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International Journal of Greenhouse Gas Control

Comparison of carbon capture and storage with renewable energy technologies regarding structural, economic, and ecological aspects in Germany

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ARTICLE INFO

Article history:
Received 31 July 2006
Received in revised form
24 January 2007
Accepted 26 January 2007

Keywords:
Carbon capture and storage (CCS)
Life cycle assessment
Prospective LCA
Renewables
Electricity

ABSTRACT

For the option of "carbon capture and storage", an integrated assessment in the form of a life cycle analysis and a cost assessment combined with a systematic comparison with renewable energies regarding future conditions in the power plant market for the situation in Germany is done.

The calculations along the whole process chain show that CCS technologies emit per kWh more than generally assumed in clean-coal concepts (total CO_2 reduction by 72–90% and total greenhouse gas reduction by 65–79%) and considerable more if compared with renewable electricity. Nevertheless, CCS could lead to a significant absolute reduction of GHG-emissions within the electricity supply system.

Furthermore, depending on the growth rates and the market development, renewables could develop faster and could be in the long term cheaper than CCS based plants.

Especially, in Germany, CCS as a climate protection option is phasing a specific problem as a huge amount of fossil power plant has to be substituted in the next 15 years where CCS technologies might be not yet available. For a considerable contribution of CCS to climate protection, the energy structure in Germany requires the integration of capture ready plants into the current renewal programs. If CCS retrofit technologies could be applied at least from 2020, this would strongly decrease the expected CO_2 emissions and would give a chance to reach the climate protection goal of minus 80% including the renewed fossil-fired power plants.

1. Introduction

Long-term energy system scenarios usually show a trend towards reducing coal as a source of energy for climate protection reasons. However, coal is the most abundant fossil fuel and many countries have considerable amounts within their borders. The question therefore arises how coal can be used in the future in a more environment-friendly way. In this regard, the option of "carbon capture and storage" (CCS) is discussed. At present there are still many unanswered

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doi:10.1016/S1750-5836(07)00024-2

questions regarding safe, socially compatible as well as ecological and economic sound applications of CCS. A future oriented integrated assessment in form of a life cycle analysis (ecological balance) and a cost assessment combined with a systematic comparison with other measures of CO_2 reduction options (renewable energies, energy efficiency measures) till now has been missing. These questions are examined in an interdisciplinary project considering the situation in Germany, coordinated by the Wuppertal Institute for Climate, Environment and Energy (WI et al., 2007).

This paper is organized as follows. Section 2 gives a brief outline of the underlying assumptions (on fossil fuel price development as well as on CCS based and renewable based power plants) and the methodology used for ecological and economic assessment. Section 3 presents the models' results which are discussed in Section 4. The paper closes with some conclusions in Section 5.

2. Methodology

2.1. Assessment methods

2.1.1. *Life cycle assessment*

The ecological assessment of technologies and scenarios is done via a life cycle analysis (LCA). An LCA assesses the resource consumptions and emissions occurring along the whole life cycle of a product that means the extraction of raw materials, their processing, the materials' transport, the manufacture of the product, its use, dismantling, and disposal. While the standards ISO 14.040ff (Guinée, 2002; ISO, 1997) state extended requirements on an LCA including an external review process, in this study only a screening LCA is carried out. A full LCA requires more detailed data which are not all available for this future oriented assessment at this state of development. The energy and materials used for production, operation, and dismantling of the considered technologies are modelled in a material and energy flow network using the software Umberto (IFEU and IFU, 2006). As Fig. 1 shows, material flow networks consist of three elements: transitions, places and arrows. *Transitions* stand for the location of material and energy processes (e.g. the transition *Pulverised hard coal-fired power plant*). They play a vital role in material flow networks because material and energy transformations are the source of material and energy flows. Another defining characteristic of material flow networks is the concept of *places*, represented by circles. Places separate different transitions, which allows a distinct analysis of every transition. *Arrows* show the path of material and energy flows between transitions and places. Finally, every transition can represent another material and energy (sub-)network which results in a hierarchical structure (see the subnet on level 2, representing the former mentioned power plant transition in detail).

The framework to carry out this LCA is defined as follows:

- The reference year is 2020 when the first commercially operated power plant including CCS is expected to start operation.
- The reference area is Germany; that means LCA modules describing power plants and fuel cycles provided in Germany or Europe are used.

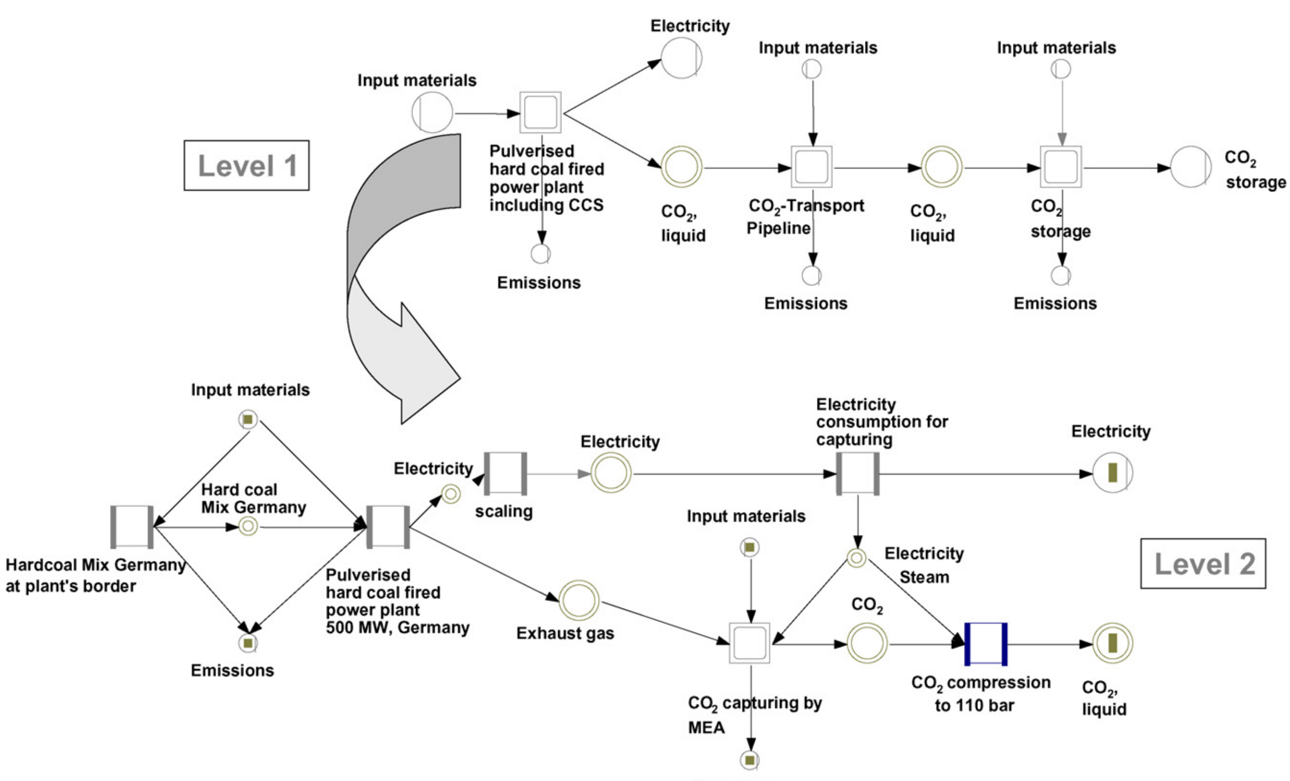

Fig. 1 – Material and energy flow network of a coal-fired power plant including CO_2 capture and storage.

- The functional unit is chosen as 1 kWh electricity delivered to the power grid.
- The impact categories are chosen according to the ''UBA-Verfahren'' which is an impact assessment method developed by UBA, the German Federal Environmental Agency (UBA, 1995, 1999).

In contrary to conventional LCA, this assessment covers technologies lying in the future (called a prospective LCA). To consider future conditions higher efficiencies of the power plants are assumed (see Section 2.2). Furthermore, sensitivity analyses on crucial parameters (hard coal methane emissions, leakage rates, CO_2 capture rate, and operation materials) are done.

Life cycle assessments of conventional power plants as well as fuel processes and gas pipelines are taken from the Umberto LCA database (IFEU and IFU, 2006) and the ecoinvent database (Ecoinvent, 2006). Future technologies like IGCC and capturing methods are modelled according to literatures (Briem et al., 2004; IPCC, 2005; Göttlicher, 1999). The high voltage direct current (HVDC) transmission system needed for the long distance transport of renewable electricity from wind and solar thermal power plants is modelled in May (2005), the LCA for wind power plants is taken from Bruno (2003) and Chataignere and Boulch (2003), the LCA for solar thermal power plants from Viebahn (2004).

2.1.2. *Experience curves and learning rates*

For cost calculations and comparisons, an interest rate of 10%/a and an amortisation period of 25 years are assumed. Future cost development will follow mass market effects and technology improvements and is modelled using experience curves and corresponding learning rates. An experience curve describes how unit costs decline with cumulative production. The progress of cost reduction is expressed by the progress ratio (PR) and the corresponding learning rate (LR). A progress ratio of 90%, for example, means that costs are reduced by 10% each time the cumulative production is doubled and therefore the learning rate is defined as 10% (Neij et al., 2003).

Fossil-fired power plants without CCS are technical mature (or expected to be mature in 2020 in case of an IGCC) so that only minor improvements are expected from 2020. In contrast, capture and storage technologies will be only at the beginning of their experience curve. CCS based power plants are modelled using an economy of scale of 12% following Rubin et al. (2004) who stated a rough PR of 88% for capture technologies using analogy with sulphur capture systems.[1]

Assumptions for renewable energy technologies (learning rates, world wide cumulated installed capacities) are used as defined in former DLR studies (BMU, 2004; WI et al., 2005). They are based on progress ratios between 75 and 90% realised for renewables in the last decades and are expected to increase to values between 88 and 95% until 2050. For example, the following PR are applied for the calculations of future technologies: photovoltaics 90%, biomass 95%, solar thermal electricity 88.5%, and wind 91%. It should be noted that these progress ratios are based on scenarios describing a worldwide ambitious advancement and diffusion of renewable energies as described in BMU (2004).

Of course, future cost development is connected with uncertainties – it may be possible that neither CCS technologies nor renewables will reach the predicted cost reduction.

2.2. *Fossil fuel price development in the future*

For the fossil fuels' price increase a lower and an upper variant are chosen (see Fig. 2a). The lower one is based on the study ''Energiereport IV'' (EWI and Prognos, 2005) describing a business-as-usual approach until 2030 based on the oil and natural gas prices before the recently price increases. The upper variant based on BMU (2004) takes into account recent price increases and extrapolates them. Additional to fuel prices in both scenarios a CO_2 penalty is being added considering that the German power plants are part of the European CO_2 emission trading system. EWI and Prognos

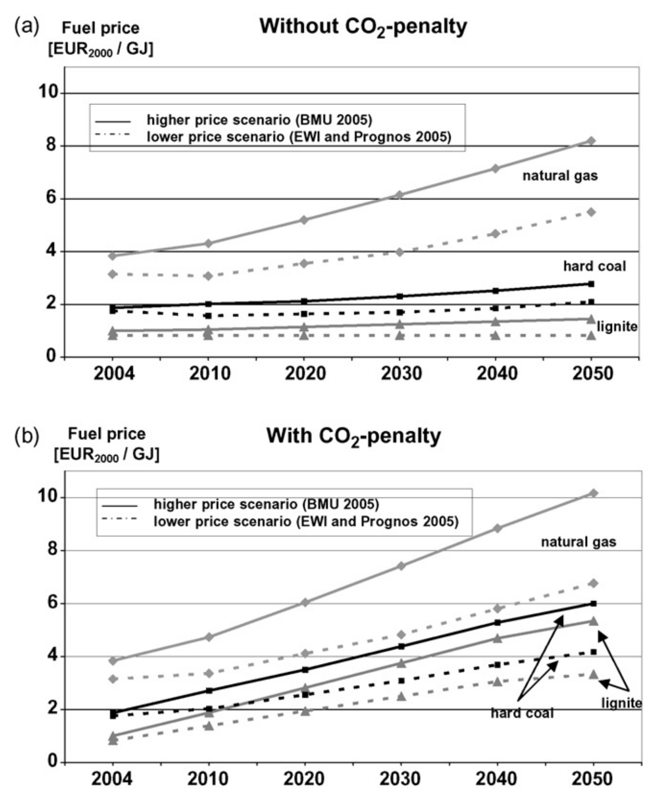

Fig. 2 – Two different fossil fuel price developments for natural gas, hard coal, and lignite: lower price increases by EWI and Prognos (2005) (dashed lines), higher ones by BMU (2004) (solid lines). (a) Prices without CO_2 penalty; (b) prices with CO_2 penalty (certificate prices developing from 5 €/t in 2010 to 22.5 €/t in 2050 in case of the lower scenario and from 7.5 €/t in 2010 to 35 €/t in 2050 in case of the higher price scenario).

[1] Rubin recently published new calculations for complete power plants with capture. According to Rubin (2006), progress ratios for the full plant are higher (that means the cost decrease is lower) than for capture systems because many of the plant components are already mature so their costs change very slowly with new capacity compared to the capture system. That means that our calculation benefits CCS based electricity costs.

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Table 1 – Data of fossil-fired power plants to be installed in 2020

Data	Pulverised hard coal	IGCC[a] (hard coal)	Pulverised lignite	NGCC[b] (natural gas)
(A) Without CO_2 capture				
Power (MW_{el})	700	700	700	700
Operating time (h)	7000	7000	7000	7000
Efficiency (%)	49	50	46	60
Investment cost (€/kW_{el})	950	1400		400
Operating cost (€/kW_{el},a)	48.3	53		34.1
LEC[c], lower fuel price (ct_{EUR}/kWh_{el})	3.51	4.27		3.56
LEC[c], higher fuel price (ct_{EUR}/kWh_{el})	4.89	5.66		4.94
Fuel's CO_2 intensity (g CO_2/MJ)[d]	92	92	112	56
Electricity's CO_2 intensity (g CO_2/kWh_{el})	676	662	849	337

Data	Pulverised hard coal		IGCC[a] (hard coal)	Pulverised lignite	NGCC[b] (natural gas)
(B) With CO_2 capture					
Capturing method	Post-combustion	Oxyfuel	Pre-combustion	Post-combustion	Post-combustion
Scrubber	Chemical (MEA)[e]	Only condensing	Physical (Rectisol)	Chemical (MEA)[e]	Chemical (MEA)[e]
Power (MW_{el})	570	543	590	517	600
Efficiency (%)	40	38	42	34	51
Decrease of efficiency (%-points)	9	11	8	12	9
Investment cost (€/kW_{el})	1750		2100		900
Operating cost (€/kW_{el},a)	80		85		54
LEC[c], lower fuel price (ct_{EUR}/kWh_{el})	5.52		6.06		5.04
LEC[c], higher fuel price (ct_{EUR}/kWh_{el})	6.13		6.64		6.16
Capture rate (%)	88	99.5	88	88	88
CO_2 to store (Mt/a)	3.570	4.249	3.400	5.113	1.704

[a] IGCC, integrated gasification combined cycle.
[b] NGCC, natural gas combined cycle.
[c] LEC, levelised electricity generation costs; interest rate: 10%/a, lifetime: 25 a, annuity: 11%/a.
[d] Source: UBA (2003).
[e] MEA, monoethanolamine.

(2005) assume a very low CO_2 certificate price starting from 5 €/t in 2010 to 15 €/t in 2030, here extrapolated to 22.5 €/t for 2050. BMU (2004) considers a stronger but moderate price development from 7.5 €/t in 2010 to 35 €/t in 2050. These prices are allocated to the fossil fuels according to their specific CO_2 emissions (see Fig. 2b) which especially burdens coal with its high carbon content.

2.3. Assumptions on fossil-fired power plants and sequestration technologies

2.3.1. Power plants

The fossil-fired power plants (each of 700 MW_{el} and 7000 h/a in operation) are modelled to be located in the ''Ruhrgebiet'' (western part of Germany), one of the biggest industrial areas in Europe with a long tradition of coal based electricity production. A future situation (2020) is regarded by using higher efficiencies than in case of today's power plants (Table 1).

2.3.2. Carbon dioxide capture

To capture the carbon dioxide, the three most common methods (pre-combustion, post-combustion and oxyfuel combustion) are considered. The economic data are derived from Williams (2002), IEA (2003), Hendriks et al. (2004), and IPCC (2005) and is applied to the pulverised hard coal power plant, the IGCC, and the NGCC regarding the economic parameters mentioned above.

2.3.3. Carbon dioxide transport and storage

The CO_2 captured at the power plants is compressed to 11 MPa (110 bar) and assumed to be transported via a 300 km pipeline to North Germany where a lot of empty natural gas fields exist. According to the publications mentioned in the former paragraph, the costs for liquefaction, transport, and storage are estimated to 0.2 ct_{EUR}/kWh_{el} (NGCC) and 0.4 ct_{EUR}/kWh_{el} (coal-fired power plants). In the reference case, no underground storage leakage rate is assumed. Due to the lack of data, the storage step cannot yet be modelled within the LCA and is estimated.[2]

2.4. Assumptions on renewable power plants

As an example of renewable energies wind offshore power plants located in the deep North Sea and solar thermal power plants to be built in North Africa are considered within the LCA. They are expected to run economically in the year 2025

[2] Usually, the transport costs are cheaper than the storage costs depending on the site. Within our case study, a transport distance of 300 km and the storage in a natural gas field onshore is assumed. For this case, Hendriks et al. (2004) specify transport cost of 5 €/t CO_2 and storage cost of 1.1–3.6 €/t CO_2, depending on the storage depth. Assuming a mean of 2.35 €/t CO_2, the storage step requires about 50% of the costs caused by the transport process. As a first approximation, the same share is used to calculate the impacts on the environment which are caused by the infrastructure needed for the storage system.

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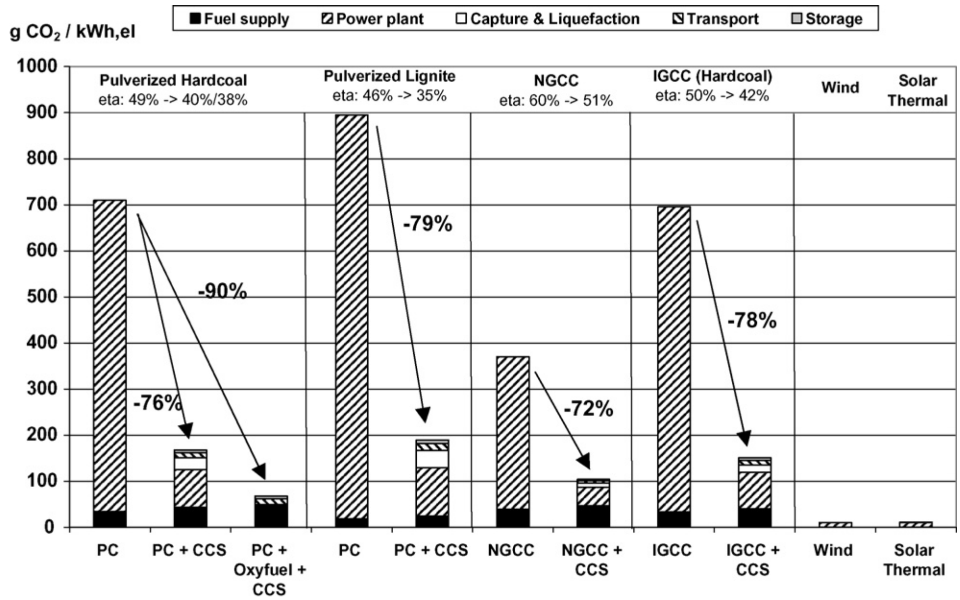

Fig. 3 – Comparison of CO_2 emissions for pulverised coal power plants (PC), an NGCC, and an IGCC (each of them excluding CCS and including CCS with a CO_2 capture rate of 88% for post- and pre-combustion and of 99.5% for oxyfuel combustion), and renewables (wind offshore, solar thermal electricity).

(DLR, 2006). The electricity is assumed to be transported via high voltage direct current (HVDC) transmission lines to the "Ruhrgebiet" to consider the same location as chosen for the fossil-fired power plants. Data for cost development of renewables and transmission lines is taken from BMU (2004) and DLR (2006).

3. Results

3.1. *Life cycle assessment of CCS based fossil-fired power plants and of renewables*

3.1.1. *CO_2 emissions and global warming potential*

The fossil-fired power plants described in Table 1 are compared with each other (each of it without and with CCS) and with electricity delivered from wind and solar thermal power plants. Figs. 3 and 4 show the results for the CO_2 emissions as well as for the global warming potential (GWP 100) measured in terms of CO_2 equivalents[3] and their possible reduction by implementing CCS. The life cycle emissions are shown for the five phases fuel supply, power plant (electricity production), capture and liquefaction, transport, and storage.

Although the carbon dioxide locally emitted at the power stations' stack are reduced by 88%, the life cycle assessment for post- and pre-combustion processes shows lower reductions of CO_2 emissions (minus 72–79%) as well as of greenhouse gases in total (minus 65–79%). Oxyfuel combustion with a CO_2 capture rate of 99.5% results in a reduction of 90% (CO_2) and 78% (GHG), respectively. This is due to the fact that capture, transport, and storage require a lot of additional energy and that CO_2 and methane are also emitted during the fuel supply chain (mining industry, transport). In comparison, renewable electricity causes 1–3% of the CO_2 emissions and 1–4% of the greenhouse gas emissions in relation to the different fossil-fired power plants (mainly emitted during the power plants' manufacturing).

3.1.2. *Further impact categories*

In addition to the global warming potential several baseline impact categories have to be considered during an LCA. Within this screening LCA, the categories photo-oxidant formation, eutrophication, acidification and human toxicity (PM10-equivalents and cancer risk) completed by the cumulated energy demand (CED) are selected. Fig. 5 shows by way of the pulverised hard coal power plant (PC) how these categories would change through introducing CCS. All impact parameters increase by about 40% which is again due to the additional energy consumption (increase by 34%) required for the different phases. Actually, photo-oxidant formation shows an additional increase by about 60 percentage points (in total: 96%), caused by the monoethanolamine's production used as a solvent during the capture process. Not considered at this stage is that some flue gas emissions (SO_2, dust, HCL) will react with the solvent. This would lead to a decrease of the power plants' share for the categories acidification and PM10-equivalents.

3.1.3. *Sensitivity analysis of the methane emissions occurring during mining processes*

In contrary to common life cycle assessments, which concern existing technologies in this study, a future oriented LCA is carried out. Therefore, it is necessary to have a look at crucial parameters not known in detail at the moment. One of these

[3] As greenhouse gas emissions carbon dioxide, methane, and N_2O are accounted for, weighted with the CO_2-equivalent factors 1, 21, and 310, respectively (IPCC, 2001).

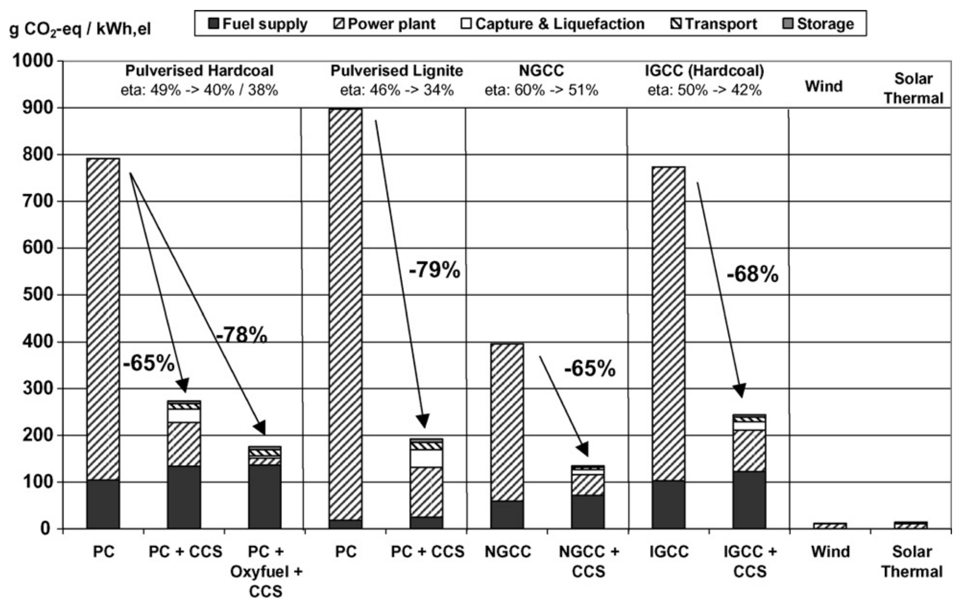

Fig. 4 – Comparison of greenhouse gas emissions (measured as GWP 100) for pulverised coal power plants (PC), an NGCC, and an IGCC (each of them excluding CCS and including CCS with a CO_2 capture rate of 88% for post- and pre-combustion and of 99.5% for oxyfuel combustion), and renewables (wind offshore, solar thermal electricity).

parameters is the methane emissions released by coal mining processes causing a much higher climate impact than the same amount of carbon dioxide. In Germany, more and more companies try to exhaust these emissions and use them energetically in combined heat and power plants. Currently, German hard coal has a share of 62% in the German hard coal mix. Therefore, in a sensitivity analysis, a methane emissions' reduction during the German mining process (currently 454 kg/TJ hard coal) by 20, 40, 60, and 80% and its impacts on the global warming potential is modelled for the pulverised hard coal power plant. Fig. 6 shows that the reference scenario based GHG-reduction of 65% could be reduced by further 10 percentage points if the German hard coal methane emissions would be reduced by 80%. In this case, the hard coal power plants' emissions equal with those of the CCS based lignite-fired power plant shown for comparison to the right.

3.1.4. *Sensitivity analysis of storage leakage rates*

Another value not known is the expectant leakage rate. At the moment nobody is guaranteeing a leak-proof storage system as assumed in the reference case. The IPCC report states that "if continuous leakage of CO_2 occurs it could at least in part offset the benefits of CCS for mitigating climate changes" (IPCC, 2005). Therefore, in a sensitivity analysis, a leakage rate "L_rate" is assumed varying from 0.1 to 0.0001%/a. The

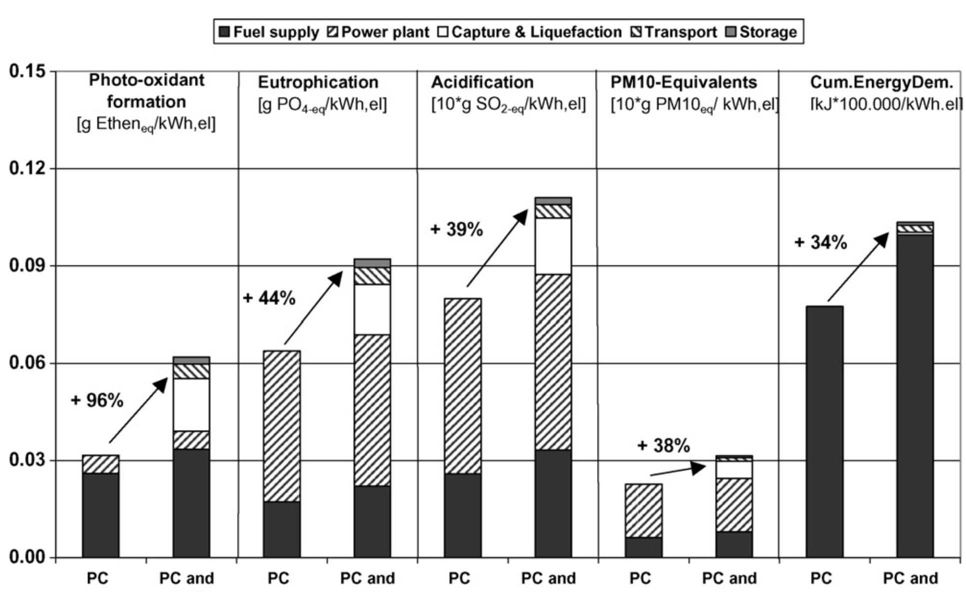

Fig. 5 – Further impact categories illustrated by way of the pulverised hard coal power plant (CO_2 capture rate of 88%).

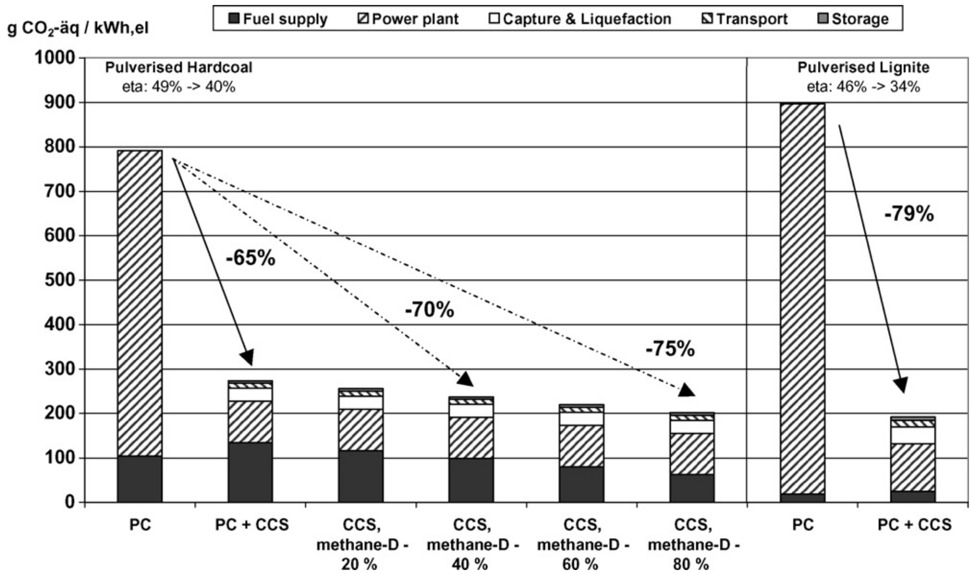

Fig. 6 – Sensitivity analysis 1: greenhouse gas emissions of a hard coal-fired power plant depending on a change of the methane emissions from hard coal mining and comparison with a lignite-fired power plant (each of them with a CO_2 capture rate of 88%).

full rate L_rate is valid beginning from the time *T* when the storage is completely filled. During the storage process ($t \leq T$) a smaller rate (calculated as L_rate $\times$ t/T) is assumed. Depending on the time in which the CO_2 is released into the atmosphere the emissions are (arbitrarily) accounted for middle-term (up to 10,000 years) and long-term (>10,000 years) emissions (Fig. 7).

In case of a leakage rate of 0.1%/a, the whole carbon dioxide stored in the underground would be released into the atmosphere within the next 6000 years. Assuming smaller leakage rates the release would move to time horizons longer than 10,000 years more and more – but in total the same emissions occur as in case of higher leakage rates as an LCA does not differentiate between emissions at different points of time. In this case, the smallest leakage rate thinkable would mean that the application of CCS causes a 31% increase of CO_2 emissions and therefore of the global warming potential. The problem arises how to handle such a tradeoff between current and future impacts. Therefore, an LCA method has to be developed how to discount CO_2 emissions occurring in the remote future as it was done by Hellweg et al. (2003) for waste incineration, where immediate emissions to the air had to be weighted against future emissions of slag landfills.

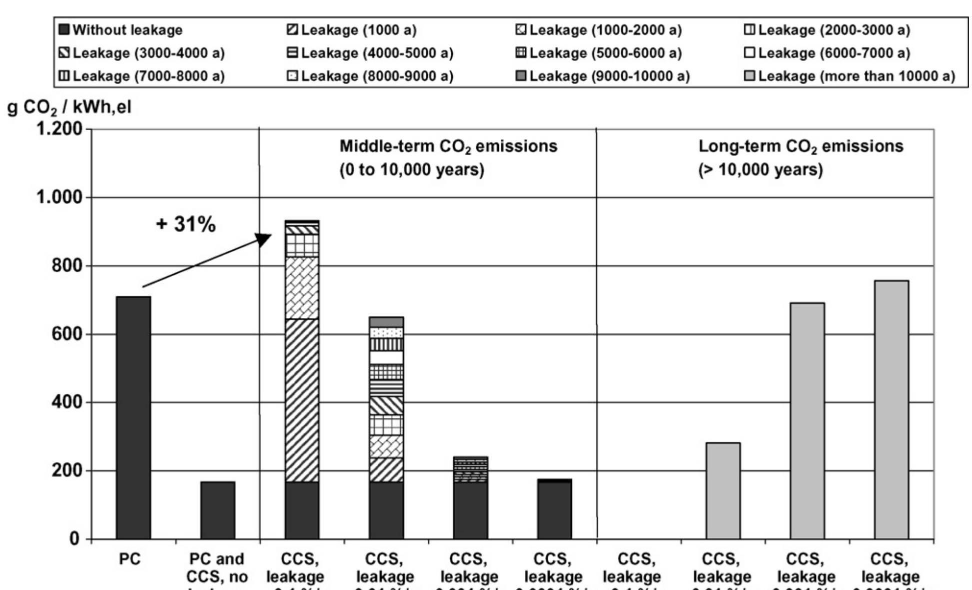

Fig. 7 – Sensitivity analysis 2: assuming different storage leakage rates (0.1–0.0001%/a). Comparison of middle-term and long-term release of carbon dioxide by way of the pulverised hard-coal power plant (CO_2 capture rate of 88%).

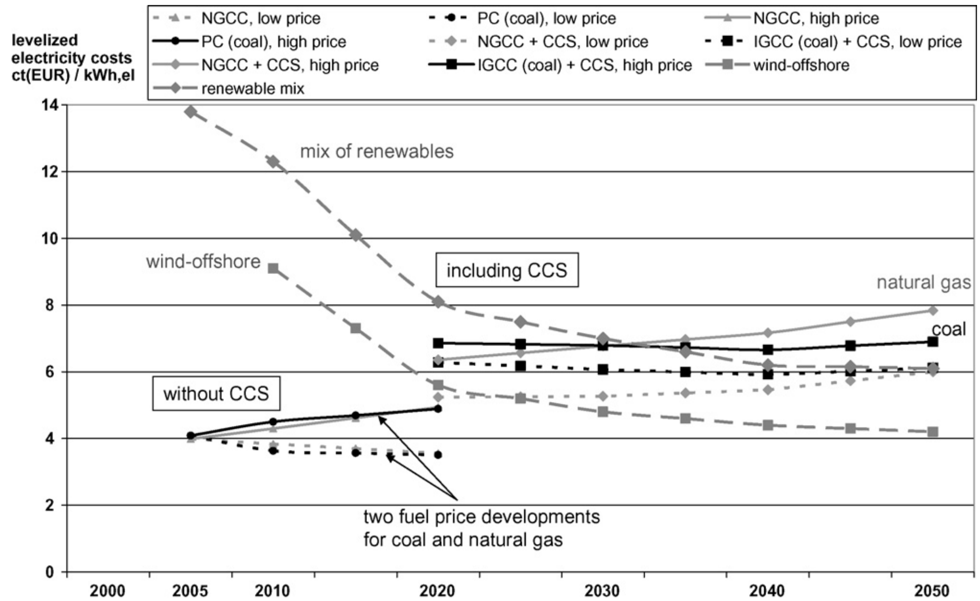

Fig. 8 – Levelised electricity generation costs in Germany – comparison between CCS based power plants and renewable power plants between 2005 and 2050 (each with a low and a high development of fossil fuel prices; interest rate = 10%/a).

3.2. *Economic assessment of CCS based power plants versus renewables*

Fig. 8 shows a levelised electricity cost generation (LEC) comparison of fossil fuel power stations and plants based on renewable energies for a time period until 2050 regarding the situation in Germany. The calculation until 2020 is based on the installation of new natural gas combined cycle (NGCC) plants as well as new pulverised hard coal plants both without CCS. For the situation after 2020, new CCS based hard coal-fired IGCC as well as new CCS based NGCC are assumed to be installed. While the fossil power plants LEC develop from 4 ct_{EUR}/kWh_{el} in 2005 to 3.5 ct_{EUR}/kWh_{el} (lower price variant) and to 4.9 ct_{EUR}/kWh_{el} (upper price variant) in 2020, the implementing of CCS technology causes an additional cost jump of about 50% in 2020. CCS based power plants finally reach LEC of 6 and 6.9–7.8 ct_{EUR}/kWh_{el}, respectively. Both plants follow a similar cost increase caused by different reasons: in the case of the NGCC, the cost development is influenced mainly by the natural gas price increase whereas in the case of IGCC it is caused mainly by the consistently rising CO_2 certificate price.

Renewable electricity production is distinguished between wind-offshore power plants on the one hand and a mix of all renewables on the other hand regarding the German situation, likewise. Their cost development is based on learning rates as explained in Section 2.1. Especially, the wind power plants cost curve is based on the newest cost development review and predictions on future offshore investment costs provided by the German government (BMU, 2007).

Assuming mass market effects and technology improvements the LEC of new installed power plants can be decreased from 13.1 ct_{EUR}/kWh_{el} currently (2006) realised in Germany to 8.1 ct_{EUR}/kWh_{el} in 2020 (within a range of 5.6 ct_{EUR}/kWh_{el} for wind-offshore and 19.6 ct_{EUR}/kWh_{el} for photovoltaics). In 2050, a further cost reduction to 6.1 ct_{EUR}/kWh_{el} (wind-offshore: 4.2 ct_{EUR}/kWh_{el}) is expected.

According to the upper variant of medium prices of fossil fuels a mix of renewable energies can become more economic than CCS based gas-fired power stations starting from 2031. The intersection with coal-fired power stations including CCS moves later to 2033. With smaller price increases the intersection moves to 2050. Electricity from wind-offshore power alone will become cost competitive around 2020. Since wind power plants cannot just replace fossil-fired power plants in the grid the mix of renewables (which can reach shares of more than 65% in the electricity mix in 2050 according to BMU 2004, see Fig. 11) is the more relevant comparison.

3.3. *Energy economic view of CCS application in Germany*

The time when CCS technology is introduced into the market will have an impact on climate policy and energy economics. Substantial factors are the average running time of power stations as well as the availability of CCS technologies and the development of energy demand over time. Fig. 9 shows that there is a substantial need to replace power stations in Germany in the coming two decades (including the substitution of present fossil-fired as well as nuclear power plants). But within this period CCS technologies will not be available on an industrial scale (for example, between 2002 and 2020, 60 GW of fossil-fired power plant capacity are expected to be retired).

In March 2006, the German power utilities announced a first power plant renewal program. Thirty-two power plants (most of them fired by coal, some few fired by natural gas) with an installed power of 18 GW will be modernized in the next decade. This leads to a substantial structural determination of Germany's future electricity system. On one hand, the CO_2 emissions are reduced definitely by replacing for example old coal-fired power plants with an efficiency of 36–38% by new

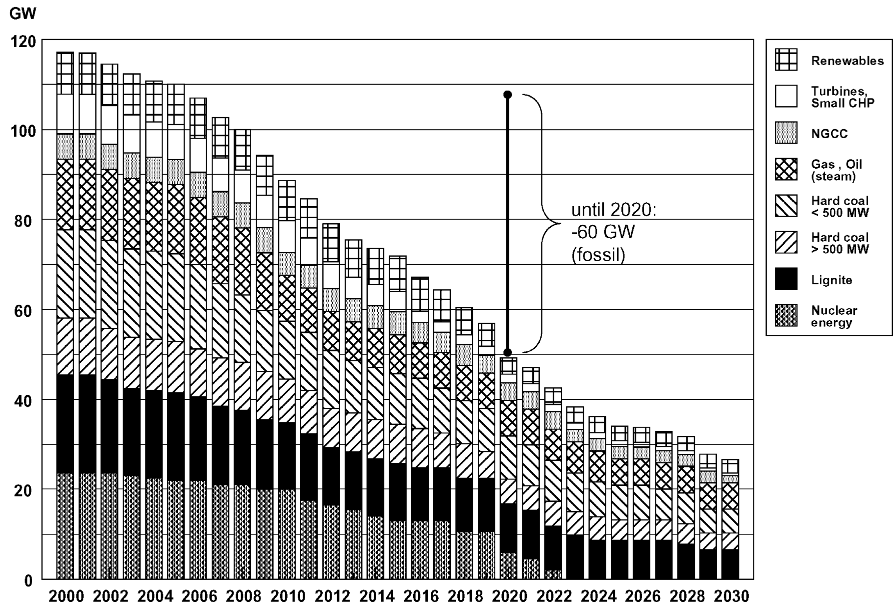

Fig. 9 – Decommissioning of presently installed power plant capacity in Germany (regarding a running time for fossil power plants of 40 years, for small combined heat and power plants (CHP) of 30 years, and for renewables of 20–50 years).

plants with an efficiency of 46%. This means a relative reduction of one quarter or at least one-fifth and could significantly contribute to the given climate protection targets. On the other hand, in absolute numbers these power plants cause CO_2 emissions of about 65 up to 70 Mt/a which are determined over the next 40 years and could prevent not only the investors themselves but also the government from establishing an effective climate protection regime.

This aspect is crucial so far as currently the rules are determined and defined for the emission allowances of fossil-fired power plants within the discussion of the National Allocation Plans (NAP) as central element of the European emission trading system. For Germany, the ongoing discussion shows that once more specific incentives shall be integrated into the NAP to accelerate the construction of those new power plants substituting older plants with less

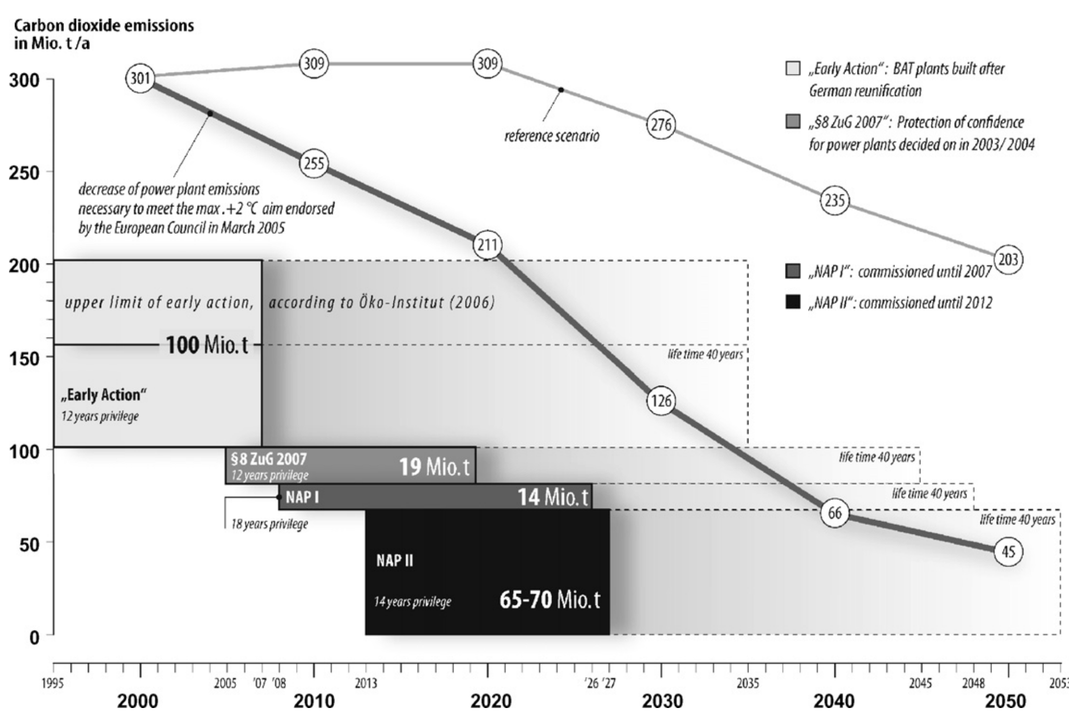

Fig. 10 – Power plant capacity planned in Germany (18 GW) at odds with ambitious mitigation aims – a perspective development of CO_2 emissions following the currently discussion within the National Allocation Plan.

overall efficiency. These kinds of power stations shall receive guaranteed emission rights over a time period of at least 14 years. Together with early actions (which in this case means power plants built within the 1990s, especially in the eastern part of Germany) a structural determination of CO_2 emissions (depending on assumptions about load factor, energy prices, and merit order) between 150 and nearly 200 Mt CO_2 is resulting. In the long term, a contradiction between CO_2 emissions from central power plants and necessary CO_2 reduction goals is obvious. Fig. 10 makes this aspect clear regarding the requested ambitious climate reduction target by the Intergovernmental Panel on Climate Change (IPCC) and other climate scientists guaranteeing that the impacts of climate change do not exceed the ecological limits too far.

Against this background, the crucial question is, how should or how can the potential conflict be handled. One option which is already in discussion is the question how far technologies aiming for a CO_2 capture could be retrofitted in existing power plants and how far "capture ready" concepts can be foreseen for the power plants to be constructed within the next years. In general, CO_2 sequestration is not a state of the art technology, several R&D targets have yet to be fulfilled. But from today's technology point of view, the use of CO_2 capture in already existing plants should be possible at least starting from the year 2020. Hence, to several restrictions, it cannot be expected that the majority of existing power plants will be retrofitted with CO_2 capture units. Therefore, a discussion of the structure building process related to the currently announced plans of the energy utilities to install lot's of new fossil fuel power plants is more than necessary.

In that context, a comparison with alternative scenarios about the future development of the electricity structure in Germany which was elaborated for the German Ministry for Environment (BMU) makes clear that there is a strong alternative to the ongoing process of substitution old and central power plants by new ones. In contrast to the current situation, a climate protection scenario as developed in BMU (2004) with the aim of reducing the CO_2 emissions by 80% in 2050 is based on a broader mix of options, putting the further integration of renewable energies and decentralized cogeneration systems together with additional efforts regarding energy efficiency. No CCS is included in this calculation. For conventional condensing power plants, no more than just 65–70 Mt/a CO_2 emissions are allowed in the middle of the century (see Fig. 11). The crucial point is that this amount will exclusively be taken up by the currently planned power stations yet.

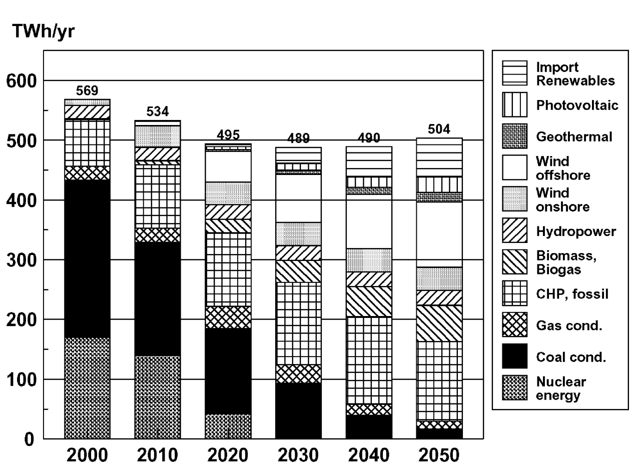

Fig. 11 – Contribution of conventional condensing power plants within a climate protection scenario for the German electricity production until 2050 (source: BMU, 2004).

4. Discussion

4.1. *Life cycle assessment*

The current discussion only focuses on the reduction of CO_2 from the operation of the power stations themselves. Additionally, we argue, the emissions of the pre-processes (e.g. coal extraction and transport to the power plant) as well as transport and storage of CO_2 have to be included. Furthermore, according to the Kyoto Protocol not only the CO_2 emissions, but also the greenhouse gases in total have to be reduced—in the case of Germany by 21% until the year 2010. Therefore, it is necessary to balance not only the CO_2 emissions but the greenhouse gas emissions in total. It is notable that the cleanest power plant *without* CCS (natural gas combined cycle) causes only 45% more emissions (400 g CO_2-equ./kWh) than the worst power plant *with* CCS (pulverised hard coal with 274 g CO_2-equ./kWh). Even if regarding a combined use of heat and electricity and an according credit for avoided heat generation the NGCC without CCS would be in the same or a better range than the coal plant with CCS.

In each case, CCS requires an additional energy consumption of 23–40%, depending on the power plants' efficiency. Considering the pulverised hard coal plant, for example, this results in 37–96% higher values for the other life cycle impact categories which should not be neglected in the environmental discussion.

The first sensitivity analysis showed by way of a pulverised hard coal-fired power plant that a methane emissions' reduction of 80% during the mining process would result in a total greenhouse gas reduction of 75% (which means a 10 percentage points increase compared to the former calculated 65% reduction). This means that a similar reduction potential as calculated for the lignite-fired power plant (minus 79%, see Fig. 4) could be reached.

The second sensitivity analysis raised the question how to assess the impacts of carbon dioxide released thousands of years later than stored in geologic formations. As an LCA usually does not differentiate between emissions at different points of time a methodology has to be developed how to handle such a tradeoff between current and future impacts. CO_2 emissions released in 10,000 years cannot be counted for the GWP 100 which considers the global warming potential with a time horizon of only 100 years.

4.2. *Economic assessment*

The economic assessment results show a trend towards the renewable energies even if it is taken into consideration that the calculations are based on only moderate fossil fuel price increasing in the future. The "lower price scenario" assuming an almost constant fuel price development seems to be unrealistic considering the price development in the recent years. The ''upper variant'' updates the current development whereas an extreme fuel price increase has not been taken into consideration so far.

Whatever price scenario is taken, it is clear that climate protection measures using fossil energy technologies are always depending on fuel price development, a definite advantage for renewables using their ''fuel'' mostly for free. But it should be taken into consideration that the renewables' price development will only occur as illustrated under an ambitious extension of renewable power plants—a precondition for mass market effects and technology improvements and therefore a cost decrease.

The coal-fired power plants' price increase in the future is based on increasing prices for CO_2 certificates. One could argue that a certificate's price increase to 35 €/t in 2050 is unrealistic and a lower increase should be assumed. On the other hand, this would mean that CCS power plants would not become competitive and therefore not be built because of their higher levelised electricity generation costs. The conclusion is that CCS technologies will get at the same eye level as renewables (provided a CO_2 reduction goal of minus 80%) which is useful for both technology lines.

Some additional issues have to be included to get a comparison under ''real'' market conditions. Only through a comparison of electricity supply structures with different shares of renewables the influence of issues like security of supply, advantages of decentralised energy production systems, intermittency problems usually faced by wind or photovoltaic sources on the cost development can be evaluated. On the other hand, for wind-offshore power plants 4000 full load hours are expected. Even solar thermal power plants with LEC near to wind-offshore plants could provide Europe with firm power capacity from 2020 and run around-the-clock using efficient thermal storage systems as provided in DLR (2006).

4.3. *Energy economic view*

From an energy economic perspective, the development of the electricity generation and the resulting demand for new plants over time is the crucial factor determining the potential for CCS in Germany. The main impact factors are the average operation time of the power plants, the availability of CCS technology for the power plant market, the nuclear energy policy, the resulting electricity demand, and the fossil fuel mix. Regarding an ambitious sustainable electricity scenario with an ecologically optimized extension of renewable energy utilization, the option CCS might come too late for Germany. Concerning this background, the question of the retrofit possibility of CCS arises: To what extent can conditions be created, so that a later coupling of a CO_2 capture process is technically possible and can be applied with the smallest auxiliary costs? For sure cost reduction might be necessary for CCS in general as well as a significant limitation of additional energy demand (or in other word efficiency losses) is needed as foreseen for the currently planned power plants. For retrofitting concepts additional aspects are important. Especially specific properties of the place where the power stations are running are important. The selection of places may be influenced by a later CO_2 capturing (e.g. restrictive space for additional components, primary energy supply structure, access to a CO_2 transport infrastructure) as well as specific technology aspects (e.g. additional requests for reduction of SO_2 in the exhaust steam as precondition of a viable regeneration of amines if a typical MEA flue gas scrubbing solution is selected). In that context, it should be discussed more in detail if and how power stations could be prepared for the later installation of a CO_2 capture unit and which kind of incentives are necessary to go in that direction. In some countries (e.g. The Netherlands), rules are already in discussion making ''capture ready'' a legal precondition for the installment of new power plant stations. Furthermore, rules in context of the National Allocation Plans are thinkable where only those power plants with elaborated ''capture ready'' concepts get guaranteed emission allowances for a long time period.

5. Conclusions

This analysis shows that a future oriented approach is necessary to assess new technologies depending on several parameters currently not known. Most studies only consider state-of-the-art conditions or – if at all – a situation in 2020, when CCS power plants are expected to run commercially. Our results show that conclusions based only on a year 2020 analysis could lead to wrong and insufficient results and clarify the necessity to think under long term conditions and to analyze the impacts of measures launched today on the time frame having long term targets in mind.

Furthermore, looking on new technologies like CCS, not only single, isolated aspects should be investigated but brought together as done in this integrated assessment. For the German situation this approach arrives at the following conclusions:

- CCS technologies emit per kWh more than generally assumed in clean-coal concepts (total CO2 reduction by 72–90% and total greenhouse gas reduction by 65–79%) and much more if compared with renewable electricity – nevertheless, CCS could lead to a significant absolute reduction of GHG-emissions within the electricity supply system;
- depending on the growth rates and the market development, renewables could develop faster and could be in the long term cheaper than CCS based plants;
- especially, in Germany, CCS as a climate protection option is phasing a specific problem as an huge amount of fossil power plants has to be substituted in the next 15 years where CCS technologies might be not yet available. For a considerable contribution of CCS to climate protection the energy structure in Germany requires the integration of capture ready plants into the current renewal programs. If CCS retrofit technologies could be applied at least from 2020, this would strongly decrease the expected CO_2 emissions and would give a chance to reach the climate protection goal of minus 80% including the renewed fossil-fired power plants.

All in all it should be kept in mind that there are a lot of uncertainties in both the renewables as well as the CCS technology scenarios. For example, if the proposed cost decrease of renewables for which an ambitious worldwide extension of renewable power plants is assumed will not occur with the assumed speed CCS technology may play an important role to reduce greenhouse gases in the decades from 2020 on. On the other hand, considering a fuel price increase much higher than the steady but moderate increase assumed in the ''upper price scenario'' a contrary development with uneconomical CCS power plants but much more efficient renewables would follow. Therefore, this economic assessment shows one possible development path under specific assumptions regarded in the authors' view as a more likely path.

Finally, we would like to emphasise that our scenario analysis refers to the situation in Germany. For other countries in Europe as well as out of Europe, the energy economic perspective could be very different depending on the power plants' structure, the fuel prices, the CO_2 storage capacity, or even the predicted increasing electricity demand. Especially while looking on countries with an increasing electricity demand and a huge amount of coal resources like China, the necessity of CCS as a strategic climate protection option could be much more evident.

Acknowledgement

The authors gratefully acknowledge the financial support for this project by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.

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