ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 1 (2009) 4015–4022

Energy Procedia

www.elsevier.com/locate/procedia

GHGT-9

ECO2 : Post-combustion or Oxyfuel - A comparison between coal power plants with integrated CO_2 capture

Pierre-Antoine Bouillon[a]*, Sophie Hennes[b], Céline Mahieux[c]

[a]*IFP Lyon, BP3, 69 390 Vernaison, France*
[b] *ALSTOM Power Plant, 3 avenue des Trois Chênes, 90018 Belfort, France*
[c]*ALSTOM Power Plant Business, Brown Boveri Strasse 7, 5401 Baden, Switzerland*

Abstract

This paper presents a study of two integrated processes for power production with CO_2 capture : a post-combustion process involving an amine based CO_2 capture unit; and an oxyfuel process involving air separation units, O_2 combustion boiler and flue gas purification. These two integrated processes have been compared to a base case air-fired CFB boiler using bituminous international coal as fuel. A complete techno-economical study has been carried out, and electricity production costs have been compared to the base case. The results were also expressed in equivalent CO_2 penalties (€/tco_2) as an economic limit to allow CCS processes to be economical against CO_2 taxes.

It has been found out that both zero emissions post-combustion and oxyfuel integrated process have a big impact on the power plant economics. The study showed oxy- and post-combustion processes led to similar CO_2 penalty: around 44€/tco_2 for post-combustion capture and 46€/tco_2 for the oxyfuel process.

Keywords : CO_2; capture; post-combustion; oyfuel; coal

1. Introduction

CO_2 emissions have become an important concern in last years, especially in the power production industry where fossil fuels are widely used to produce electricity. Many studies[1-2], including pilot scale experiments, are under progress to evaluate the different technologies available to produce a clean electricity, i.e. with a sequestration of the CO_2 emissions. This study [3-9] was realized with the support of ADEME (French Environment and Energy Management State Agency) into two conventions (04 74 C0075 and 06 74 C0051). Among the different options, the two main routes to a clean power production are 1- a classical fuel combustion with air coupled with a post-combustion CO_2 capture unit to purify the CO_2 for sequestration; 2- a combustion of fuel with pure oxygen allowing CO_2 to be stored directly. When looking to CCS technologies, power producers will make their choice considering

---

* Corresponding author. Tel.: +33-4-78-02-21-85; fax: +33-4-78-02-20-08.
E-mail address: p-antoine.bouillon@ifp.fr.

doi:10.1016/j.egypro.2009.02.207

the economics of the overall plant. As CO_2 is a non valuable product in the considered scale (unless used for EOR), CCS technologies will impact negatively the profitability of a zero emission power plant compared to a standard power plant. However, power companies will have to consider the coming penalties on CO2 emissions. The study presented in this paper is a complete economical evaluation of the two main routes - post-combustion and oxyfuel integrated processes – which are compared to a base case in order to calculate an equivalent cost of CO_2 penalty in each cases.

2. Post-combustion integrated process

Figure 1 presents the Process Flow Diagram of the power plant with the integrated CCS process.

2.1. Power production

This study is based on a super critical CFB power plant, using coal as fuel, for a design capacity of 600MWe. The main characteristics of the thermodynamic cycle of the power plant are described here after :

HP live steam – turbine inlet	: 270 bara
Live steam temperature – turbine inlet	: 600°C
Feed water temperature	: 295°C
Sea water temperature	: 15.7°C
Condenser pressure	: 35 mbara
Fuel flow rate	: 54.8 kg/s (International bituminous coal)
Design capacity	: 1400 MJ/s

The characteristics of the power plant without CO_2 capture are given as following :

Gross production	: 685 MWe
Net production	: 630 MWe
Net efficiency	: 44.9%

The simulation of the power plant was performed using Alstom's internal simulation tools.

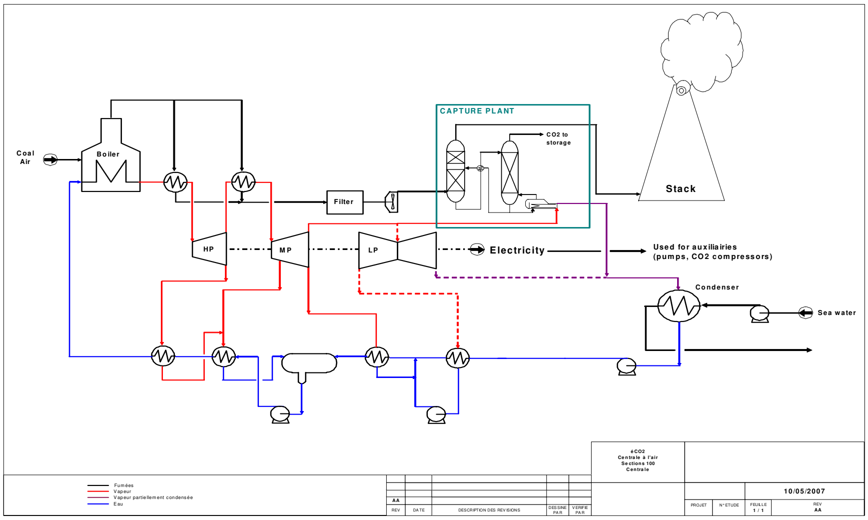

Figure 1 : PFD of the post-combustion integrated process

2.2. CO_2 Capture plant

2.2.1. Flue gas

The flue gas produced by the power plant are described bellow :

Flow rate : 1 750 000 Nm^3/h
Temperature : 120°C
Pressure : 1.01 bar abs
Composition N_2 : 74.1%vol.
CO_2 : 13.5%vol.
H_2O : 7.1%vol.
O_2 : 4.4%vol.
Ar : 0.9%vol.

2.2.2. Amine loop

The capture section is based on a classical amine loop technology using MEA at 30%wt as a solvent. The unit has been designed to capture 90%mol of the CO_2 emissions of the power plant.

The capture process is composed of different sections :

- A quench and washing section to cool down the flue gas to 30°C and remove the remaining SOx and NOx down to 10 mg/Nm^3 and 20 mg/Nm^3 respectively
- An absorption section where the cooled and washed flue gas is contacted with the solvent to remove 90%mol of the CO_2 in a packed column (structured packing Mellapack 252Y is considered in that study).
- A regeneration section where the acid gas is released and the solvent regenerated. This packed column is also design with structured packing Mellapack 252Y.

The capture plant was simulated and optimized using AspenTech Hysys software (amine package). An optimization of the solvent loading has been performed to design the unit [10].

2.2.3. CO_2 compression

The compression of the CO_2 obtained at the top of the regeneration section is performed through 4 stages of centrifugal compressors with intercooling of the CO_2 at 25°C between each stages (figure 2). The CO_2 is dried with a glycol unit between the third and fourth stage of compression to avoid corrosion and hydrate formation in the transport pipes. After the fourth stage of compression, the CO_2 is condensed and pumped to 110 bar for transportation.

2.3. Heat integration

The first integration is the use of a part of LP steam to regenerate the solvent, instead of being used in the LP turbine to produce electricity. Other heat integrations between the steam cycle and the CCS process were also considered, allowing some energy saving [11] (table 1).

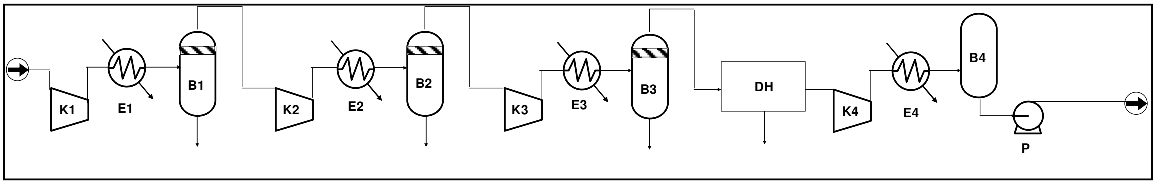

Figure 2 : CO_2 compression train

Table 1 : Post-combustion heat integration

Heat sources	Inlet Temperature (°C)	Outlet Temperature (°C)	Available heat (MJ/sec)	Heat recovered (MJ/sec)
Condenser top of the stripper	105	25	190	60
Lean solution sub-cooling	52	25	200	0
CO_2 compressors intercooling	108	25	60	0

Regenerator's condenser :

At the top of the stripper, a huge quantity of water is condensed as a reflux. The energy lost at this condenser can be easily used to pre-heat the feed water of the power plant, leading to an increase of the overall efficiency of the power plant.

Lean solution subcooling :

Even if there is an important quantity of energy available, it was not possible to recover it because of a too low temperature (52°C).

CO_2 compressors intercooling :

This possibility of heat integration has been studied but addition of heat exchangers in the compression will generate an additional pressure loss which lead to an uneconomical option.

2.4. Dynamic studies

A dynamic study has been performed to study the start up and shut down procedures of such an integrated process. The study showed that for a base mode power plant, the start up and shut down of the unit will force CO_2 capture plant to shut down as long as no steam will be available for solvent regeneration during these phases, leading to a decrease in global capture rate as well as a decrease in operability. It has been found that for post-combustion process, the overall capture rate will be 88% while CO_2 capture plant is designed for 90% capture rate.

3. Oxy-combustion process

Figure 3 presents the Process Flow Diagram of the power plant with the integrated CCS process.

3.1. Power production

As for the post-combustion process, the power plant is based on a super critical CFB power plant, using coal as fuel, for the same design capacity of 600MWe. The main characteristics of the thermodynamic cycle of the power plant are described here after :

HP live steam – turbine inlet : 270 bara
Live steam temperature – turbine inlet : 600°C
Feed water temperature : 295°C
Sea water temperature : 15.7°C
Condenser pressure : 35 mbara
Fuel flow rate : 54.8 kg/s (International bituminous coal)
Design capacity : 1400 MJ/s

The characteristics of the power plant considered for the oxyfuel case are given as following :
Gross production : 709 MWe
Net production : 574 MWe
Net efficiency : 41%

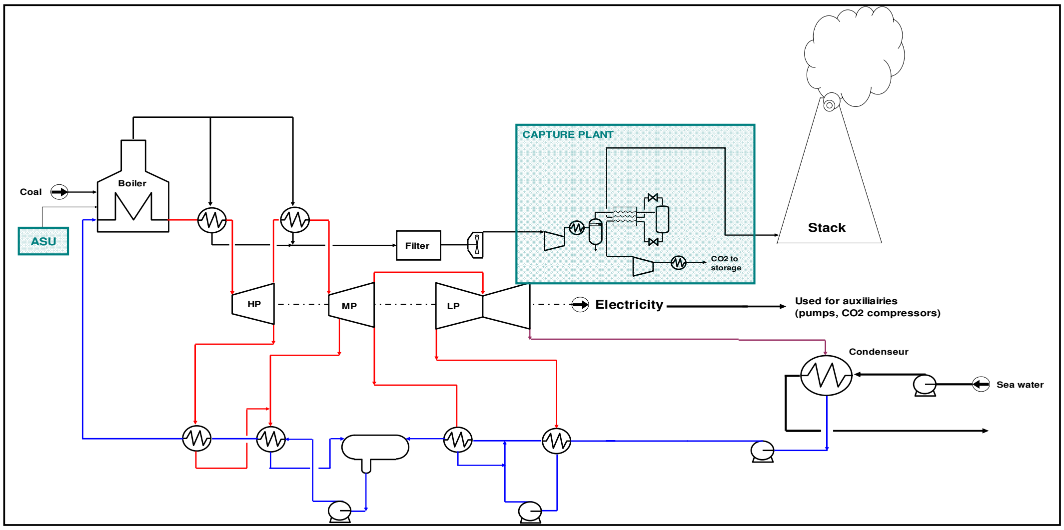

Figure 3 : PFD of the oxyfuel integrated power plant

The gross efficiency of an oxyfuel power plant is higher than for an air-fired power plant. As the auxiliary consumption is higher (due to oxygen production), without capture, the net efficiency of an oxyfuel power plant is lower than for an air-fired power plant. The advantage of oxy-combustion process will be regarding CO_2 capture - as CO_2 in the flue gas is highly concentrated there is no need for an amine loop unit to purify the CO_2 stream.

Air Separation Units (ASU) were considered and simulated with AspenTech Hysys to supply a 95% pure oxygen stream to the boiler. The simulation of the power plant was performed using Alstom's internal tools.

3.2. CO_2 capture plant

3.2.1. Flue gas

The flue gas produced by the oxyfuel power plant are described bellow :

Flow rate : 315 000 Nm^3/h
Temperature : 120°C
Composition N_2 : 2.26%vol.
CO_2 : 68.8%vol.
H_2O : 23.9%vol.
O_2 : 2.27%vol.
Ar : 2.6%vol.
SO_2 : 0.17%vol.

3.2.2. CO_2 purification and compression

Due to the need for oxygen excess in the boiler to guaranty the complete combustion of the fuel, as well as the purity of the O_2 stream considered in that study, the flue gas produced still contains some impurities (O_2, Ar, N_2) which have to be removed to allow the liquefaction and transportation of the CO_2 stream (figure 4).

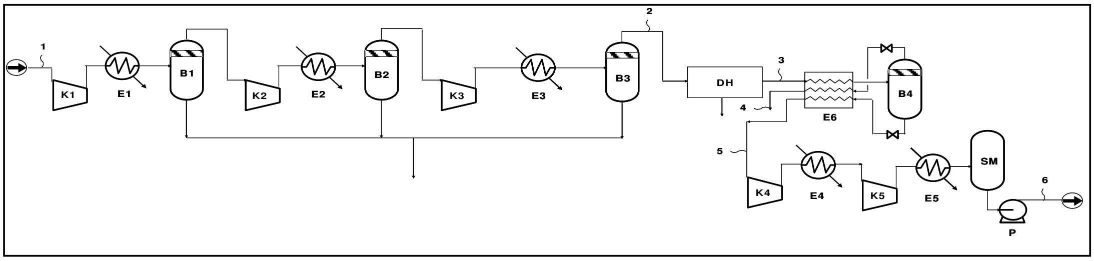

Figure 4: CO_2 compression train

The purification of the CO_2 stream is performed during the compression step by a cryogenic flash obtained by a release of the pressure between the third and fourth stage of compression. As for the post-combustion process, the CO_2 stream is first compressed into three stages and dehydrated with a glycol unit. The dry CO_2 stream is then purified through the cryogenic flash to be further compressed and transported. The pressure and temperature conditions of that cryogenic flash are tailored to keep less that 10%vol CO_2 loss in the impurities stream (90%vol CO_2 capture rate as well as for the post-combustion process) and to minimize the energy loss due to the forced pressure drop in the compression section. The pure CO_2 stream is then compressed in two more compression stages, liquefied and pumped to 110 bar for transportation.

3.3. Heat integration

As for the post-combustion process, several possibilities of heat integration have been investigated to increase the overall efficiency of the integrated process. In the oxyfuel case, there is no need for LP steam in the capture process. Here after are described the relevant options which have been implemented in the design (table 2).

During air compression (ASU) and CO_2 compression, the compressed gas is heated up and have to be cooled down before entering in the next compression stage. This heat can be recovered in the power plant water cycle by preheating the boiler feed water. Heat recovery exchangers have been installed in the air compression inter stages as well as in the first three stages of the CO_2 compression section to preheat the boiler feed water, leading to an increase of the overall plant efficiency.

3.4. Dynamic studies

As well as for the post-combustion process, a dynamic study has been performed to study the start up and shut down procedures of such an integrated process. It has been found that for the oxyfuel process, the overall capture rate will be 87% while CO_2 capture plant is designed for 90% capture rate. In that case, the capture rate decrease is due to longer stabilization of the power plant during start up phases.

Table 2 : Oxyfuel heat integration

Heat sources	**Inlet Temperature (°C)**	**Outlet Temperature (°C)**	**Available heat (MJ/sec)**	**Heat recovered (MJ/sec)**
ASU compressors intercooling	**110**	**25**	**91**	**68**
CO_2 compressors intercooling 3 stages	**140**	**25**	**55**	**48**

4. Economical analysis

4.1. Operating costs

For both integrated processes, as all the utilities needed for the capture and compression sections are taken from the power plant (except amine consumption), the operating costs are expressed in net efficiency loss; i.e. decrease of the electrical production due to auxiliary consumption (electricity and steam). Table 3 summarizes the main results obtained. The energy efficiency losses are 10.3 points for the post-combustion integrated process and 8.3 points for the oxyfuel integrated process. The impact of CO_2 capture on the plant efficiency is important in both cases, with a small advantage for the oxyfuel integrated process.

Table 3 : Process energy efficiencies

	Reference	Post-combustion	Oxyfuel
Plant capacity	1400 MWt	1400 MWt	1400 MWt
Gross production	685 MWe	604 MWe	709 MWe
Auxiliary consumptions	55 MWe	119 MWe	197 MWe
Power plant	*55 MWe*	*55 MWe*	*45 MWe*
Compression	-	*64 MWe*	*62 MWe*
ASU	-	*0 MWe*	*90 MWe*
Net production	**630 MWe**	**485 MWe**	**512 MWe**
Net Efficiency	**44.9 %**	**34.6 %**	**36.6 %**

4.2. Investment costs

Investments costs were estimated using proprietary methods. The study is based in Europe, prices are given in euros for 2006 with a +/-30 % uncertainty. The table 4 gives the details of the investments needed for the different sections. Thanks to the reduction of flue gas volume in the boiler, the power plant in the oxyfuel case is slightly cheaper than in the reference and post-combustion cases where the power plant remains identical. The overall CAPEX is higher for the oxyfuel process, mainly due to the cost of ASU. For both integrated processes, the over cost due to CO2 capture is high, respectively +60% and +40% for post-combustion process and oxyfuel process.

Table 4 : Investment costs

	Reference	Post-combustion	Oxyfuel
Power Plant	676 M€	680 M€	619 M€
Amine loop	-	184 M€	-
ASU	-	-	300 M€
Compression section	-	100 M€	170 M€
TOTAL CAPEX	**676 M€**	**964 M€**	**1089 M€**

4.3. Cost of electricity and CO_2 penalty

With the investment and operating costs (including variables and fixed costs), it is possible to calculate the production cost of electricity in the two studied cases as well as for the base case. The tables 5 and 6 summarize the techno-economical study for the three different cases, showing the production costs as well as the CO_2 penalties for the two integrated zero emissions power plants. Note that for the post-combustion process, the increase in variable costs is due to solvent make up.

Table 5 : Economical analysis hypothesis

Amortization	25 years
Discount rate	10%
Investment spread over	3 years
Interest rate	8%
Owner costs	10%
Fixed costs	2.8% of investment (€ / kW)
Coal price	43.4 € / t

Table 6 : Results of the techno-economical study

	Reference	Post-combustion	Oxyfuel
CAPEX	676 M€	964 M€	1088 M€
Net efficiency	44.9 %	34.6 %	36.6 %
Net production	630 MWe	485 MWe	512 MWe
Operability	7290 h / an	7132 h / an	6940 h / an
Variable costs	3.9 M€ /an	12.2 M€ / an	3.8 M€ / an
Cost of electricity	**38.2 € / MWh**	**65.9 € / MWh**	**67.2 € / MWh**
CO_2 emissions	750 t / kWh	115 t / kWh	119 t / kWh
CO_2 penalty	**-**	**43.9 € / tCO_2**	**46.2 € / tCO_2**

5. Conclusion

The study showed similar CO_2 penalties for both postcombustion and oxycombustion integrated processes, around 44€/tCO_2. The two technologies showed different advantages but leading to similar results according to CO_2 penalty and cost of electricity. This study also shows that the importance of start-up and shut-down procedures has to be taken into account for the evaluation of the capture rate. Heat integration has been investigated for the main heat sources available on the different parts of the overall process, to go further in the integration, one step will be the use of lower temperature flues.

6. Acknowledgements

The presented work were financially supported by ADEME.

7. References

1. IEA Greenhouse Gas R&D Programe, CO_2 capture in low rank coal power plants, 2006/2, January 2006.
2. IEA Greenhouse Gas R&D Programe, Estimating future trends in the cost of CO_2 capture technologies, 2006/5, January 2006.
3. P. Broutin, A. Féraud, Porcédé intégré de production d'électricité à partir de charbon avec capture et stockage du CO_2, Club CO_2, Paris, June 2005.
4. T. Burkhardt, PA. Bouillon, JC. Magdelenat, éCO2 project – Rapport final phase 1, convention ADEME 04 74 C0075, August 2006.
5. S. Hennes, PA. Bouillon, P. Broutin, Etude éCO2 – Rapport final, convention ADEME 06 74 C0051, September 2007.
6. P. Broutin, A. Féraud, Integration of Post-Combustion CO_2-Capture technology into a coal-fired power station, Energia da carbone pulito, Milan, Italy, July 16th, 2006.
7. T. Burkhardt, P.A. Bouillon, A comparison between power plants with integrated CO_2 post-combustion or oxy-fuel capture and compression, 6th Annual Conference on Carbon Capture & Sequestration Pittsburgh, Pennsylvania, May 7 - 10, 2007.
8. P. Delage, P. Broutin, Integrated CO_2 capture study for e coal fired station, 10th International CO_2 capture network of the IEA GHGT Research Program, Lyon, France, May 24-25, 2007.
9. S. Hennes, C. Mahieux, P.A. Bouillon, P. Broutin, Etude d'un procédé intégré de production d'électricité à partir de charbon avec CCS, Club CO_2, Paris, March 2008.
10. T. Burkhardt, J. Camy-Portenabe, A. Fradet, A. Tobiesen, H. F. Svendsen, Optimization of the process loop for CO_2 capture by solvents, GHGT-8, Trondheim, 2006.
11. T. Burkhardt, P.A. Bouillon, J.C. Magdelenat, Process for the removal of CO_2 including a thermally integrated regenerator, FR patent 2.907.025, 2008.