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Integrated assessment of carbon capture and storage (CCS) in the German power sector and comparison with the deployment of renewable energies

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ABSTRACT

If the current energy policy priorities are retained, there may be no need to focus additionally on carbon capture and storage (CCS) in the power plant sector of Germany. This applies even in the case of ambitious climate protection targets, according to the results of the presented integrated assessment study. These cover a variety of aspects: Firstly, the technology is not expected to become available on a large scale in Germany before 2025. Secondly, if renewable energies and combined heat and power are expanded further and energy productivity is enhanced, there is likely to be only a limited demand for CCS power plants, as a scenario analysis of CCS deployment in Germany shows. Thirdly, cost analysis using the learning curve approach shows that the electricity generation costs of renewable electricity approach those of CCS power plants. This leads to the consequence that, from 2020, several renewable technologies may well be in a position to offer electricity at a cheaper rate than CCS power plants. In addition, a review of new life cycle assessments for CO_2 separation in the power plant sector indicates that the greenhouse gas emissions from 1 kW h of electricity generated by first-generation CCS power plants could only be reduced by 68% to 87% (95% in individual cases). Finally, a cautious, conservative estimate of the effective German CO_2 storage capacity of approximately 5 billion tonnes of CO_2 is calculated, including a fluctuation range yielding values between 4 and 15 billion tonnes of CO_2. Therefore, the total CO_2 emissions caused by large point sources in Germany could be stored for 12 years (basic value) or for 8 or 33 years (sensitivity values).

1. Introduction

In Germany, the debate on CCS has gained a particularly high degree of public attention as the country is pursuing ambitious CO_2 mitigation targets of minus 40% by 2020 and at least minus 80–95% by 2050 (both compared to 1990 levels). At the same time, the country is the European Union's (EU) largest coal producer, with about 44% of its electricity supply coming from coal-fired power plants [1]. The heated CCS debate calls for a profound and integrated scientific analysis which takes into account all dimensions affecting the deployment of the CCS technology in Germany – including "hard" and "soft" aspects. "Hard" aspects encompass technical, economic and environmental parameters of CCS, the available national CO_2 storage capacity as well as a long-term scenario analysis of the technology's potential in Germany. "Soft" aspects comprise the role of stakeholders and public acceptance and the regulatory framework for CCS in Europe and Germany. While the Wuppertal Institute together with other research organisations presented a first integrated assessment of CCS for Germany in 2007 which compared the technology's potential with renewable energy technologies [2], in the meantime several determining factors have changed. These are the technical development of both CCS and renewable energy technologies, an increasing critical public discussion on CCS as well as ambitious national and European renewable energy targets set in the EU's "green package" at the end of 2008 [3]. The earlier study was therefore enhanced and updated, leading to the submission of a more comprehensive assessment of CCS than that published 3 years ago [4].

To our knowledge, no similar assessment has been published before, not for Germany or abroad. One integrated assessment available for CCS, published in 2006, refers to the UK [5]. However, it does not include a comparison with renewable energies, nor does it consider the compatibility of CCS with renewable energies and other options within energy scenarios at the UK level. Instead, it covers geological storage, risks and potential impacts of leakage, legal aspects of geological CO_2 storage, technical and economic feasibility, and public acceptability.

The presented paper first describes the methodologies applied in the individual assessment aspects of the study (due to space restrictions, only the "hard" aspects are discussed). The outcome of each assessment step is then shown. Subsequently, the authors combine the assessment dimensions to present an overall result

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from an integrated perspective and to recommend where and how to proceed in the current CCS debate. The paper closes with an outlook on the needs for future research.

2. Methodology

In this paper, an integrated approach is chosen to assess CCS in the power plant sector, since CCS is part of a complex and dynamic energy system. However, each dimension of the system considered in this paper is investigated with its specific scientific methods.

(1) The *large-scale availability of CCS technology* is based on the screening of technical studies, presentations and statements of German and international CCS experts on the current state and expected course of development of CCS in the years ahead. Furthermore, the progress of on-going or planned CCS demonstration projects in Germany was studied.

(2) *Energy scenario analysis* is used to explore the future role CCS could play in the electricity sector in comparison to renewable energies in Germany. Use of CCS is depicted in a scenario family "CCS-REN/CHP", comprising six variants of the expansion of CCS capacity. These scenarios are based on the Lead Scenario 2008 of the German Ministry for the Environment, which aims to reduce energy-related CO_2 emissions by 80% in 2050, compared to the 1990 level. Since neither nuclear energy nor CCS will be used in the base scenario in 2050, a large quantity of both installed capacity (71%) and electricity generation (66%) is based on renewable electricity (130 out of 184 GW and 419 out of 635 TW h/a, respectively). The remaining fossil load is based primarily on coal and natural gas [6].

For our scenarios, it is assumed that energy policy targets set by the German government and incorporated into the Lead Scenario will indeed be implemented. These targets are: (1) Doubling energy productivity by 2020 compared to 1990 levels; (2) reaching a 25% share of combined heat and power generation (CHP) in 2020; (3) enabling a significant expansion of renewable energies (REN) (a 30–35% share of renewable energies in electricity generation by 2020 and an approximately 50% share by 2030). However, it is assumed that the *necessary efficiency measures* will only be realised to a moderate extent if the implementation of energy efficiency strategies is delayed. The varying use of CCS is envisaged for the remaining demand for electricity from fossil sources, and the overall target is to determine under which of the CCS-based scenarios the climate target could also be reached. The other default values on the development of a renewable energy mix and CHP are adopted without alteration.

While the upper variant of the scenario family, "Maximal-theoretical", assumes that each new power plant will either be CCS-based or retrofitted later on, the lower variant "Realistic II" foresees only 50% of newly built steam power plants and 30% of newly built CHP plants being based on CCS and only 30% and 15% of older ones being retrofitted, respectively. The remaining scenarios are situated between the upper and the lower variant (see Table 1). A differentiation is made between new power plants and retrofitted power plants commissioned between 2010 and 2020 as well as between large-scale condensation power stations and CHP plants, which generally have less capacity. It is furthermore assumed that new fossil fuel-fired power plants built between 2005 and 2010 will be replaced by new CCS power plants at the end of their operating time, i.e. between 2045 and 2050.

(3) Analysing the *development of the levelised cost of electricity generation* (*LCOE*), the investment costs and operating costs for CCS-based power plants are based on a literature review; those for renewable energies are cited from [6]. In both cases, the learning curve approach is used to update future investment costs, while the LCOE are calculated using the annuity method. The basic figures used for our assessment are given in Table 2.

Table 1
Share of power plants equipped with CCS in the six variants of CCS-REN/CHP scenarios.

Scenario variants	Condensing power plant		Combined heat and power plant	
	New (%)	Retrofitted (%)	New (%)	Retrofitted (%)
1. Maximal – theoretical	100	100	100	100
2. Maximal – realistic	100	65	75	35
3. Maximal – new	100	–	75	–
4. Realistic I	75	40	40	20
5. Realistic I (only coal)	75	40	40	20
6. Realistic II	50	30	30	15

Table 2
Basic parameters of "early commercial" CCS power plants in 2020, "mature commercial" CCS power plants in 2040 and their reference power plants without CO_2 capture.

		Natural gas NGCC		Hard coal Steam		Hard coal IGCC		Lignite Steam	
		2020	2040	2020	2040	2020	2040	2020	2040
(A) Without CO_2 capture									
Degree of utilisation	%	60.0	62.0	49.0	52.0	50.0	54.0	46.0	49
Investment	€/kW_{el}	400	400	950	900	1300	1100	1100	1050
Operation, maintenance	€/kW_{el},a	34.1	32	48.3	45	53	49	56	52.5
CO_2 emissions, direct	g/kWh_{el}	337	326	690	650	676	626	880	827
(B) With CO_2 capture									
Degree of utilisation	%	51.0	55.0	40.0	44.0	42.0	46.0	34	39
Reduction of degree of utilisation	% points	9	7	9	8	8	8	12	10
Investment	€/kW_{el}	900	750	1750	1600	2000	1700	2030	1870
Difference in investment	€/kW_{el}	500	350	800	700	700	600	930	820
Operation, maintenance	€/kW_{el},a	54	50	80	74	85	78	94	86
Difference in operation, maintenance	€/kW_{el},a	20.1	18	31.7	29	32	29	38	33.5
Compression, transport and storage	ct/kWh_{el}	0.20	0.18	0.40	0.36	0.40	0.36	0.40	0.36
Capture rate	%	88	92	88	90	88	92	88	90
Additional use of fuel	%	18	13	23	18	19	17	35	26
CO_2 emissions, direct	g/kWh_{el}	48	29	101	77	97	59	143	104
CO_2 emissions, avoided	g/kWh_{el}	289	297	589	573	579	567	737	723