Future Electricity Technologies in Germany under CO_2 Emissions Policy: The Potential Role of Fossil Fuels and CCS[1]

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Abstract

The European Commission has targeted challenging reductions of greenhouse gas emissions in the electricity sector for the coming decades and the technological option of fossil fuel fired power plants with CCS is brought into the discussion. In this paper we develop the existing EMELIE[3] model of the electricity market in order to assess investments in fossil fuel based electricity technologies with the option of CCS on the oligopolistic German market. Using common projections of the natural gas and hard coal prices we find that some CCS technologies become competitive with conventional fossil fuel technologies at carbon prices between 30 and 40 Euro per ton of CO_2 and emission reductions of more then 60 percent can be achieved until the middle of the century. However, under oligopolistic competition the producer prices for electricity increases from currently 4 to more than 7 Eurocent per kilowatt hour.

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[3]**E**lectricity **M**ark**E**t **L**iberalisation **I**n **E**urope.

1 Introduction

The German energy industry, like other energy industries in Europe, has to cope with a twofold challenge in the next two decades. On the one hand, a gap in the production capacity of about half of the installed thermal generation capacity - roughly fifty gigawatt in Germany - has to be replaced due to the depreciation of existing plants and a nuclear phase-out. On the other hand, climate policy demands ever-growing climate emission reductions.

The forced use of renewable energies and the increase of overall energy efficiency provides answers to this challenge. Moreover, an increase of energy efficiency reduces costs and emissions per output and consequently has a double benefit. However, possibilities for an improvement of energy efficiency on the supply side are limited. Nevertheless, the increased use of combined heat and power and the replacement of old plants by power plants with the latest technology may cut German CO_2 emissions by one fifth until 2050. A further emission reduction can be achieved by the switch from coal to natural gas as primary energy carrier which requires emission prices of about 20 Euro per ton of CO_2 if natural gas prices are moderate compared to today. Under this assumptions roughly half of the emissions of the electricity sector will be saved if all coal fired power plants would be replaced by natural gas fired combined cycle plants. But such a shift would greatly narrow the supply diversification, since natural gas at reasonable prices would come predominantly from Russian sources and, hence, could decrease the security of supply in an unacceptable way. Therefore, a complete switch to low cost natural gas can be regarded as highly unrealistic. In order to cut emissions in the electricity sector by more than a half of its current level other technologies have to be introduced. Unfortunately, most of the limited renewable energy potential becomes - at current fossil fuel prices - only competitive under emission prices above 60 Euro per ton of CO_2.

But the more the emission target is biting the more likely becomes the installation of so-called clean coal and clean gas technologies. By means of carbon capture and storage (CCS) the carbon dioxide (CO_2) - which is an inherent by-product of conventional fuel combustion - can technically be prevented from emission into the atmosphere. The technology is discussed controversially. CCS is called into question by the following disadvantages that are attributed to its application:

- significant decrease of the overall conversion efficiency, and consequently increased use of primary energy,
- risk of leakage in all parts of the CO_2-treatment - capture, transportation and storage - with its adverse consequences for life and GHG-reduction,
- long term management of storage sites,
- limitation of storage opportunities.

On the other hand, among the advantages of CCS are

- enhanced oil and gas recovery,
- possibility of low emission use of fossil fuel resources with their high reliability for the electricity system,
- potential for permanent reduction of the total amount of CO_2 that is eventually stored in the atmosphere (in contrast to the mere delay of emissions by an increase of efficiency).

However, under the current climate policy regime and the prevailing carbon prices of not even 20 Euro per ton of CO_2 the CCS-Technology seems to be not competitive. Nevertheless, a presumably efficient way to reach the targets is to tighten the emissions cap set by the European Emission Trading System, which will increase the emissions price almost inevitably, thus bringing CCS closer to the market.

In order to simulate the investment in fossil fuel power plants that is likely to occur on an oligopolistic market, a computable partial equilibrium model has been developed that is based on the original model by Kemfert (1999). Following this model, a whole family of models has been applied to the analysis of behavioral assumptions and environmental impact (Kemfert et al. 2003), mergers and acquisitions (Ellersdorfer et al. 2001), electricity infrastructure enhancement and market power (Ellersdorfer et al. 2003), and environmental impacts of demergers (Lise et al. 2006). Unlike these static models, the present model allows for investment opportunities and thus is able to project future trends in the market development.

The main objective of this paper is to investigate which role CCS with its controversial properties will play if the technology choice is left to a market that is on the one hand regulated by an emission trading system and is on the other hand distorted by oligopolistic behavior of the major companies. In the next section we provide a algebraic description of the computable model which is followed by a summary of the input data and a brief description of the calibration of the model in section 3. Thereafter, we report main findings of the model in section 4. Threshold prices for emissions that trigger a change in the choice of technology are determined and the simulated developments of emissions and investment structure until the year 2050 are illustrated. Finally, the model results are discussed in the light of the advantages, disadvantages and limitations of CCS that are not modeled.

2 The Model

We model m electricity producers in a situation where a capital stock of producer i that is capable of producing $q_{\text{lim}}^{i,t}$ units of electricity exists in time period t element of the set of time periods T. The existing capital stock scraps linearly over the models time horizon. Furthermore, the firms have the possibility of choosing new capital $k_{i,t,n}$ from the menu of available technologies N up to the firms specific investment restriction[4] $k_{\text{lim}}^{i,t}$. In the model the new capital is assumed to have a lifetime of just one model period, more precisely 25 years, such that the investment corresponds one to one to output produced in these units. The total production of one period sums up to $X^t = \sum_{i \in I} x^{i,t}$ where $x^{i,t} = \sum_{n \in N} k^{i,t,n} + q^{i,t}$, while the demand is represented by an iso-elastic inverse residual[5] demand function: $P^t(X^t) = (X^t)^{-\frac{1}{\epsilon}} \frac{P^0}{X^0}$ which yields the respective elasticity of residual demand: $\epsilon = \left| \frac{dX \sec}{dP(X)} \frac{P^0(X)}{X^0} \right|$, where a "0" indicates the reference values in the base period.

Furthermore, the cost functions of the firms are written as $C^{i,t}(q^{i,t})$ for existing production facilities and $C^{i,t,n}(k^{i,t,n})$ for new investment. The production is linked to emissions via the emission functions: $E^{i,t}(q^{i,t})$ and $E^{i,t,n}(k^{i,t,n})$,

[4] The investment restriction is described in the following section.

[5] The term "residual demand" stands for the demand experienced by the oligopolistic firms, i.e. total demand minus the supply of the price taking fringe firms.

i.e. every production level of a producer corresponds to a unique level of emission. Finally, the cost of an emission unit for the producer is represented by the exogenous price of emission certificates σ.

The optimization problem of the m firms that are members of the set of firms M depends on the output decisions of the firms other then i, $x^{-i} = \sum_{j \neq i} x^j$, and can be expressed as the following Lagrangian of the Kuhn-Tucker type:

$$L^i(x^i, x^{-i}) = \sum_{t \in T} [(P^t(X)x^{i,t} - C^{i,t}(q^{i,t}) - \sigma E^{i,t}(q^{i,t}) - \kappa^{i,t}(q^{i,t}_{\text{lim}} - q^{i,t})$$
$$- \sum_{n \in N} C^{i,t,n}(k^{i,t,n}) - \sum_{n \in N} \sigma E^{i,t,n}(k^{i,t,n}) - \iota^{i,t}(\sum_{n \in N} k^{i,t,n} - k^{i,t}_{\text{lim}})], \ \forall i \in M. \quad (1)$$

If we denote the market share of firm i with $\vartheta^{i,t}$ the t Kuhn-Tucker optimality conditions of the firms with respect to production in existing plants q^i can be written as[6]:

$$P^t(X^t)(1 - \frac{\vartheta^{i,t}}{\epsilon} l^i) \leq C_q^{i,t}(q^{i,t}) + \sigma E_q^{i,t}(q^{i,t}) + \kappa^{i,t},$$

and

$$q^{i,t}(P^t\left(X^t\right)\left(1 - \frac{\vartheta^{i,t}}{\epsilon} l^i\right) - C_q^{i,t}(q^{i,t}) - \sigma E_q^{i,t} - \kappa^{i,t}) = 0,$$
$$\forall i \in M, \forall t \in T \quad (2)$$

where l^i is a binary variable reflecting the behavior of the firms: If l^i is zero the firm i acts as price takers, and according to Nash-Cournot strategic behavior else.

Using the same notation, the n times t Kuhn-Tucker optimality conditions of the firms with respect to the investment decisions $k^{i,t,n}$ are:

$$P^t\left(X^t\right)\left(1 - \frac{\vartheta^{i,t}}{\epsilon} l^i\right) \leq C_k^{i,t,n}(k^{i,t,n}) + \sigma E_k^{i,t,n}(k^{i,t,n}) + \iota^{i,t},$$

[6]Lower letters indicate first derivatives of the cost and emissions functions.

and

$$k^{i,t,n}(P^t\left(X^t\right)\left(1-\frac{\vartheta^{i,t}}{\epsilon}l^i\right)-C_k^{i,t,n}(k^{i,t,n})-\sigma E_k^{i,t,n}-\iota^{i,t})=0,$$

$$\forall i\in M,\forall t\in T,\forall n\in N. \tag{3}$$

The differentiation with respect to the Kuhn-Tucker multipiers $\kappa^{i,t}$ and $\iota^{i,t}$ yields:

$$q_{lim}^{i,t}-q^{i,t}\geq 0,\ \forall i\in M,\forall t\in T \tag{4}$$

and

$$k_{lim}^{i,t}-\sum_{n\in N}k^{i,t,n}\geq 0,\ \forall i\in M,\forall t\in T. \tag{5}$$

Additionally the following nonnegativity conditions have to hold: $q^{i,t}\geq 0$, $\kappa^{i,t}\geq 0$, $\kappa^{i,t}(q_{lim}^{i,t}-q^{i,t})=0$, $k^{i,t,n}\geq 0$, $\iota^{i,t}\geq 0$, $\iota^{i,t}(k_{lim}^{i,t}-\sum_{n\in N}k^{i,t,n})=0$.

3 Data and Calibration

The supply side of the model is based on data on the electricity generation capacity of the four main players on the German electricity market - i.e. eon, RWE, Vattenfall and the EnBW - and the aggregated smaller, mostly municipal generators termed residual in the following. These generation capacities are characterized by the energy carrier which is used - dammed water, uranium, hard coal, lignite, natural gas and heavy oil - and in case of the thermal power plants additionally by the technology that is applied. Altogether the production capacity is represented by ten technology classes as can be seen from table 1.

Both, the power plants that burn solid fossil fuels and the nuclear power plants use steam turbines for electricity generation. These plants are classified into efficiency clusters ranging from 32 percent in case of small nuclear power plants up to 43 percent for comparatively new hard coal and lignite firing units. Natural gas and heavy oil may are used in power plants equipped with gas turbines as well as steam turbines. In principle even the combination of both technologies - the so called combined cycle gas turbines (CC) - with high efficiencies ranging from 52 to 59 percent might be applied for

fuel type	plant type	efficiency	fuel price [€-cent/kWhfuel]	emissions factor [kg/kWhel]	variable cost [€-cent/kWhel]
	small	0,32	0,21	0,00	0,66
uranium	large	0,34	0,21	0,00	0,62
	old	0,34	0,45	0,46	1,32
lignite	new	0,43	0,45	0,37	1,05
	old	0,34	0,54	0,39	1,59
hard coal	new	0,43	0,54	0,30	1,26
	conventional	~0,38	1,05	~0,26	~2,76
natural gas	combined cycle	0,55	1,05	0,15	1,91
	gas turbine	0,33	0,84	0,30	2,55
heavy oil	steam turbine	0,38	0,84	0,22	2,21

Source: Own calculations.

Table 1: Technology characteristics of existing German power plants.

oil and gas firing plants. However, in Germany only natural gas units are equipped with this advanced technology since almost no oil fired plants have been built in the last fifteen years.

The figure 1 shows the installed net generation capacities of the four main players on the German electricity market and the competitive fringe that is termed as "Rest". The numbers are calculated using extensive plant ownership data accounting for several layers of ownership relations. The control of the firms over capacities is then calculated as share times capacities if only on layer of ownership structure exists. If there are several layers the shares are multiplied with each other to get the part of a power plant which is controlled by one of the major players. The residual, i.e. parts that are not controlled by major players, are aggregated to the category "Rest".

Apparently, the four players differ considerably in terms of controlled capacities. The largest firm Eon controls more then thirty percent of the capacities followed by RWE with about twenty five percent. Vattenfall and EnBW control fifteen and ten percent of the capacities respectively while the "Rest" represents about nineteen percent. Notably, with regard to the plant types there are similarities among Eon and EnBW as well as among RWE and Vattenfall: Eon and EnBW both have a comparatively high share of nuclear capacities while RWE and Vattenfall control the bulk of lignite fueled power plants. In contrast, the mainly municipal utilities of the aggregated "Rest" lack both of these two cheap production opportunities. Instead of

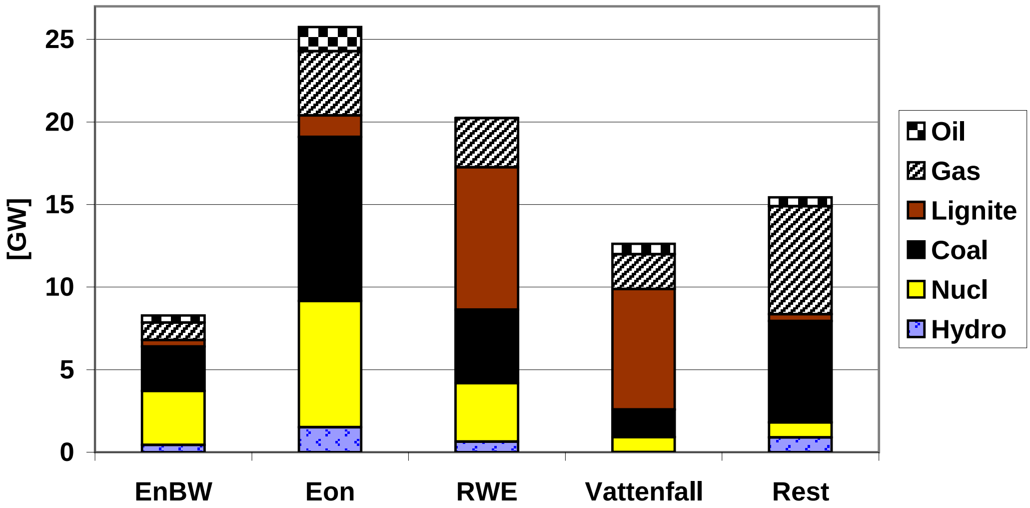

Figure 1: Installed electric generation capacity of the German players and the competitive fringe firms (Rest).

nuclear and lignite a relatively high fraction of the capacities of the "Rest" are natural gas facilities.

With regard to the investment opportunities, the technologies have experienced some progress and are expected to learn further. For instance, the efficiency of conventional hard coal power plants is projected to rise from currently 46 up to 50 percent in the next 25 years, thereby reducing the emission factor from 0.7 to about 0.64 kilo CO_2 per kilowatt hour. Similar advances are expected to take place in the other applied conversion technologies. Table 2 summarizes assumptions concerning the technological and financial conditions that have been made on the basis of projections of the International Energy Agency[7] (IEA 2006) that we used in order to model the investment in natural gas combined cycle (CC), integrated gasification combined cycle (IGCC) and conventional hard coal (HC) - each with and without CCS. Furthermore, we assumed the interest rate for capital service to be 7 percent per annum and the capture efficiency of CCS is set to 80 percent[8]. The fuel prices for hard coal are kept constant at 2.6 Euro per Gi-

[7]Further sources are Rubin et al. 2004, David and Herzog (2000) and the overview of new electricity technologies given in Schumacher (2006) pp. 3931-3932 .

[8]IEA (2006) assumes a capture efficiency of eighty five percent. In order to account for losses due to transport and storage leakages we assume that about six percent escapes

	Efficiency	Capital Cost	O&M cost	CO_2 - Emission	Levelized Cost
	[%]	[cent/kWh]	[cent/kWh]	[kg/kWh]	[€-cent/kWh]
CC	60-62	0,50	0,49	0,29-0,30	3,9-4,6
IGCC	51-54	1,26	1,47	0,59-0,63	4,0-4,1
HC	45-50	1,00	0,78	0,64-0,71	3,2-3,4
CC ccs	50-56	0,80	0,49	0,06-0,07	4,5-5,6
IGCC ccs	39-46	1,41	1,47	0,14-0,16	4,4-4,7
HC ccs	31-39	1,51	0,78	0,16-0,21	4,1-4,6

Table 2: Technology outlook for fossil fuel power plants, Source: IEA 2006, own calculations.

gajoule while the natural gas price fluctuates, i.e. gas prices are 7.8, 6.5 and 8.45 Euro per Gigajoule in the initial, second and third period respectively and refer to IEA (2006).

As can be seen from table 1 there is a trade-off between coal and gas technologies under our fuel price assumption: coal power plants have lower variable costs compared to gas power plants which in turn have lower emission factors. Thus one can expect the emission prices to be crucial for the choice of technology.

The data described so far is used to construct increasing marginal cost and emission functions of exponential form. The marginal cost function of firm i in time period t is

$$C_q^{i,t}(q^{i,t}) = a^i \exp(b^i \frac{q^{i,t}}{q_{\lim}^{i,t}}), \tag{6}$$

where $q_{\lim}^{i,t}$ denotes the maximum annual generation from already installed capacities of firm i in period t.

The production capacity of thermal power plants depreciates linearly over time while the hydropower capacity q_{hyd}^i remains constant. Hence, the depreciated capacity in period t is:

$$q_{\lim}^{i,t} = q_{\lim}^{i,0} - \frac{t}{2}(q_{\lim}^{i,t} - q_{hyd}^i), \ t = 0, 1, 2. \tag{7}$$

after capturing.

The depreciation of installed plants makes way for new investment. Additionally, we assume that the strategic players as well as the competitive fringe may increase their total generation capacity by one sixth compared to their initial capacity in each time step. Thus, the restriction of the investment of firm i in period t becomes:

$$k_{\lim}^{i,t} = q_{\lim}^{i,0} - \frac{t}{2}(q_{\lim}^{i,t} - q_{hyd}^{i}) + \frac{1}{6} q_{\lim}^{i,0}, \; t = 0, 1, 2. \tag{8}$$

Similar to the marginal cost function of existing generation capacity the marginal cost of production in newly commissioned capacity of technology n in period t is represented by:

$$C_k^{i,t,n}(k^{i,t,n}) = c^i \exp(d^i \frac{k^{i,t,n}}{k_{\lim}^{i,t}}). \tag{9}$$

The emission functions are closely linked to the production. Each production level of firm i yields in each period a unique level of marginal emissions. The marginal emission function of firm i for production in installed capacity is:

$$E_q^i(q^{i,t}) = f^i \exp(g^i \frac{q^{i,t}}{q_{\lim}^{i,t}}). \tag{10}$$

Accordingly the marginal emission functions of new investments in technology n of firm i writes:

$$E_k^{i,t,n}(k^{i,t,n}) = h^i \exp(j^i \frac{k^{i,t,n}}{k_{\lim}^{i,t}}). \tag{11}$$

The reference demand of the model is simply the demand calculated from Eurostat (2006) information about the 2005 electricity consumption where the production of wind power is subtracted. The model is calibrated by the choice of the residual demand elasticity which yields the reference prices and demand for Cournot-Nash behavior and an emission price of 10 Euro per ton of CO_2. In this version of the model the reference prices and quantities are 4 euro cent per kilowatt hour and 527 terra watt hours respectively, which yields an elasticity of residual demand of 0.5. These values are not changed over the time horizon. The reasons are twofold. Firstly, the German electricity demand is projected to rise only slightly[9]. Secondly, any rise in electricity demand will almost certainly be compensated by an increased energy efficiency and the use of renewable energy which is not simulated by the model.

4 Results

This section features results of the model runs that are obtained from emission prices ranging between zero and one hundred Euro per ton of CO_2. The focus is on the following questions:

1. What are threshold emission prices for the choice of technology?
2. What is the impact of strategic behavior of the firms on the threshold emission prices, the total emissions, electricity prices and overall investments?
3. How does the technological choice depend on the natural gas price?

As depicted in figure 2, the technology choice of investments in new power plants crucially depends on the emission price. In the case of an emission price of 10 Euro per ton of CO_2 - i.e. at the current level - or below the firms invest solely in conventional hard coal (HC). Under emission prices higher then 20 Euro per ton of CO_2 the hard coal is subsequently replaced by hard coal with CCS (HC+) and combined cycle gas fired plants (CC). At a level of 40 Euro per ton of CO_2 even the simple combined cycle gas fired technology is no longer efficient so that firms invest in CC only in combination with CCS (CC+). 40 Euro per ton of CO_2 is the threshold value for investment in integrated combustion with CCS as well. This investment mix of the three technologies with CCS stays relevant for the whole range of emission prices up to 90 Euro per ton of CO_2 while at an unrealistic[10] high emission price of

[9] For instance the EWI/Prognos(2005) report for the German Ministry for Economy and Labor projects an almost constant electricity demand.

[10] At a price of 90 Euro per ton of CO_2 many other technologies such as wind power and biomass with or without CCS break even. Therefore a higher price of emissions is unlikely.

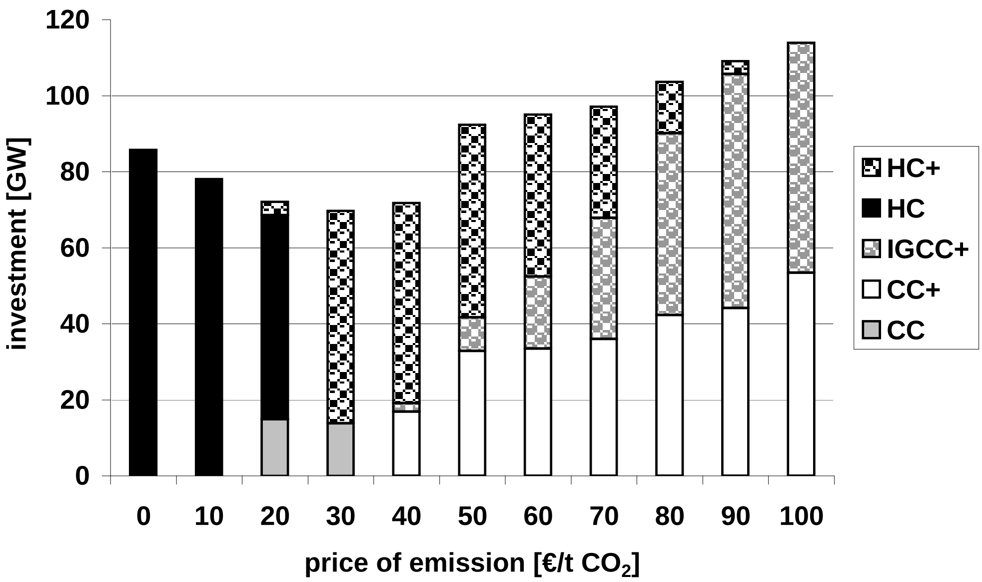

Figure 2: Investment in new power plants until 2050 under oligopolistic competition.

100 Euro per ton simple hard coal with CCS is not chosen for new investment anymore.

If we assume price taking behavior of investors the picture changes in the size of investments significantly. The investment effect of price taking behavior compared to oligopolistic behavior is shown in figure 3 which highlights the differences.

First of all the investment effect of price taking behavior is clearly positive and amounts to 18 to 35 gigawatt. A second more remarkable effect presented in figure 3 is that technologies like hard coal with CCS and integrated gasification combined cycle with CCS which benefit from the competitive scenario at higher emission prices suffer from price taking behavior at lower emission prices. The reason for this less intuitive result is the investment choice of the competitive fringe which overinvest in the oligopolistic scenario due to higher electricity prices.

Particularly, if we focus on emission prices of 40 and 50 euro per ton of CO_2 there is only investment in integrated gasification combined cycle with CCS if we assume oligopolistic competition: In the high natural gas price period in

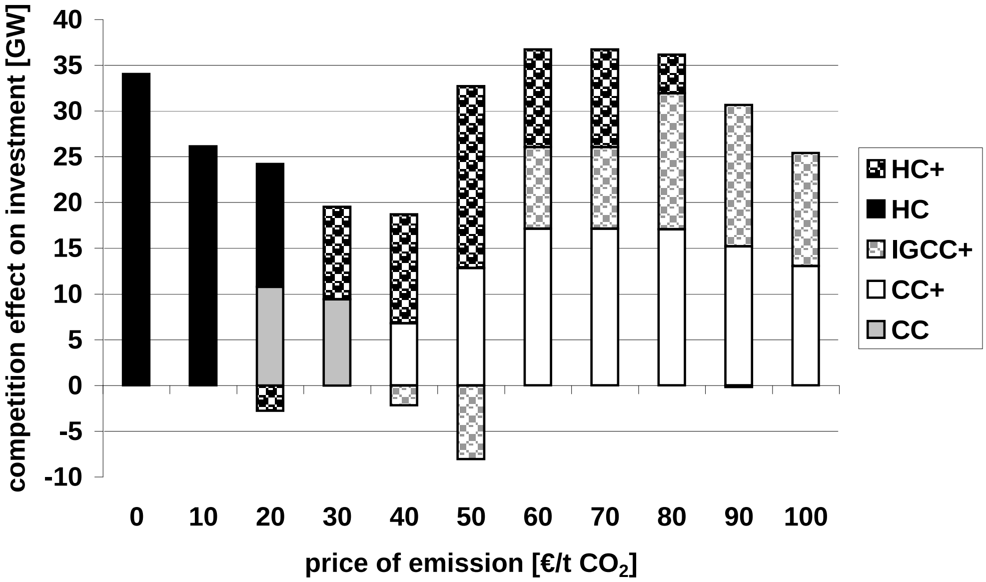

Figure 3: The effect of the behavioral assumption on investment decisions.

2050 the competitive fringe overinvests in hard coal CCS such that integrated gasification combined cycle with CCS becomes a premature option that would not be chosen under the cost efficient price taking behavior. These findings suggest an ambiguous effect of the firm behavior on total emissions since the emission effect of oligopolistic output contraction might be overcompensated by inefficiencies that stem from over investment of the fringe firms. In the subsequent investigation of the total emissions we will keep this suspicion in mind.

Moreover, total investments exhibit a jump when we move from 40 to 50 euro per ton of CO_2 under both behavioral assumptions. A better understanding of the peculiarities can be obtained from the figure 4, where the investment decisions for emission prices between 0 and 60 euro per ton of CO_2 for the periods 2025 and 2050 are shown. In the final model period 2050 the investors choose solely coal technologies due to comparatively high natural gas prices. Furthermore, there is a negative relation between emission prices and the amount of investments.

By contrast, in the period 2025 this relationship is changing. For low emission prices the relationship is negative while under higher emission prices

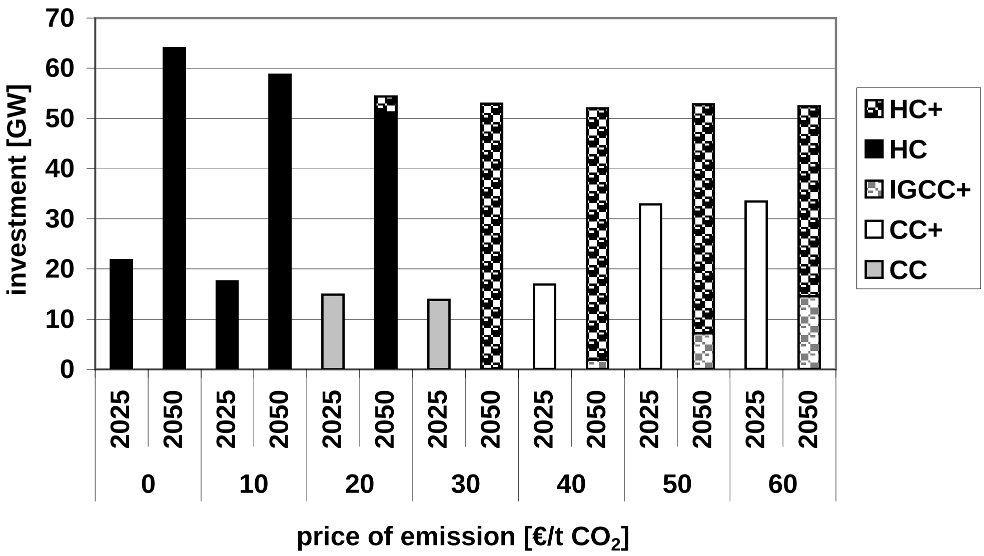

Figure 4: The investment decisions in 2025 and 2050 under oligopolistic behavior.

more investments are undertaken if the emission price increases. This shift in the sign of the relation corresponds with a change from investment in simple combined cycle natural gas plants to combined cycle natural gas plants with CCS. These findings can be explained with the increased obsolescence of the old power plants under higher emission prices such that new investments become more attractive compared to the use of already built plants.

Figure 5 summarizes the annual emissions over the whole time horizon for emission prices between 0 and 100 euro per ton of CO_2. Under emission prices between 0 and 20 euro per ton of CO_2, emissions first fall and then increase again in the last period. The initial effect is due to a sharp electricity price increase and a fall in natural gas prices from the first to the second period. The emission increase towards the final period is mainly caused by a massive installation of conventional hard coal units. However, under higher emission prices the emissions decline continuously over the model's time horizon. Furthermore, the emissions in the second period fall drastically compared to the first period if we have emission prices of at least 50 euro per ton of CO_2 due to the complete shift of investments into CCS. With regard to the final period a comparable drop of emissions is already caused by 30 euro per ton of CO_2 since the complete restructuring of the thermal part

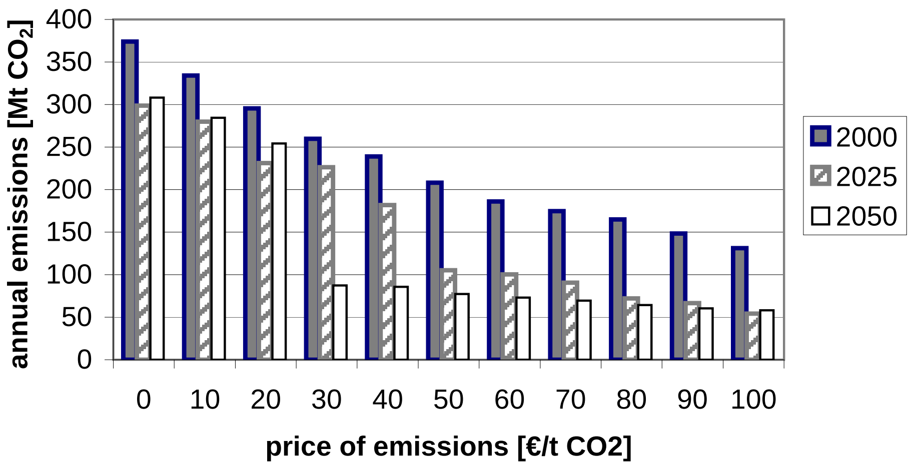

Figure 5: Emission development under oligopolistic competition.

of the industry into CCS is not limited by old thermal capacities and low natural gas prices.

Let us now turn to the question of the impact of the behavioral assumption on emissions. Figure 6 portrays the change of annual emissions if we change from an oligopolistic regime to a regime of price taking behavior. Although we find that the oligopolists seem to be good friends of the environmentalists, since emissions are reduced by imperfect competition in most cases, noticeable exceptions appear in our setting . If we have high emission prices and consider the second period where significant old power plants are still available and the natural gas prices are low, the figure 6 shows decreasing emissions when we move towards competition. This means the emission effect of the oligopolistic output contraction is overcompensated by higher emissions per output unit. As suspected earlier this effect is due to overproduction in old facilities of the competitive fringe firms.

With regard to the capture and storage of CO_2 the model results suggest that the storage capacities in the comparatively safe saline aquifers in Germany are not a limiting factor until 2050. But if we take the results for 2050 as an estimate for the annual storage in the second half of the century the picture changes considerably. With an annual storage of between 230 and 310 megatons of CO_2 the amount stored totals to around 20 gigatons in the price taking scenario and 14 gigatons under oligopolistic competition in the

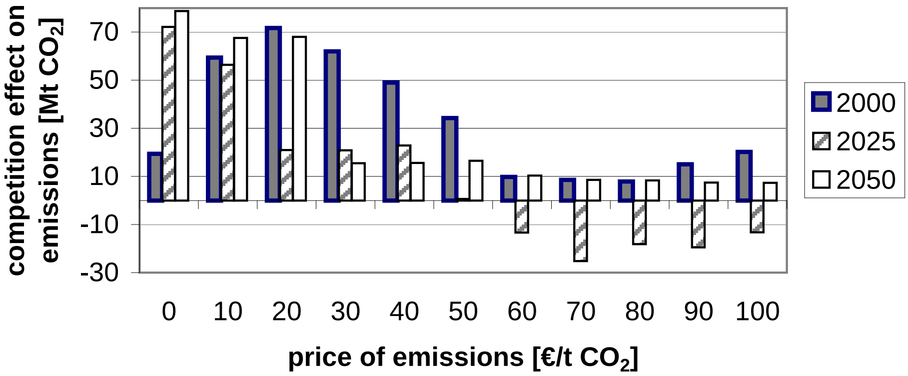

Figure 6: The effect of the behavioral assumption on emissions.

end of the century, while the lower limit of the storage capacity estimate in saline aquifers in Germany is according to Christensen and Holloway (2004) 23 gigatons of CO_2. Notably, the assumed behavior of the firms plays the dominant role while the CO_2-price has - as long as it is above 30 euro per ton of CO_2 - a much smaller impact on the stored amount.

5 Conclusion

With the help of a computable equilibrium model of the German electricity market we have assessed the likely investment and emission development until 2050 under different assumptions about the price for CO_2 emission and about the behavior of firms. Taking the oligopolistic scenario as a reference, we find that CCS is an advantageous option if emission prices are above 40 euro per ton of CO_2 and other abatement options are not available. In this case only CCS is used for both, natural gas and coal fired powered plants, and by 2050 emissions are cut by two thirds compared to today. Accordingly, the amount of stored CO_2 reaches circa 250 million tons in the final model period. Together with additional CO_2 from other emitting sectors that may be stored as well, comparably safe and accessible saline aquifers may run out of capacity by the year 2100. In addition producer prices for electricity climb from currently 4 to about 7.8 euro cent per kilowatt hour.

These results show that CCS can be viewed as a technology that is able to achieve major reductions in the emission of greenhouse gases. But these reductions are achieved at high costs. Especially in Germany, where CO_2 storage can not be used to enhance oil recovery, abatement costs may account for one third of the total unit costs of production. Furthermore, the option of CO_2 storage can not provide a sustainable answer to the energy-climate problem since the storage facilities are limited and exhaustion of fossil fuel resources is accelerated due to a significant loss in efficiency. Therefore, CCS may be seen as a viable bridge that could close the gap until new technologies become available. This may be earlier the case than predicted elsewhere if in addition, high permit prices result in electricity prices of almost 8 euro cent per kilowatt hour under oligopolistic competition.

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