400 euros per tC. In these cases, the carbon price is introduced in the year 2005 and held constant thereafter. All of these scenarios are shown relative to historical carbon emissions (DIW [4]) and Germany's Kyoto emissions target. Fig. 2 also includes projections of carbon emissions from the U.S. Energy Information Administration [5]. The carbon price can be interpreted as either a carbon tax or as the market price of emissions rights in an emissions trading system.

Several advanced electric generating technologies are embedded in the projections in Fig. 2, including integrated gasification combined cycle (IGCC) from coal, natural gas combined cycle (NGCC) and wind. Carbon capture and disposal is introduced after 2010, 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. Within electricity, capital lifetimes vary between 20 and 40 years.

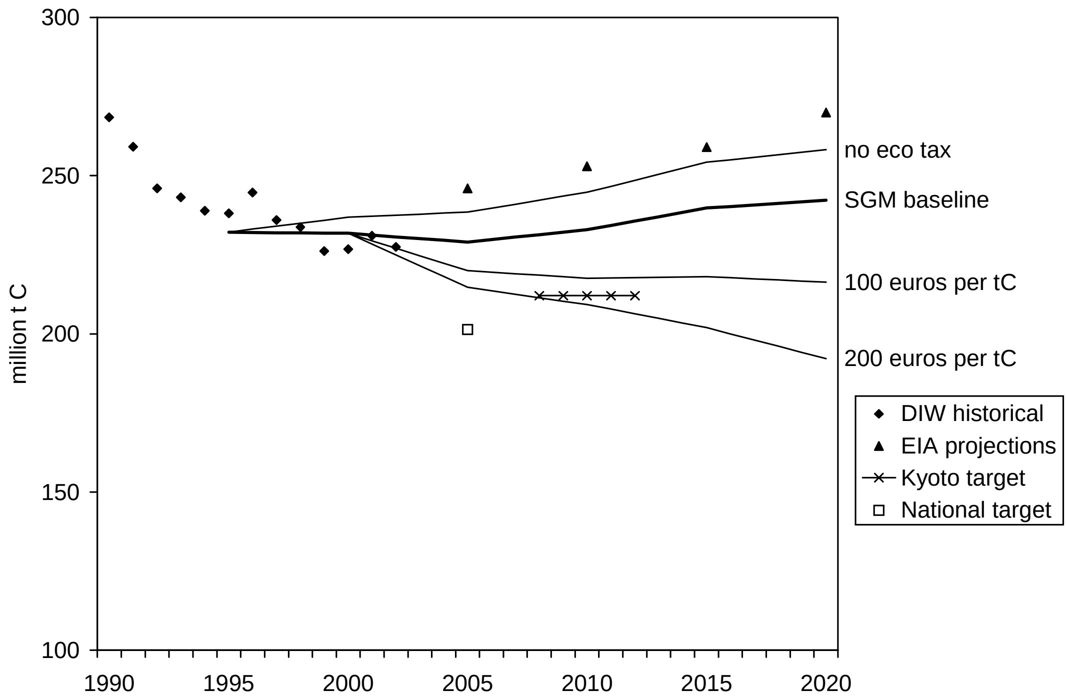

Fig. 2. Projections of carbon emissions in Germany. Advanced electric generating technologies in these scenarios include integrated gasification combined cycle (IGCC), natural gas combined cycle (NGCC), and wind. Carbon capture and disposal is introduced after 2010 in new generating plants.

4. Electricity sector in SGM-Germany

This section provides some background on the electricity sector within SGM-Germany. Other references for SGM include Edmonds et al. [6], MacCracken et al. [7], and Sands [8]. 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 [9]). The second is a 1995 energy balance table for Germany, which is essentially an energy input-output table (AGEB [10]). 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 an engineering cost model for each electric generating technology. This is used to construct a fixed-coefficient production function for these technologies. SGM is a combination of constant-elasticity-of-substitution (CES) production functions for activities other than energy transformation, and of fixed-coefficient technologies within the electricity sector.

Fig. 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 consume fossil fuels. 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.

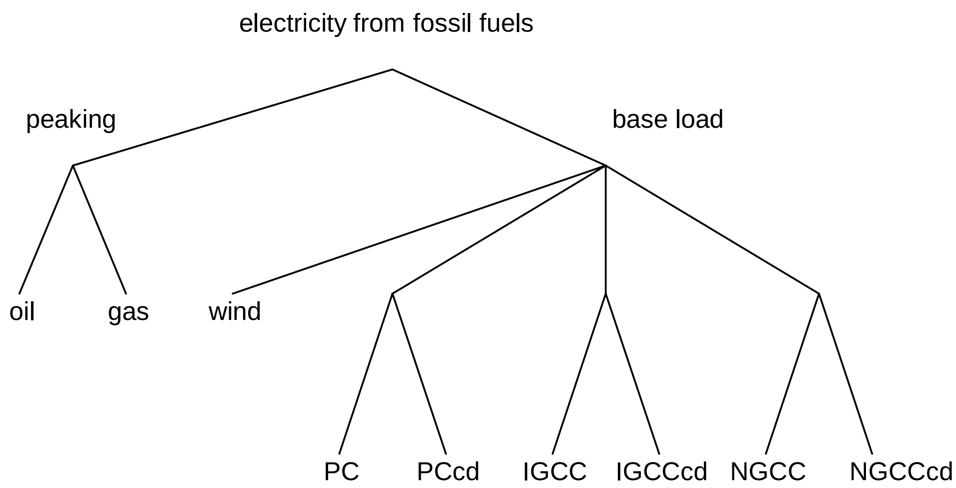

Fig. 3. Nested logit structure of electric generating technologies in SGM-Germany.

Assumptions on capacity, generation and costs for the new electricity technologies are shown in Table 2. Data on carbon capture are based on David and Herzog [11]. The data on wind power is for a hypothetical off-shore plant (30km distance from the coast) assembled for the IKARUS project, a joint research effort for the Federal Ministry of Economics and Labor (IKARUS [12]).

Table 2
Cost assumptions for electricity technologies

		New Electricity		with Carbon Capture			
		NGCC	Coal IGCC	NGCC	Coal IGCC	PC	Wind
Capacity	MW	1,000	1,000	871	847	743	2
Generation	GWh	6,570	6,570	5,722	5,563	4,885	6
Fuel Cost	cent/kWh	1.9	2.5	2.1	2.9	3.4	0
Capital Cost	Euro/kW	1,227	1,433	1,804	1,983	2,171	2,045
Capital Cost	cent/kWh	1.9	2.2	2.8	3.1	3.4	7.8
Ann. Capital Cost	Million Euros	125.5	146.5				0.5
O & M cost	cent/kWh	0.8	0.8	1.1	1.1	1.6	2.3
O & M cost	Million Euros	49.7	49.7				0.14
Disposal cost	cent/kWh			0.4	0.9	1.1	0
Total cost	cent/kWh	4.5	5.4	6.5	8.1	9.5	10.1

Fig. 4 provides plots of levelized cost per kWh as a function of carbon price for two advanced technologies (IGCC and NGCC), with and without carbon capture. 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, carbon capture and disposal 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 carbon capture and disposal. The crossover carbon price is much lower for IGCC than for NGCC. The crossover price for each technology includes a constant 40-euro per ton of carbon disposal cost. The second dimension of competition is between coal and natural gas as a fuel, which is influenced by the relative prices of these fuels and the interest rate. The cost per kWh of NGCC or NGCC with capture is lower than IGCC or IGCC with capture at all values of the carbon price in Fig. 4. This pattern could reverse with higher natural gas prices.

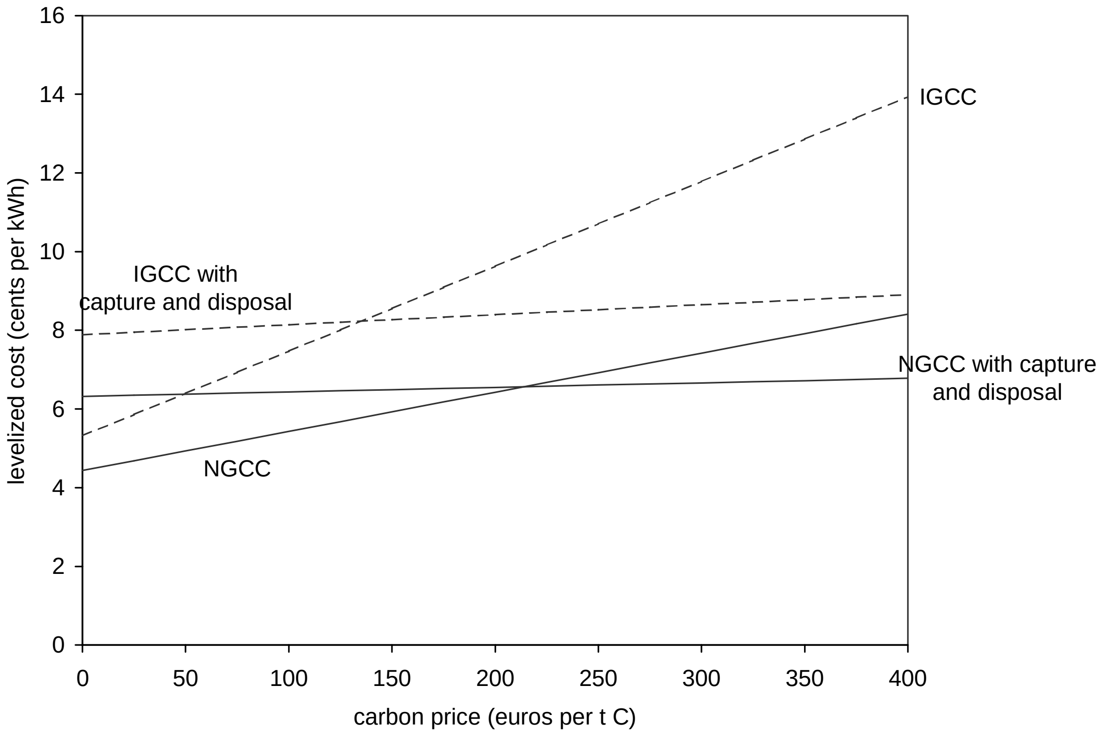

Fig. 4. Levelized cost of electricity generation as a function of carbon price. For either IGCC or NGCC, a break-even carbon price indicates the crossover point to carbon capture and disposal. Carbon disposal costs are assumed to be a constant 40 euros per ton of carbon.

5. Electricity simulations

Fig. 5a shows the share of electricity generation by technology for an SGM-Germany baseline through year 2040. Total electricity generation is fairly stable through 2020 and then declines slowly after 2020. Nuclear power has an assumed lifetime of 30 years and is phased out as old plants retire. The share of nuclear power goes to zero by 2025. Wind power 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 have an assumed lifetime of 40 years, except for nuclear (30 years) and wind (20 years).

Fig. 5b shows the results of a carbon price of 200 euros per tC introduced in year 2005 and held constant thereafter. Total electricity generation is lower relative to Fig. 5a because the price of electricity increases along with the carbon price, and less electricity is demanded by consumers. The shares of wind and NGCC increase, while the shares of pulverized coal and IGCC decrease. With the carbon price, energy technologies that are less carbon-intensive increase their share of electricity generation.

Electricity scenarios in Fig. 5a and Fig. 5b do not allow for carbon capture and sequestration. However, the baseline case would look the same even if capture and disposal were available. Carbon capture and disposal achieves no market share at a zero carbon price. Fig. 5c presents a scenario with a 200 euro per tC price and allows for carbon capture and disposal. This carbon price is well beyond the crossover price for IGCC, as shown in Fig. 4, so almost all IGCC capacity includes carbon capture by 2040. A carbon price of 200 euros per tC is just below the crossover price for NGCC, so slightly less than half of NGCC capacity includes carbon capture by 2040. Carbon capture in this scenario applies to new generating plants only, and is phased in as old plants retire.

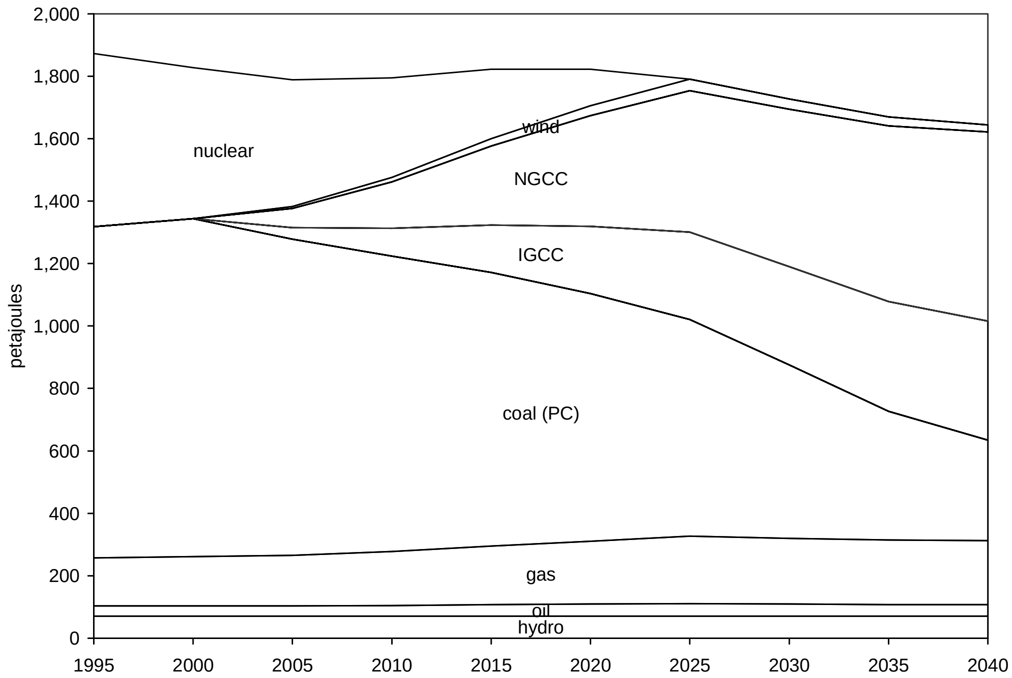

Fig. 5a. Baseline shares of electricity generation. The generating technologies are hydroelectric power (hydro), oil-fired generation (oil), gas other than combined cycle (gas), pulverized coal (PC), integrated gasification combined cycle (IGCC), natural gas combined cycle (NGCC), wind turbines (wind), and nuclear fission (nuclear).

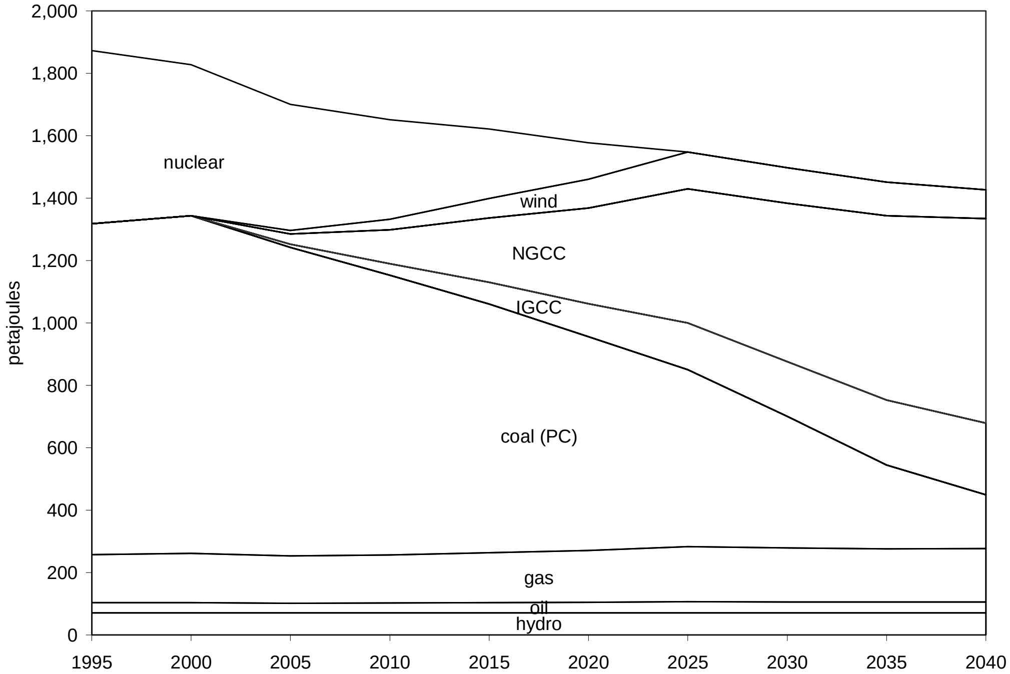

Fig. 5b. Shares of electricity generation with at 200 euros per tC. Generating technologies are the same as in Fig. 5a.

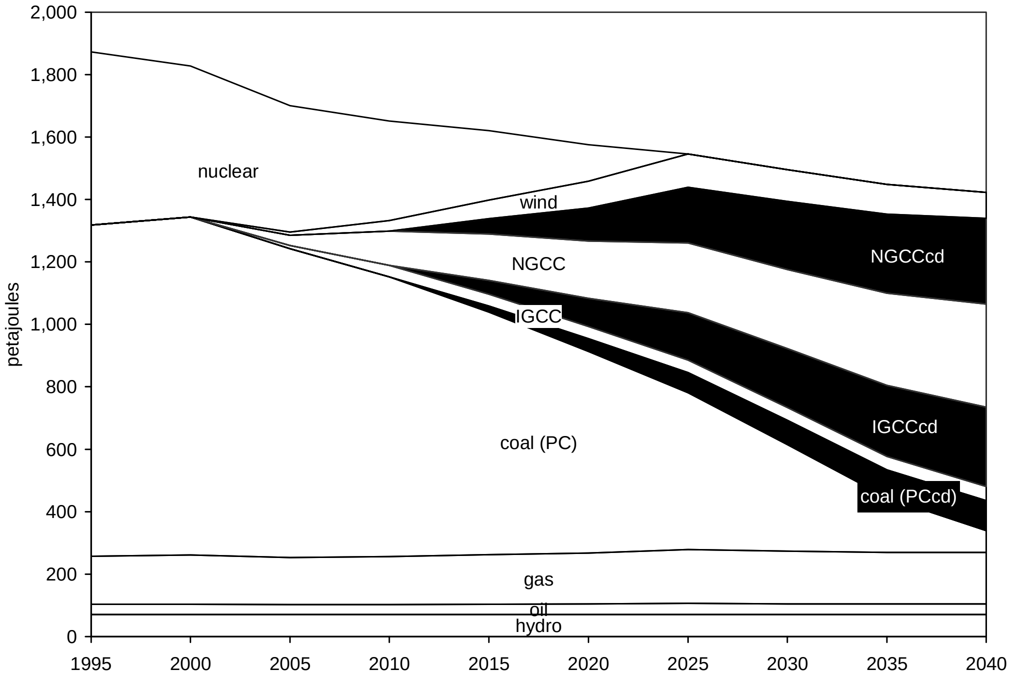

Fig. 5c. Shares of electricity generation with at 200 euros per tC. This scenario allows carbon capture and disposal after 2010. The capture and disposal technologies are

pulverized coal (PCcd), integrated gasification combined cycle (IGCCcd), and natural gas combined cycle (NGCCcd).

6. Conclusions

This paper describes the development of a computable general equilibrium model for Germany with two major goals. The first goal was to demonstrate a methodology for addressing the gap between top-down economic production functions and bottom-up engineering cost models that describe specific electric generation technologies. We have embedded an electricity sector built up from engineering data, using a logit algorithm to determine investment shares, in a computable general equilibrium model. Various advanced electric generating technologies, including IGCC, NGCC, wind, and carbon capture, were demonstrated using this approach. Future work will include sensitivity analysis on cost assumptions and how they might change over time.

The second goal was to construct a model that could be used to evaluate alternative carbon policies in Germany. So far, we have characterized the response of SGM-Germany to a series of constant-carbon-price experiments. The marginal cost per ton of carbon required to meet a target such as Germany's Kyoto target depends on assumed baseline emissions, the policy start date, the set of available energy technologies, and the fraction of the economy exposed to the carbon policy. For the simulation in this paper, a carbon price between 100 and 200 euros per tC is required to meet the Kyoto target. Future work will provide a more realistic evaluation of emissions trading programs, with emissions trading targeted to specific economic sectors such as electricity production and energy-intensive industries.

Appendix A. Ecological tax in Germany

Table A1
Ecological tax rates

Energy Carrier	Tax Rate before April 1 1999	Energy Tax per unit - yearly increase -		Cumulative increase 1999 to 2003		Total Tax burden in 2003	
	Pf/unit	from April 1 1999 on	yearly increase thereafter	Pf/unit	DM/GJ	Pf/unit	DM/GJ
Coal (kg)	-	-	-	-	-	-	-
Fuel Oil heavy[1)] (kg)	3,00	-	0,5[2)]	0,5	0,12	3,50	0,85
Fuel Oil light (l)	8,00	4,00	0	4,00	1,12	12,00	3,37
Natural Gas (kWh)	0,36	0,32	0	0,32	0,89	0,68	1,89
Electricity[)] (kWh)	0,00	2,00	0,5	4,00	11,11	4,00	11,11
Gasoline (l)	98,00	6,00	6,00	30,00	9,27	128,00	39,55
Diesel (l)	62,00	6,00	6,00	30,00	8,38	92,00	25,71
[1)] Consistent tax for heavy fuel oil since 2000.- [2)] One time increase in 2000.							

Sources: *Gesetz zum Einstieg in die ökologische Steuerreform (Bundesgesetzblatt I, S. 378, 1999), Gesetz zur Fortführung der ökologischen Steuerreform (Bundesgesetzblatt I, S. 2432, 1999); DIW (2000).*

Special provisions and exemptions to the 'Eco Tax'

Exceptions applying to manufacturing industries and agriculture and forestry:

1. Should the additional tax burden for electricity and heat exceed 1000DM per year each, the exceeding energy consumption will be taxed at a reduced rate of 20% of the regular tax rate. (does not apply to gasoline).
2. In addition, industries (mining, utilities, manufacturing and construction industries) can claim a 'balance of net burden': Should the tax burden exceed the associated reduction in social security payments (more specifically, the reduction of industry's contribution to employee's pension plan payments) by more than 20%, the exceeding electricity and gas and fuel oil tax will be reimbursed.

Additional exceptions:

1. Gas and oil consumption for either electricity or heat production are exempt from the tax increase, as are CHP plants with a conversion efficiency of more than 60%.
2. Existing exemptions for taxation of mineral oil still apply.
3. Electricity consumption for public transport is taxed at 50% of the above rate only.
4. From 2000 on, the tax increase for oil products in public transport will only be half the regular rate (i.e. 3 Pf/year)
5. Gasoline with high sulfur content (more than 50mg/kg starting in 11/01/2001, from 1/1/2003 the limit will be reduced to 10mg/kg) will be taxed with an additional 3Pf/l.
6. Electricity for 'night storage heating' will be taxed at half the regular rate if installed before 4/1/1999.

Exceptions for efficient power plants:

1. CHP with conversion efficiency of more than 70% are exempt from all energy taxes.
2. Combined Cycle power plants with conversion efficiency of more than 57.5% are exempt for five years if they are built between 1/1/2000 and 12/31/2003.
3. Power plants of less than 2 MW capacity are exempt from the electricity tax (increased in 1/1/2000 from 0.7 MW).

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