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Energy-Economic and Structural, and Industrial Policy Analysis of Re-Fitting Fossil Fired Power Plants with CO_2 Capture in North Rhine-Westphalia / Germany

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Abstract

Considering the traditional coal-based energy infrastructure in the German state North Rhine-Westphalia the question arises how to face the needs of embanking climate change. To reduce greenhouse gas intensive electricity generation in the Ruhr area, the introduction of carbon capture and storage (CCS) is an option of particular relevance. The paper investigates and discusses possibilities of setting up a CCS infrastructure in NRW. It shall clarify whether, and possibly how, highly efficient conventional fossil fired power plants could be refitted with CO_2 capture to flexibly react to potentially changing climate policy conditions and to keep up with the market.

Keywords: Retrofit; CCS; coal fired power plants; CO_2 capture, North Rhine-Westphalia; CCS infrastructure

1. Introduction

Considering the traditional coal-based energy infrastructure in the German state North Rhine-Westphalia (NRW) (Ruhr area) the question arises how to face the needs of embanking climate change. The Ruhr area is of special interest with regard to reducing carbon intensive production because it causes nearly 50% of the German CO_2 emissions from large stationary sources although it encompasses only 10% of the German territory. While the energy production in NRW caused 177 Mt of CO_2 emissions in 2005, other industrial sources like refineries, metal industry, chemicals industry, as well as the cement and glas industry, were responsible for more than 50 Mt (only emitters >1 Mt/a, see Figure 1, left). 42% of the fossil fired power plants installed in Germany are located in NRW (Figure 1, right) and 30% of the German electricity is produced in NRW.

Therefore the application of CCS is – besides the fostered use of renewable energies – an option of particular relevance to reduce greenhouse gas intensive electricity generation and industrial production in NRW. In fact, it is not only an option but a climate policy obligation due to NRW's energy and climate strategy adopted in 2008: Its

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main contribution to the carbon reduction goal will be the successive replacement of old power plants by highly-efficient new ones which shall reduce CO_2 emissions by 30 Mt (18.4 % of all energy related emissions in NRW) by 2020. Together with other measures from the state and the federal government the total reduction of NRW's CO_2 emissions shall reach 81 Mt/a by 2020 (minus 29% compared to 2005; minus 33% compared to 1990) (NRW [1]). On the other hand, these measures prohibit compliance with the long-term climate protection goal of more than minus 80% of greenhouse gases by 2050: Since the fossil fired power plants will operate for 40 years they make the CO_2 emissions permanent on a high level – even if they achieve high efficiencies. This structural problem can only be solved by retrofitting all power plants which will be built in the next ten years with CO_2 capture equipment from 2020. Therefore it needs to be analysed what this would imply regarding the necessary infrastructure.

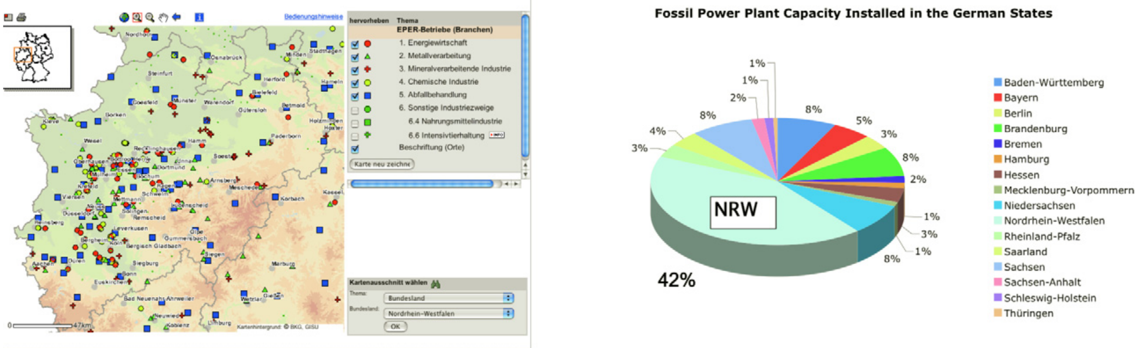


Figure 1: *Left*: CO_2 emitters of North Rhine-Westphalia (energy generation and other large point sources) (Source: excerpt from the European Pollutant Emission Register www.EPER.de). *Right*: Fossil fired power plants installed in NRW and the other German states (Source: own figure)

This paper is organized as follows. Section 2 gives a brief outline of the power plants in NRW which have already been renewed, which are announced to be renewed, and which are expected to be renewed. Section 3 presents our results of grouping those power plants which are suitable for retrofitting (together with other large point sources) into CCS clusters while section 4 combine these clusters with different possible storage sites. Section 5 shows four sensitivity analyses to regard uncertainties in the application of CCS. The paper closes with a comparison of the "NRW CCS strategy" drafted here and the requirements of embanking climate change in Germany in total in section 6.

2. The power plant sector in NRW

2.1. Approach and assumptions

The approach chosen for determining the capacity of power plants suitable for CO_2 capture is as follows:

1. *At first*, the power plants recently renewed are compiled. They won't be retrofitted with CO_2 capture since they do not comply with the necessary requirements (see below).
2. *Secondly*, all power plants which are announced to be renewed in the next decade are selected from public sources. Their target efficiencies are quoted from (NRW [2]).
3. *Finally*, to be in agreement with NRW's energy and climate strategy, the remaining power plants are assumed to be replaced by highly efficient new ones after reaching the end of their life time. Plants whose end of life is reached before 2020 are replaced by "capture ready" plants and retrofitted after 2020 if possible; new plants built after 2020 are assumed to be fully integrated CCS plants (IGCC).

The assessment is based on the following assumptions:

- CCS won't be *commercially available* before 2020 as most sources say.
- As stated in (IZ Klima [3]) all German power plants being in the planning phase are assumed to be designed "*capture ready*". This enables their retrofit from 2020.

- Only those power plants younger than 13 years will be *retrofitted*. According to (McKinsey&Company [4]) “retrofitting CCS is unlikely for plants older than ten to twelve years, as the total cost would be at least 30 percent higher than that of new power plants … and possibly much more, depending on the specific case”.
- As life time we assumed 40 years according to most sources. If one or two blocks of a power plant are at the end of their life time but other blocks are younger, the older ones are assumed to run 5-10 years longer to be able to replace the whole power plant at once.

The calculation of captured CO_2 is based on:

- As *efficiencies* of the power plants in the year 2015 and 2020 and efficiency losses caused by CCS we assumed, respectively: natural gas combined cycle (59% / 60% / -9%), hard coal pulverised plant (48% / 49% / -9 %), hard coal oxyfuel (- / 49% / -11%), hard coal IGCC (- / 50% / -8%), and lignite pulverised plant (45% / 46% / -12%).
- A higher *efficiency penalty for retrofitted power plants* compared to fully integrated newly built CCS plants is assumed (McKinsey&Company [4]). Since no detailed assessment exists, an additional decrease by (arbitrarily chosen) further three percentage points is calculated.
- As capture rate we assumed 99.5% for Oxyfuel and 88% for the other technologies.

2.2. Power plants in NRW – renewed and retrofitted

Figure 2 gives the results obtained by applying the three steps outlined above. It shows that in NRW a capacity of

- 4 GW has already been installed between 2000 and 2008 (which is not suited for retrofitting due to its age);
- 18.7 GW is left to be installed until 2020 (thereof 8.7 GW already announced by the energy utilities) – we assume that all of this capacity will be designed as “capture ready”;
- the same 18.7 GW has to be retrofitted after 2020 – in the figure we assume that each power plant is retrofitted 10 years after its erection;
- 6.3 GW will be installed after 2020 and is assumed to become fully integrated new-built (IGCC) CCS plants.

In addition to the net power installed or retrofitted after 2020 further power is required due to the energy penalty of CCS-based plants. This adds up to 6.4 GW “penalty load”.

In total, about 30 GW have to be equipped with CO_2 capture technologies within a short period from 2020 to 2030. Otherwise most plants become too old for retrofits.

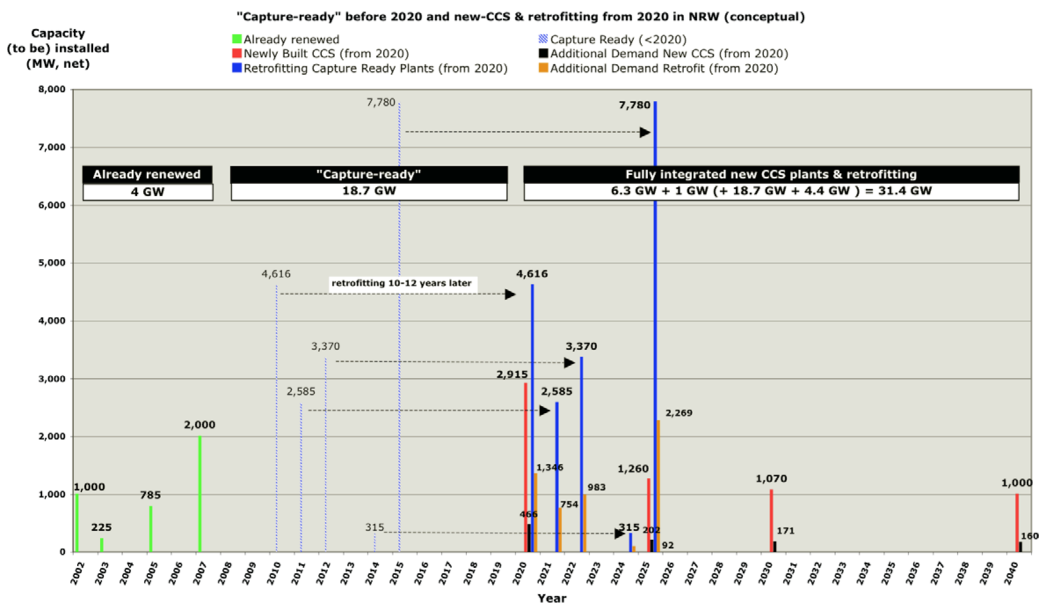


Figure 2: Capacity already installed, to be installed as “capture ready” (before 2020), and to be installed as integrated new-built IGCC (after 2020) as well as retrofitted (after 2020) in NRW (Source: own calculation)

3. CCS clusters in NRW (power plants and other point sources)

3.1. CO_2 captured from power plants

Based on key parameters like the calculated capacity, the efficiency, the penalty, and the capture rate, we derive the *yearly amounts* of carbon dioxide captured from power plants in NRW. This figure determines the diameter of pipelines needed to transport the CO_2 from the source to possible storage sites. Considering also the remaining life time it is possible to calculate the *total amount* of captured CO_2 for each power plant. This value enables us to determine the possible storage capacity needed per power plant.

3.2. Industrial applications usable for CO_2 capture

Besides power plants other industrial emitters of carbon dioxide might be interesting for the application of CCS. For sites like steel and cement plants, petro-chemical plants, or refineries, CO_2 capture could be suitable. Table 1 shows large industrial emitters located in NRW as an excerpt of Figure 1 (left). Chosen to be suitable for capturing CO_2 are all plants with CO_2 emissions exceeding 1 Mt per year. Their CO_2 concentrations are given as an average value for the appropriate sector (WI [5]).

For this study an (arbitrarily chosen) capture rate of 90% is assumed – not considering that for some sources more efficient CO_2 capture methods might be available. Furthermore, only CO_2 emissions captured at the stack are calculated. It has not been considered that additional heat and electricity is necessary for post-combustion which would cause additional CO_2 emissions (in case of Bayer Leverkusen, Hüttenwerke Krupp, and Thyssen Stahl the power plants existing directly on the companies' sites could provide this penalty).

Table 1: CO_2 emissions and captured CO_2 of big industrial emitters in NRW

Industrial Source	CO_2 Concentration	CO_2 Emissions	CO_2 Capture
	%	Mt/a	Mt/a
Thyssen Stahl Hamborn	15-20	4.66	4.19
Thyssen Stahl Schwelgern	15-20	5.57	5.01
Thyssen Stahl Beeckerwerth	15-20	1.55	1.40
Hüttenwerke Krupp/Mannesmann	15-20	4.83	4.35
Bayer Chemie Krefeld	8-13	1.15	1.04
Innovene Köln	8-13	2.99	2.69
Bayer Leverkusen	8-13	1.35	1.22
Rheinkalk Wülfrath	15-25	2.17	1.95
Infracor Chemie Marl	8-13	2.93	2.64
Raffinerie Ruhr Öl Scholven	3-18	3.26	2.93
Total		**30.46**	**27.41**

Although cost data and studies on the application of CCS in the *non-power sector* are scarce we include the largest emitters into our analysis. This enables us to take into account areas within NRW where a lot of power plants and industrial sources are located nearby. The location of these sources illustrates one of several general conditions which should be considered while planning a CCS infrastructure. A CO_2 pipeline, for example, should be layed out in a way that neighboured sites could be subsequently connected without a lot of effort.

3.3. Developing CO_2 clusters in NRW

Based on the power plants and the industrial sources being suited for CO_2 capture, two areas in NRW which could become a future CO_2 cluster are identified (see Figure 3 for details). Both clusters include an area of about 75 x 25 km and 106 Mt/a of CO_2 captured in "NRW West" (thereof 22 Mt/a from industrial application) and 47 Mt/a of CO_2 captured in "NRW Middle" (thereof 6 Mt/a from industrial sources), respectively.

4. Transport infrastructure

4.1. Comparison with possible storage sites

In the next step suitable storage sites must be identified in which the CO_2 captured at the power plants identified above could be sequestered. Currently only a very rough estimation on possible storage sites in Germany and their storage capacity exists. Until the German storage register, which is being developed by the German Geological Survey and is announced to be finalized in 2011, is completed, each demand of an individual storage site would seem rather hypothetically. On the other hand this study focuses on retrofitting power plants and the implications of applying CCS for the state government. Therefore, to make clear the dimensions of the infrastructure necessary for CCS, in a mind game possible storage sites were matched with the sources and connected via pipelines.

First of all it should be noticed that although NRW causes nearly 50% of the German CO_2 emissions from stationary sources, almost no storage sites are available in this state. Only in the North-Eastern part of NRW several small aquifers exist of whom only one aquifer has a storage capacity of more than 100 Mt, the minimum useful lifetime capacity required for large-scale CCS projects (BERR [6]). The only appreciable storage potentials are located in the Northern part of Germany (Lower Saxony and Schleswig-Holstein), which means that long-distance transportation of CO_2 has to be enabled.

4.2. Storage and transport scenarios

Based on the cluster analysis outlined above three different storage scenarios are developed:

1. *Onshore Germany*: The CO_2 captured within the clusters “NRW West” and “NRW Middle” is sequestered into possible storage sites in Schleswig-Holstein. These sites are chosen because RWE DEA has selected them for further investigations with the aim to use them for their upcoming CCS plants (currently announced is the IGCC demo to be erected in Hürth near Cologne, RWE [7]). The CO_2 emissions of one power plant in the east of NRW can be sequestered in the only NRW storage site available with a suitable capacity 100 > Mt (“NRW East”). One further power plant which is too far away to be included into the cluster “NRW West” could be connected with a short pipeline to the Dutch CO_2 network drafted in (Damen et al. [8]) (“NRW NL”).
2. *Offshore Germany*: The onshore storage sites in Schleswig-Holstein described above are exchanged with offshore sites in the same region, also under investigation by RWE DEA.
3. *Onshore Netherlands*: The main sites “NRW West”, “NRW Middle”, and “NRW NL” are connected with the Dutch CO_2 network, while “NRW East” does not change. It should be mentioned that is has not been proved whether the Netherlands have “free capacity” from 2020 – the calculation is only made for the visualization of infrastructural demands.

By use of a geographical information system (GIS) a suitable pathway for a possible CO_2 pipeline network connecting the cluster identified above with the different storage sites is explored. These pathways follow existing routes of natural gas pipelines to simplify both the approval procedures and pipelines construction. Based on the amount of CO_2 to be transported one (or more) suitable pipelines are selected from a list of available types of pipelines characterized by diameter, flow rate, and capacity (Göttlicher [9]). The length of the pipelines is determined via GIS.

4.3. Results and interpretation

Figure 3 shows the results for the *storage scenario A*. This scenario requires two main pipelines (DN 160 and DN 150, in parallel) of 465 km length which connect the cluster “NRW Middle” with the onshore storage site in Schleswig-Holstein (DN 160 is the maximum diameter possible for CO_2 pipelines according to (Göttlicher, 2004, 167). Two parallel connection pipelines transport the CO_2 from the cluster “NRW West” to the start of the main pipelines. The network is complemented by two individual pipelines of short length (31-34 km) for the single power plants “NL” and “East”. The total length of this network accumulates to 1,195 km (for details see Table 2). If, for different reasons, several pipelines with a smaller capacity are required, the total length would increase, respectively.

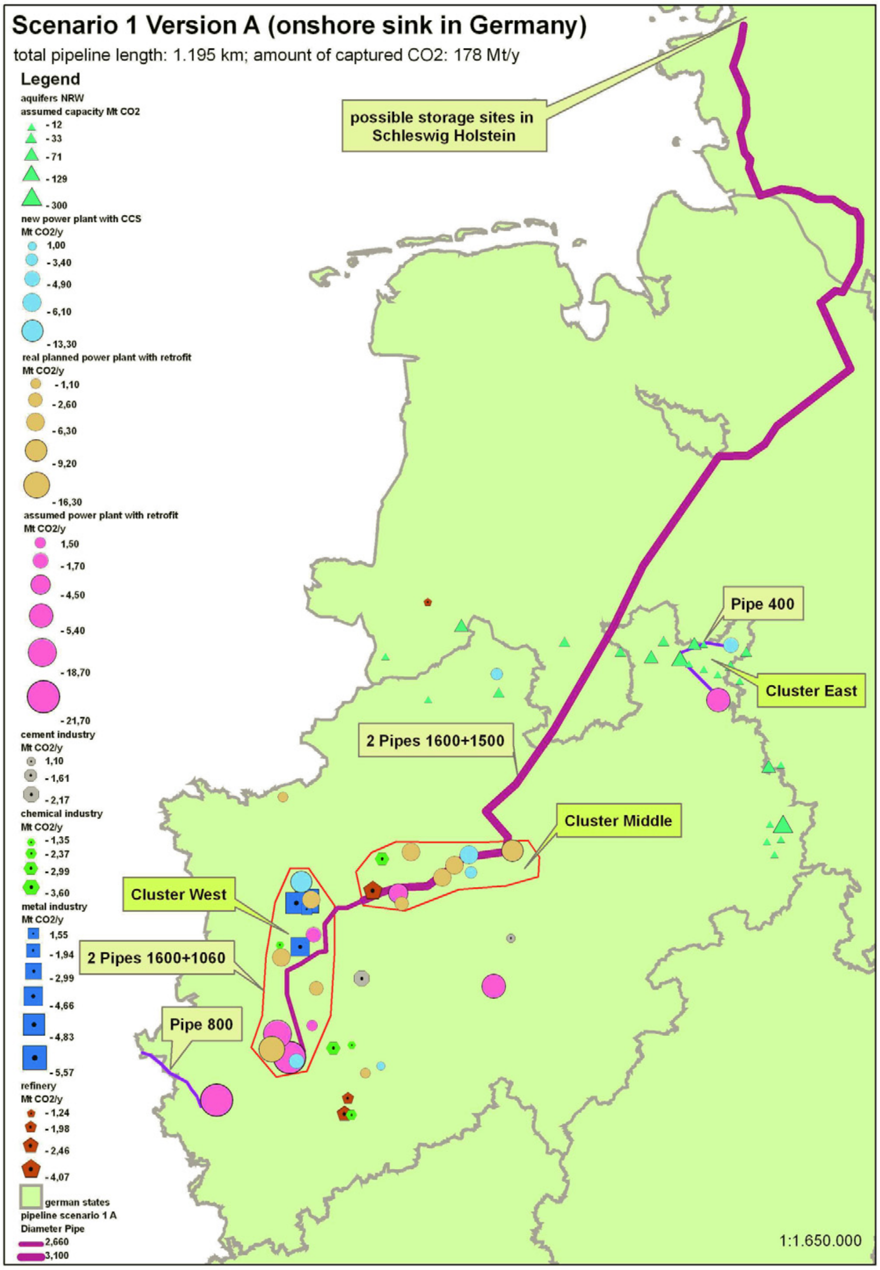
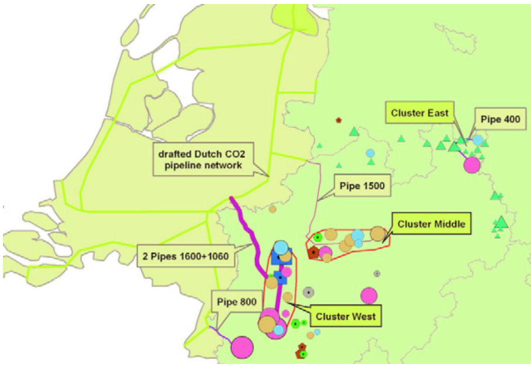


Figure 3: Storage scenario A – CO_2 cluster, transport, and possible storage sites in Schleswig-Holstein (source: own calculation)

In the *storage scenario B* (not shown) the main pipelines follow a slightly different way to the coast instead of the onshore storage site. This decreases the total length by 100 km to 1,095 km.

The largest difference is visible in *storage scenario C* (Figure 4). Since in the drafted CO_2 network of the Netherlands one main pipeline is proposed close to the border, only short connecting pipelines between both clusters



and the Netherlands are necessary. In case of "NRW Middle" a connecting pipeline already foreseen on the Dutch side can be used. Therefore the total length of the German network accumulates to 323 km. However, it should be noted that the carbon dioxide has to be transported over long distances in the Netherlands since its main storage sites are (besides the Groningen field in the North-East) on the seaside and not in the midland.

Figure 4: Storage scenario C – CO_2 cluster, transport, and possible storage sites in the Netherlands (source: own calculation; Dutch CO_2 network: Damen et al. [8])

Table 2: Parameters of the drafted pipeline network for scenario 1 and scenario 2 (sensitivity analysis) (source: own calculation)

Basic scenario: replacement of power plants in NRW 1:1

			Pipe 1	Pipe 2	Pipe 3	Pipe 4	Pipe 5	Pipe 6	Total
A: onshore			**"NRW West"**		**Main pipe to the North**		**"NRW NL"**	**"NRW East"**	
6.1	CO_2 captured	Mt/a	106		153		20	5	178
km/Mt,a	DN of pipe	m	160	106	160	150	80	80	
	Transportdist.	km	154	154	354	354	31	34	1,081
B: offshore			**"NRW West"**		**Main pipe to the North**		**"NRW NL"**	**"NRW East"**	
6.1	CO_2 captured	Mt/a	106		153		20	5	178
km/Mt,a	DN of pipe	m	160	106	160	150	80	80	
	Transportdist.	km	154	154	354	354	31	34	1,081
C: Netherlands			**"NRW West"**		**NRW Middle"**		**"NRW NL"**	**"NRW East"**	
1.8	CO_2 captured	Mt/a	106		47		20	5	178
km/Mt,a	DN of pipe	m	160	106	150		80	80	
	Transportdist.	km	85	85	88		31	34	323

Sensitive scenario: hard coal and natural gas are shifted to the North Sea coast if non-combined-heat-and-power

			Pipe 1	Pipe 2	Pipe 3	Pipe 4	Pipe 5	Pipe 6	Pipe 7	Total
A: onshore			**"NRW West"**		**Main pipe to the North**		**"NRW NL"**	**"NRW East"**	**Coast**	
6.8	CO_2 captured	Mt/a	93		133		20	5	37	195
km/Mt,a	DN of pipe	m	160	60	160	150	80	80	106	
	Transportdist.	km	154	154	354	354	31	34	247	1,328
B: offshore			**"NRW West"**		**Main pipe to the North**		**"NRW NL"**	**"NRW East"**	**Coast**	
6.4	CO_2 captured	Mt/a	93		133		20	5	37	195
km/Mt,a	DN of pipe	m	160	60	160	150	80	80	106	
	Transportdist.	km	154	154	354	354	31	34	158	1,239
C: Netherlands			**"NRW West"**		**NRW Middle"**		**"NRW NL"**	**"NRW East"**	**Coast**	
2.8	CO_2 captured	Mt/a	93		40		20	5	37	195
km/Mt,a	DN of pipe	m	160	60	150		80	80	106	
	Transportdist.	km	85	85	88		31	34	225	548

5. Sensitivities

Four main sensitivity analyses are performed to regard risks and uncertainties in the application of this new and unproven technology:

1. To avoid long-distance transport of both the CO_2 and the (imported) coal feedstock it is suggested in some studies to shift the power plants to the coast and to transport the electricity to the midland. In Germany this makes sense only for hard coal as well as natural gas fired power plants, since lignite is our domestic energy carrier. Furthermore it is neither possible if the power plants are used for industrial sites too, nor if they are operated in a combined heat and power mode. Considering these constraints, only six power plants remain for a possible shift to the German coast. However, four of these plants have not yet been included into the two clusters selected above which means that this enhanced scenario results in a higher CCS capacity. On the other hand an additional pipeline along the coast with a length between 160 and 250 km has to be added to the original pipelines (see Table 2). Summarizing, in the case illustrated here, the captured CO_2 *increases* by 10% from 178 to 195 Mt/a but the specific transport needs also *increase* (between 3 and 60 %, depending on the storage scenarios).
2. Secondly we regard in our model a situation that CCS won't be commercially available by 2020 as more and more sources challenge that assumption (Pearce [10]). In this case – we assume only a moderate shift from 2020 to 2025 – the results change drastically (see Figure 2): 11 GW of power plants erected between 2008 and 2013 will be too old to become retrofitted from 2025 according to our basic assumptions. In the first year of CCS availability 10 GW installed in 2014 have to be retrofitted, otherwise they would become too old for retrofit, too. Further 3.4 GW of plants foreseen to be built as fully-integrated new plants in 2020 must be built without CCS and must be retrofitted 5-10 years later which leads to higher costs.

3. A third assumption won't have any effect on our basic scenarios but on the second sensitivity analysis: The drafted CCS directive of the EU won't allow the permission of any new fossil fired power plant emitting more than 500 g CO_2/kWh from 2015 (EurActiv.com [11]). While our drafted renewal program does not foresee any new power plant between 2015 and 2020, in case of a *later* availability of CCS 3.4 GW of plants foreseen to be built in 2020 have to wait until the year 2025.
4. Finally, whether the huge amount of plants foreseen for retrofit after 2020 will be realised successfully, depends on the market situation and the availability of sufficient manufacturing capacity. If CCS will be commercially available from 2020, power plants will be erected and retrofitted in many European countries which could lead to a serious bottleneck situation. Since only a short time slot is available for retrofitting the power plants which have been erected between 2008 and 2015, slight setbacks could lead to the situation that many of these power plants won't be equipped with CO_2 capture.

6. Conclusions

One of our main findings is that a huge infrastructual effort is necessary to face the 80% CO_2 reduction goal for 2050 if NRW's energy and climate strategy is implemented as proposed. In this case all power plants must be retrofitted with a CO_2 capture or being built as fully integrated new ones to decrease the CO_2 emissions drastically. If CCS won't be commercially applicable on a full scale from 2020 this goal won't be reached anymore. Furthermore a comparison with the German climate strategy outlined in the federal government's "Sustainable Energy Scenario" shows that even such a "CCS max" strategy won't lead to the climate goal at all if advanced measures like a transformation to a CCS based hydrogen traffic system would not been taken (WI et al. [12]).

While the results shown above are preliminary, the final report will be available from March 2009 at www.wupperinst.org.

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