CO_2 capture in low rank coal power plants

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Abstract
This paper summarizes the results of a study on low rank coal-fired power plants with CO_2 capture. The performance and costs of various power plants based on post-combustion capture, gasification combined cycles with pre-combustion capture and oxy-combustion are compared. The fuel for the plants is a German brown coal.

Keywords: CO_2, power, coal, costs

Introduction
Almost half of the world's proven recoverable coal reserves, on a mass basis, are low rank coals (lignite/brown coal and sub-bituminous coal) [1]. The ability to capture CO_2 would improve the prospects for utilizing this important resource while complying with constraints on emissions of greenhouse gases to the atmosphere.

This paper summarizes the results of a study on low rank coal power plants with CO_2 capture, carried out by Foster Wheeler for the IEA Greenhouse Gas R&D Programme (IEA GHG) [2]. The primary purpose of this study was to investigate different power plant technologies and assess their performances and costs.

The following combinations of power generation and CO_2 capture technologies were initially analyzed:

1. Pulverized coal boiler with an ultra –supercritical (USC) steam cycle and post combustion CO_2 capture using MEA solvent scrubbing
2. Circulating Fluidized Bed (CFB) boiler with a USC steam cycle and post combustion CO_2 capture using MEA solvent scrubbing
3. Pressurized Circulating Fluidized Bed (PCFB) boiler with a USC steam cycle and post combustion CO_2 capture using MEA solvent scrubbing
4. Oxy-combustion pulverized coal boiler with a USC steam cycle
5. Gasification combined cycle using Future Energy (FE) oxygen blown, dry feed, entrained gasifiers, with water quench, sour shift conversion and CO_2 capture by MDEA scrubbing
6. Gasification combined cycle using Shell oxygen blown, dry feed, entrained gasifiers, with heat recovery boilers, sour shift conversion and CO_2 capture by MDEA scrubbing
7. Gasification combined cycle using Foster Wheeler (FW) air blown, dry feed, fluidized bed gasifiers, with heat recovery boilers, sour shift conversion and CO_2 capture by MDEA scrubbing.

The study is based on use of a German brown coal with a moisture content of 50.7% and a LHV of 10,500 kJ/kg. The nominal capacity of the power plants is fixed at approximately 750 MWe but the actual power outputs of the pre-combustion capture cases depend on the capacities of existing F series gas turbines and the output of the CFB case depends on the current maximum boiler size. The plant site is an inland greenfield site in Western Germany, close to the coalmine, without special civil works implications. The average air temperature is 9°C and the cooling water system consists of raw water in a closed loop with natural draught evaporative cooling towers. The plant area is assumed to be close to river water, which is used as make-up water.

The plants include compression of captured CO_2 to 11MPa. The MEA post combustion capture process inherently produces CO_2 which contains only trace concentrations of impurities. The CO_2 from the gasification combined cycle plants contains almost all of the sulphur from the coal, mainly in the form of H_2S. The H_2S concentration in the CO_2 stream is about 0.3 mol%. A higher purity CO_2 could be produced if required using an alternative CO_2 separation process. The CO_2 from the oxy-combustion plant contains a similar concentration of SO_2 plus about 3.3% of O_2, N_2, and Ar. The impurity concentrations could be reduced by modifying the cryogenic separation unit which is already used to separate some impurities from the CO_2. In both cases, producing a higher purity CO_2 steam would increase costs.

Performance data

The most important performance data of the alternative power plants, with CO_2 capture, are summarized in Table 1.

Table 1 Power plant performance data

Case	Power plant technology	Coal feed t/h	Dried coal moist. %wt	Acid gas removal tech.	CO_2 capture efficiency %	Gross power output MWe	Aux. cons. MWe	Net power output MWe	Net electrical efficiency %
1	USC-PC	734.0	32	MEA	85.0	932.0	168.8	761.0	35.5
2	Oxy USC-PC	677.6	32	Gas liq.	93.0	1039.4	295.8	741.3	37.5
3	CFB FW	592.9	32	MEA	85.0	763.0	146.5	614.7	35.5
4	PCFB FW	727.0	32	MDEA	85.0	816.0	125.5	688.4	32.5
5	IGCC FE	653.3	10	MDEA	85.8	900.3	233.1	665.2	34.7
6	IGCC Shell	624.2	5	MDEA	85.2	868.7	238.0	628.8	34.5
7	IGCC FW	691.0	25	MDEA	82.9	900.5	211.9	686.6	34.1

The feature common to all the alternatives is the partial drying of the coal from the initial content of 50.7% to a range varying from 32% for the post-combustion alternatives to 10%-5% respectively for the IGCC alternatives based on Future Energy and Shell technology. The partial drying of the coal lignite is used to enhance the efficiency of the different power plants, utilizing low temperature heat available in the plants at various locations. In the IGCC alternatives, FE and Shell, it is necessary to reduce the moisture content of the lignite to a lower level to permit the operation of the pneumatic transportation system adopted by these technologies.

Despite the differences of the various technologies involved, the net electrical efficiency falls in a narrow range of values. The oxy-combustion USC-PC boiler is the alternative with the highest electrical efficiency and lowest CO_2 emissions.

Investment cost data

The investment costs of the different power plant technologies with CO_2 capture are shown in Tables 2 and 3. The investment costs include contingency and miscellaneous owner's costs but exclude interest during construction, start-up costs and working capital, although these are taken into account in the calculation of the cost of electricity (COE).

Since capacity is not the same for all the alternatives. The investment costs should therefore be compared on the basis of the specific investment (Euro/kW), rather than the total investment. From this comparison it appears that the CFB technology shows the lowest specific investment cost.

Table 2 Investment costs of post combustion alternatives (10^6 €)

Case	Power plant technology	Boiler Island	Process Units	CO_2 Compr.	Power Island	Utilities and Offsites	Total investment 10^6€	Specific investment €/kW
1	USC-PC	463.1	306.4	47.6	162.5	272.2	1251.8	1645
2	Oxy USC- PC	451.2	416.6	92.9	174.5	260.0	1395.2	1882
3	CFB FW	334.0	198.2	42.0	138.6	241.0	953.8	1552
4	PCFB FW	345.4	431.5	47.9	135.1	270.7	1230.6	1788

Table 3 Investment costs of pre combustion alternatives (10^6 €)

Case	Power plant technology	ASU	Process Units	CO_2 Compr.	Power Island	Utilities and Offsites	Total investment 10^6€	Specific investment €/kW
5	IGCC FE	126.3	380.3	40.1	368.9	219.1	1134.8	1706
6	IGCC Shell	114.0	472.9	38.5	367.1	212.7	1205.1	1917
7	IGCC FW	28.9	566.3	40.0	370.2	227.2	1232.7	1795

Production costs and selection of the most promising technology

Table 4 provides the cost of electricity (C.O.E.) for the different alternatives with CO_2 capture. The cost of electricity was calculated based on the following main assumptions:

- Cost of coal: 1.0 Euro/GJ (10.5 Euro/t)
- 7446 equivalent operating hours in normal conditions at 100% capacity
- Total investment cost as given in Tables 2 and 3
- 10% discount rate on the investment cost over 25 operating years

Table 4 Cost of electric power production

Case	Power plant technology	Cost of electricity c/kWh
1	USC-PC	5.39
2	Oxy USC- PC	5.46
3	CFB FW	5.34
4	PCFB FW	5.55
5	IGCC FE	5.41
6	IGCC Shell	5.94
7	IGCC FW	5.64

The cost of electricity falls in a narrow range of values and the maximum difference among the alternatives is approximately 11%. In particular, the USC-PC, CFB and IGCC-FE cases display the lowest C.O.E.. Amongst these three technologies, CFB is the one with the lowest cost and therefore it is selected for a subsequent more detailed study, aimed at evaluating the cost of CO_2 capture. However, the study demonstrated that other technologies utilizing low rank coals are very close in performances and costs and, depending on different local circumstances, they may become more competitive with respect to the CFB.

Detailed information for the most promising technology

The option with the lowest cost of electricity was selected for more detailed analysis. The performances and costs of CFB boiler plants with and without post-combustion CO_2 capture using MEA solvent are shown in the following Table 5.

Table 5 Performances and costs of CFB plants with and without CO_2 capture

		CFB-Boiler without CO_2 capture	CFB-Boiler with CO_2 capture
OVERALL PERFORMANCES			
Coal flow rate, as-received	t/h	592.9	592.9
Thermal energy of feedstock, LHV	MWth	1729.3	1729.3
Gross electrical power output[(1)]	MWe	841.9	758.2
Auxiliary Consumption	MWe	47.6	146.6
Net electrical power output[(2)]	MWe	791.8	609.7
Gross electrical efficiency, LHV basis	%	48.7	43.8
Net electrical efficiency, LHV basis	%	45.8	35.3
Net electrical efficiency, HHV basis	%	39.2	30.2
CO_2 capture efficiency	%	-	85.0
INVESTMENT COST DATA			
Total investment	10^6 €	769.3	955.1
Specific net investment cost	€/kW	1006	1567
PRODUCTION COST DATA			
C.O.E. (DCF=10%)	c€/kWh	3.46	5.39

Notes: (1) At generator terminals.
(2) At low voltage side of the step-up transformer.

Cost of avoiding CO_2 emissions

The cost of avoiding CO_2 emissions can be expressed as follows:

$$\frac{\Delta \text{ Electric Power Cost}}{\Delta \text{ Specific } CO_2 \text{ emission}} [=] \frac{\text{Euro}}{\text{t of } CO_2 \text{ captured}}$$

Where:

Δ Electric Power Cost = Electric Power Cost with CO_2 capture
- Electric Power Cost without CO_2 capture.
(The unit of measurement is Euro/kWh.)

Δ Specific CO_2 emission = Ratio of (CO_2 emission/unit of power production) without capture
- ratio of (CO_2 emission/unit of power production) with capture.
(The unit of measurement is tonne CO_2/kWh).

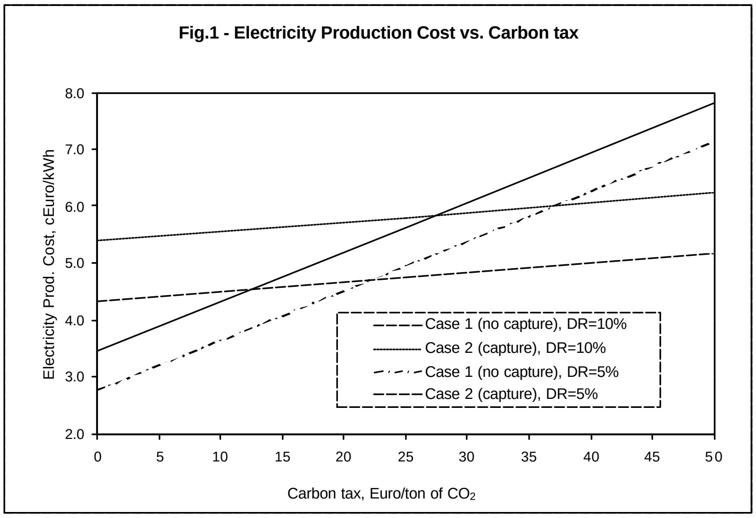
Based on the above definition, the cost of avoiding CO_2 emissions, at DCF=10%, is 27.5 Euro/tonne.

Electrical power cost in the presence of a carbon tax

Economic or regulatory mechanisms will be necessary to facilitate development and deployment of CO_2 capture technologies. There are various options, including a carbon tax or emission trading certificates.

The two CFB versions, with and without CO_2 capture, were also compared in the presence of a carbon tax. Figure 1 shows this comparison as a function of an increasing carbon tax from 0 to 50 Euro/t of CO_2 emitted. This comparison has also taken into account two different discount rates, 10% and 5%. For these two discount rates it appears that the cost of electricity (C.O.E.) of these two versions is the same when the carbon tax is respectively 27 and 22 Euro/t of CO_2 emitted.

Figure 1 Sensitivity of electricity cost to carbon tax



Sensitivity to fuel cost

The cost of low rank coal depends strongly on local conditions. A fuel price of €1/GJ was used for this study. A change of €0.5/GJ would change the cost of electricity from the CFB plants with and without CO_2 capture by 0.51 and 0.39 c/kWh respectively.

Impact of costs of CO_2 transport and storage

The costs reported in this paper exclude the costs of transporting and storing captured CO_2. If the CO_2 is used for enhanced oil recovery, the net revenue from oil production may be greater than the cost of CO_2 transport and storage. As a result, the overall costs of electricity with CO_2 capture and storage would be lower than those given in this paper. If there is no revenue from the sale of CO_2 and the cost of CO_2 transport and storage is for example 10 €/tonne of CO_2 stored, the effect would be to increase the cost of electricity from the CFB case by 0.96 c/kWh.

Co-production of hydrogen

One of the potential benefits of gasification combined cycle plants with CO_2 capture is that high purity hydrogen can be produced, for example for oil refining, chemicals production, distributed heat and power generation or for use in vehicles. Foster Wheeler assessed the performance and costs of plants which co-produce hydrogen and electricity. Two different designs were considered to produce approximately 210,000 or 70,000 Nm^3/h of 99.8% purity hydrogen at 2.6 MPa, as well as approximately 300 MWe of electric power from one F series gas turbine. Both plants were based on the Future Energy gasifier, which is shown in table 4 to be the lowest cost option for power generation with CO_2 capture. CO_2 is captured using MDEA solvent scrubbing.

Assuming an electricity value of 5.41 c/kWh, i.e. the cost of the Future Energy gasifier plant with CO_2 capture given in table 4, the cost of production of hydrogen would be 7.10 c/Nm^3 (€6.58/GJ) for the larger plant and 11.4 c/kWh (€10.57/GJ) for the smaller plant. Further cost sensitivities are reported by Domenichini [3].

Table 6 Performances and costs of electricity and hydrogen co-production plants

		H_2 production: 207,000 Nm^3/h	H_2 production: 69,000 Nm^3/h
OVERALL PERFORMANCES			
Thermal energy of feedstock	MWth	1905.4	1270.2
Gross electrical power output(1)	MWe	525.8	477.0
Auxiliary power consumption	MWe	219.5	150.4
Net electrical power output(2)	MWe	305.4	325.5
Thermal energy of hydrogen product	MWth	619.5	206.5
Net electrical efficiency	%	16.0	25.5
Hydrogen production efficiency	%	32.4	16.2
Total efficiency	%	48.4	41.7
CO_2 capture efficiency	%	85.0	85.0
INVESTMENT COST DATA			
Total investment	10^6 €	948.8	815.0
PRODUCTION COST DATA			
Price of hydrogen	c€/Nm^3	7.1	11.4
C.O.E. (DCF=10%)	c€/kWh	5.41	5.41

Notes: (1) At generator terminals.
(2) At Low Voltage side of the step-up transformer.

Analysis and conclusions

The most important conclusions of the study are:

- Partial drying of the lignite is advantageous to increase efficiency, utilizing low temperature heat sources available in the plant at various locations.
- Despite the differences of the various technologies, the net electrical efficiencies fall in a narrow range of values. The oxy-combustion USC-PC alternative shows the highest electrical efficiency and lowest CO_2 emissions.
- The cost of electricity of the different alternatives falls in a narrow range of values; the maximum difference is approximately 10%.
- The CFB plant with post-combustion capture has the lowest specific investment cost (Euro/kW) and the lowest cost of electricity. However, other technologies utilizing low rank coals are very close in performances and costs and, depending on different local circumstances, may become more competitive with respect to the CFB.
- The cost of CO_2 capture, calculated for the CFB technology is 27.5 Euro/t of CO_2 emissions avoided (DCF=10%).
- IGCC based on the Future Energy gasifier is the most attractive alternative amongst the cases investigated for pre-combustion capture
- The cost of hydrogen from an IGCC plant which co-produces electricity and hydrogen, with CO_2 capture, is 7.1-11.4 c€/Nm^3.

List of references

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