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Energy Procedia 4 (2011) 1886–1892

Energy Procedia

www.elsevier.com/locate/procedia

GHGT-10

Economic Feasibility of CO_2 Capture from Oxy-fuel Power Plants Considering Enhanced Oil Recovery Revenues

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Abstract

Considering the dramatic increase of greenhouse gases concentration in the atmosphere, especially carbon dioxide, reduction of these gases seems necessary to combat global warming. Fossil fuel power plants are one of the main sources of CO_2 emission and several methods are under development to capture CO_2 from power plants. In this paper, CO_2 capture from a natural gas fired steam cycle power plant using oxy-fuel combustion technology is studied. Oxy-fuel combustion is an interesting option since CO_2 concentration in the flue gas is highly increased. The Integrated Environmental Control Model (IECM) developed by Carnegie Mellon University (USA) is used to evaluate the effect of this capture technology on the plant efficiency and economic parameters of the system. The IECM uses regression models based on other studies to evaluate the required energy for oxygen production unit (air separation unit) and CO_2 purification and compression unit. In this work, these two units are simulated using the Aspen Plus software in parallel with the IECM, and the results are compared with the results of the IECM. This comparison verified that the power requirement evaluations from the IECM performance model and the Aspen Plus software are approximately the same. Since CO_2 capture and transport are cost and energy intensive, the cost of electricity (COE) in capture plants increases significantly. According to the assumptions in this study, the cost of electricity for both the base plant and the capture plant are calculated using the IECM cost model. The cost of electricity for the base plant is equal to 66.8 $/MWh while the cost of electricity for the capture plant is 123.7 $/MWh. In addition, cost of CO_2 avoided can be calculated by using the cost of electricity and CO_2 emission rate in the base and capture plants. If CO_2 storage cost or CO_2 benefit is not considered, the cost of CO_2 avoided is about 104 $/ton CO_2 for a 237 MW power plant. However, it is shown in this study that if the captured CO_2 is used for Enhanced Oil Recovery (EOR) in the nearby oil fields (assuming 100 km distance), the revenue gained can compensate for the extra cost of electricity produced by the oxy-fuel combustion natural gas steam cycle and consequently reduces the cost of CO_2 avoided. A rule of thumb is used to evaluate the amount of EOR revenues. According to this rule of thumb, 0.25 ton of crude oil is recovered per ton of CO_2 injected. A relation between gas and oil price is therefore required to consider an integrated natural gas fired steam power plant, CO_2 pipeline and oil field as an overall system. Assuming that natural gas price is a function of oil price, a rough estimation of oil price in which Carbon Capture and Storage (CCS) is economically feasible can be found. In this study, the relationship between oil and gas price is based on a polynomial function. This function is determined according to the time series information of natural gas and oil price in recent years (1997-2008) in the United States. The prices of these fuels in Iran were not used because the prices are heavily subsidized. The results show that at high oil prices, about $60/bbl, all the costs of CO_2 capture and transport to oil field can be compensated by EOR revenues which makes the integrated power plant and CCS with EOR economically feasible.

Keywords: CO_2 capture; oxy-fuel combustion; cost of electricity; EOR revenues; cost of CO_2 avoided

1. Introduction

Atmospheric concentration of CO_2 has increased from a pre-industrial concentration of 278 ppm to a current concentration of 379 ppm. Approximately 60% of the nearly 50 Gt per year of greenhouse gas emissions are CO_2 from fossil fuel combustion [1]. Carbon capture and storage (CCS) is emerging as an effective methods to avoid CO_2 emission to the atmosphere. A number of

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doi:10.1016/j.egypro.2011.02.067

studies have assessed different methods of CO_2 capture and CCS costs in different power plants based on technologies that are either commercial or under development [2, 3, 4]. Most studies consider only CO_2 capture costs and do not include the costs of transport and storage [2]. However, omission of transport and storage costs can lead to incorrect conclusions about the relative total cost of different power systems. Rubin et al. [3] compared the cost and performance of different fossil fuel power plants using the IECM including CO_2 transport and storage costs. In that study, it was assumed that pulverized coal (PC) and natural gas combined cycle (NGCC) plants employed an amine-based system for post-combustion CO_2 capture; while the integrated gasification combined cycle (IGCC) plant added a water gas shift reactor and a Selexol unit to capture CO_2. The captured CO_2 is injected into a deep saline aquifer or used for enhanced oil recovery. At same condition, with CCS, the IGCC plant is the lowest-cost system in all cases. With aquifer storage the PC plant has the highest; while for EOR the NGCC plant has the highest COE. Amann et al. [4] considered a NGCC power plant, and applied the oxy-fuel technology as CO_2 capture system. In their study, the impact of CO_2 capture was calculated with the Aspen Plus software. However, a NGCC power plant using oxy-fuel technology needs an advanced gas turbine to work with the new working fluid (the flue gas in oxy-fuel combustion is a combination of carbon dioxide and water vapor and the nitrogen is omitted). This specific gas turbine requires new design and development. Therefore, they concluded that in a NGCC power plant, application of oxy-fuel technology seems more efficient than amine scrubbing but more difficult to implement because of the specific gas turbine. It should be noted that a steam cycle power plant does not have this problem, since an ordinary boiler can easily be turned to an oxy-fuel boiler by the help of recycling a fraction of flue gas to combustion chamber to reduce the flame temperature.

1.1. Scope and objective of this paper

The principal objective of this paper is to assess the effect of oxy-fuel combustion technology on performance and economic parameters in a gas firing steam power plant. This assessment is done using the Integrated Environmental Control Model (IECM). The IECM uses a regression model to evaluate the required power of this unit based on the data from other studies. Also, the power requirements for CO_2 purification and compression unit is estimated by the expression derived in other studies [5, 6]. In this paper, these two units are also simulated using Aspen Plus software, and the results are compared in Section 3.

Fuel price variation causes change in both plant operating and maintenance (O&M) costs and EOR revenues. In this work, gas price is considered as a function of oil price and the revenues from EOR are also taken into account. By using a sensitivity analysis on fuel price, a rough estimation of oil price in which CO_2 capture is economically feasible can be found.

2. Analytical Tool for Comparative Assessments

To account for the many factors that affect CCS costs and emissions in power plants, the Integrated Environmental Control Model (IECM) is used. The IECM is a publicly available and widely used modeling tool developed by Carnegie Mellon University for the US Department of Energy's National Energy Technology Laboratory (DOE/NETL) [7]. The IECM employs fundamental mass and energy balances, together with empirical data, to quantify overall plant performance and emissions. Plant and process performance models are linked to a companion set of engineering-economic and financial models that calculate the capital costs and annual operating and maintenance (O&M) costs of individual plant components, plus the total COE for overall plant. Cost and performance models in the IECM draw upon a variety of detailed engineering-economic studies, resulting in a generalized modeling tool whose results are consistent with other detailed studies for the same set of input assumptions [3]. Technical documentation for each of component models is available elsewhere [7, 8, 9, 10].

In this paper, the IECM version 5.1.2 is used with all costs updated to 2005 values. The PC plant is used to model the steam cycle power plant, the fuel is changed from coal to natural gas, and the environmental control systems (electrostatic precipitator (ESP) and flue gas desulfurization (FGD)), which are necessary for coal plants, are omitted because in gas fired power plants these units are not needed. As mentioned above, the air separation unit and the flue gas post treatment units were also simulated by Aspen Plus software and the results were compared with those from the IECM.

3. Process Simulation

The Air Separation Unit (ASU) and CO_2 purification and compression unit are energy intensive. Therefore, the amount of energy used by these units has a great effect on the overall energy efficiency of the capture plant. In this study, the required energy of these two units is evaluated by two different methods: The IECM uses empirical correlations to assess the power requirement for ASU and CO_2 purification and compression unit. On the other hand, simulations have been carried out using the process software Aspen Plus to evaluate the power requirement of these two units. The results are compared in the following section.

3.1. Air separation unit

The IECM uses the following equations to estimate the power requirement of the ASU unit [5,6]. These equations are given here for the purpose of comparisons of the results with those of Aspen Plus that was used in this work.

$$MACP = 0.00175\phi + 0.1513 \quad \text{for } \phi \le 97.5\% \tag{1}$$

$$MACP = 0.0263/(100-\varphi)^{1.3163} + 0.3133 \quad \text{for } \phi > 97.5\% \tag{2}$$

$$MW_{ASU} = 5.51\text{E-}5 \times MACP \times M_{O_2} \tag{3}$$

Where MACP (KWh/m^3 O_2 product) is the power requirement and Φ is the O_2 product purity (mol %), MW_{ASU} is the ASU total power required, and M_{O2} (ton/hr) is the total oxygen requirement from ASU.

As mentioned above, the ASU is simulated by the Aspen Plus software. An ASU based on Linde's Double Column Cryogenic Process has been chosen to produce the high quantity of oxygen [11]. Although oxygen transport membranes are more effective methods of producing pure oxygen, they are still under development and are not yet suitable for large scale power generation. Further researches are still needed to scale them up to industrial applications [12]. In the proposed design (Figure 1), a two-stage centrifugal compressor, with interstage cooling, is used to compress air to 5 atm. The air is then further cooled in E-101 and E-102 by cooling water (Figure 1 below). The overhead product of T-102, which is 99% nitrogen, is sent to E-103 where it is used as a coolant. The top product of T-101 is throttled to 1.0 atm, and then fed to the top of the column, T-102. The bottoms is also throttled to 1.0 atm and fed to T-102. The bottom product of T-102 is 95% oxygen which is used for fuel combustion. In this simulation, it was assumed that the intake air is clean and dry and therefore dehumidification and filtration units were omitted from the PFD.

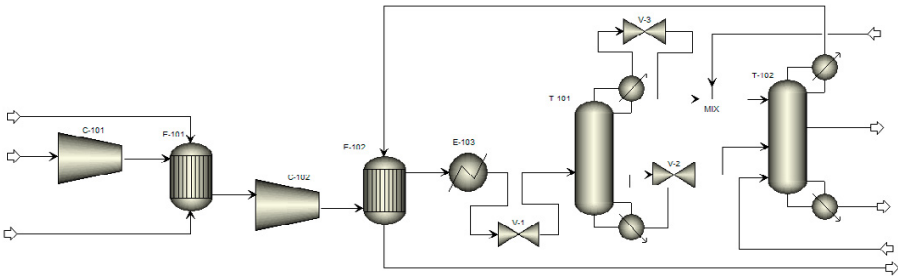

Figure 1 Air separation unit [11]

According to the mass balance which is available in the IECM performance model, the amount of oxygen required for the plant is about 150 ton/hr. The power requirement for ASU to produce this amount of oxygen with 95% purity is shown in Table 1. The difference between the two evaluations is about 6%.

Table 1. Comparison of the power requirement for ASU from Aspen and IECM models.

Parameter	IECM	Aspen plus
Power requirement (MW)	33.03	35

3.2. CO_2 Purification and Compression Unit

The IECM uses the following equations to estimate the power required for CO_2 purification and compression unit [13].

$$MW_{comp\_purif} = (e_{comp}/1000 + e_{purif}) \times M_{CO_2} \tag{4}$$

$$e_{comp} = \left[-51.632 + 19.207 \times \ln\left(14.7(P_{CO_2} + 1)\right)\right] / (1.1 \times \eta_{comp}/100) \tag{5}$$

Where:

M_{CO_2} = total mass of CO_2 captured (ton/hr)

e_{purif} = 0.109 MWh/ton, for high purity product (purity > 97.5%)

= 0.0018 MWh/ton, for low purity product

e_{comp} =KWh/ton

p_{CO_2} = CO_2 product pressure (barg)

η_{comp} = CO_2 compression efficiency (%)

The aim of the oxy-fuel combustion is to concentrate CO_2 in the flue gas. This leads to decreased gas flow rate sent to the capture unit. Thus, the CO_2 recovery is easier and the process size can be reduced compared with post-combustion capture [4].

The CO_2 purification and compression unit process is based on the IEA Report [14]. The sketch of the process is shown in Figure 2. The net flue gas, essentially raw CO_2, leaves the plant and compressed to 30 bara. The raw CO_2 gas passes through a dryer (C-201). The dryer is necessary to prevent ice formation, which could cause a blockage in the system as well as causing corrosion in the pipeline. Then, the inert (nitrogen and argon) and oxygen are separated to give 95% mol CO_2. The system uses two flash separators (C-202 and C-203) at temperatures of -27 ˚C and -55 ˚C. The necessary refrigeration for plant operation is obtained by evaporating liquid CO_2 at pressure levels of 21.5 bara and 10.5 bara, and compressing these two low pressure gas streams in the main CO_2 compressor (K-201) to the final pipeline delivery pressure of 110 bara. Further information of this process is available elsewhere [14].

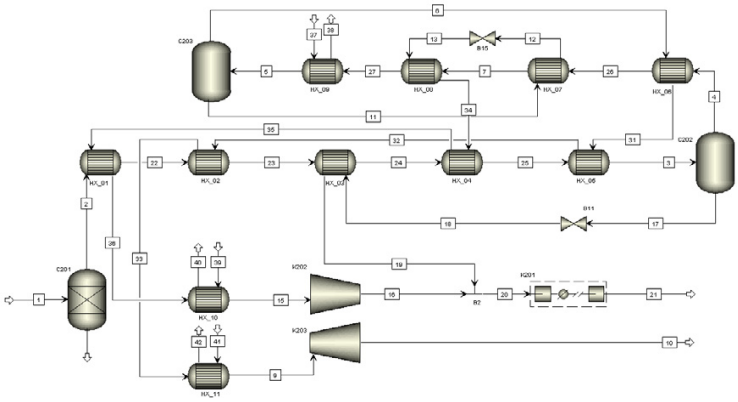

Figure 2 CO_2 purification and compression unit [14]

The power requirement for this unit to purify and compress 96 ton/hr CO_2 is summarized in Table 2. The amount of captured CO_2 is calculated using mass balance of the IECM performance model. According to Table 2, the evaluation of required power is approximately the same. The difference between these two methods is about 1.5%.

Table 2. Comparison of power requirement for CO_2 purification and compression unit from ASPEN and IECM models.

Parameter	IECM	Aspen plus
Power requirement (MW)	12.25	12.06

4. Baseline Comparisons

In this section, the "reference plant" is compared with the "capture plant". The "reference plant" is a facility without CO_2 capture, while the "capture plant" refers to the same facility with CCS. Table 3 summarizes key assumptions for this baseline analysis. The "capture plant" includes compression unit for CO_2 product stream and pipeline transport. The CO_2 stream is compressed to 110 bara and transported to oil reservoir 100 km away from the power plant through the pipeline. Table 3 lists the key assumptions for the baseline analysis and Table 4 summarizes the major results of this analysis. It should be noted that EOR revenues are not taken into account in this section.

Table 3. Key assumptions for the baseline analysis.

Discount rate (%)	Plant book life(yr)	Gas price ($/GJ, HHV)	Capacity factor (%)
10	25	3	85

Table 4. Results for the baseline cases using the IECM.

Parameter	Reference Plant	Capture Plant
Input fuel of boiler (tonne/h)	39.01	37.28
Gross plant size (MW)	237	237
Net plant output (MW)	227.6	174.2
Net plant efficiency, HHV (%)	38.98	31.22
CO_2 capture efficiency (%)		90
CO_2 emission rate (kg/KWh)	0.603	0.059
Cost of electricity ($/MWh)	66.8	123.7
Cost of CO_2 avoided ($/ton CO_2)		104

As shown in Table 4, the boiler in the reference plant uses more fuel than the capture plant because oxy-fuel technology improves the boiler efficiency. The main part of heat loss in the boilers is due to hot flue gas leaving the combustion chamber

[15]. According to the IECM performance model the boiler efficiency in the reference plant is 84.43%, while the boiler efficiency in the capture plant is 88.35%. Hence, the boiler efficiency increases due to heat loss decrease. Capture units, like air separation unit (ASU) and CO_2 purification and compression unit, are energy intensive. Therefore, the net plant output and plant efficiency reduces in capture plant compared with the reference plant. As mentioned before, using capture technology would increase the cost and energy consumed in power plants and hence increases the cost of electricity (COE). According to Table 4, the COE in the capture plant is about two times more than the reference plant. Cost of CO_2 avoided is an index to compare different CCS systems (Equation 6). Without EOR revenues, this cost would be 104 \$/ton CO_2 for the capture plant considering in this study. Obviously, it is not economically attractive.

$$Cost\ of\ CO_2\ avoided = \frac{COE_{cap.} - COE_{ref.}}{(CO_2\ Emission\,Rate)_{ref.} - (CO_2\ Emission\,Rate)_{cap.}} \tag{6}$$

Where:
COE=\$/MWh
CO_2 Emission Rate=ton CO_2/MWh

5. CO_2 Storage in Oil Reservoirs and EOR Revenues

There are a number of methods used to model oil recovery in enhanced production (e.g., CO_2 injection, polymer injection, gas injection, water flooding, etc.). These methods, in the order of both increasing complexity and data requirements, are based on rule-of-thumb estimates, semi-analytical fractional-flow models and finite difference models [16]. In this paper, a rule-of-thumb provided by the IEA Report [17] is used to predict the enhanced oil production. According to this rule-of-thumb, the minimum amount of oil recovery from a field is 0.25 ton oil per ton of CO_2 injected. In this research, the gas price is assumed to be a function of oil price. Therefore, by using the relation between gas and oil price, the effect of EOR revenues on the system (power plant and oil field as a whole system) can be assessed. The crude oil price and gas price for electricity sector are collected from EIA [18] for 1997-2008. A polynomial function between oil and gas price is determined by the Eviews software (Equation 7). As shown in Table 5, the correlation coefficient R^2 is about 0.9. In general, a chosen function can be acceptable if it can predict the variable with R^2 more than 0.8, thus the correlation used in this work is acceptable. Also the Durbin-Watson statistic is 2.16. According to a rule-of-thumb the range of 1.7-2.3 is acceptable for Durbin-Watson [19]. The Durbin–Watson statistic is a test statistic used to detect the presence of autocorrelation in the residuals from a regression analysis. Therefore, this function can predict the gas price according to oil price.

$$Gas\ price = 0.093 + 0.951 \times (oil\ price) - 0.03 \times (oil\ price)^2 \tag{7}$$

Table 5. Results for predicting gas price from oil price using Eviews Software

GAS=C(1)+C(2)*OIL+C(3)*OIL^2				
	Coefficient	Std. Error	t-Statistic	Probability
C(1)	0.093259	0.752435	0.123943	0.9041
C(2)	0.951616	0.210780	4.514747	0.0015
C(3)	-0.030296	0.011534	-2.626713	0.0275
R-squared	0.899541	Mean dependent variable		4.529444
Adjusted R-squared	0.877217	S.D. dependent variable		1.976940
S.E. of regression	0.692727	Akaike info criterion		2.315956
Sum squared residual	4.318833	Schwarz criterion		2.437182
Log likelihood	-10.89573	F-statistic		40.29462
Durbin-Watson statistic	2.164926	Probability (F-statistic)		0.000032

It should be noted that the EOR revenues in the IECM cost model is considered as a negative cost in the variable Operating and Maintenance (O&M) costs section.

6. Effect of Oil price on the Cost of CO_2 Avoided

The cost of CO_2 avoided is dependent on the COE of the reference and capture plants (Equation 6). While the cost of CO_2 avoided is negative, COE in the capture plant is less than the COE in the reference plant.

Figure 4 shows the effect of oil price on the cost of CO_2 avoided. According to Figure 4, when oil price reaches 11.11 $/GJ (64 $/barrel), the cost of CO_2 avoided becomes zero. As a rough estimation, CO_2 capture from gas firing steam plant is economically feasible for oil price higher than 64 $/barrel considering EOR revenues.

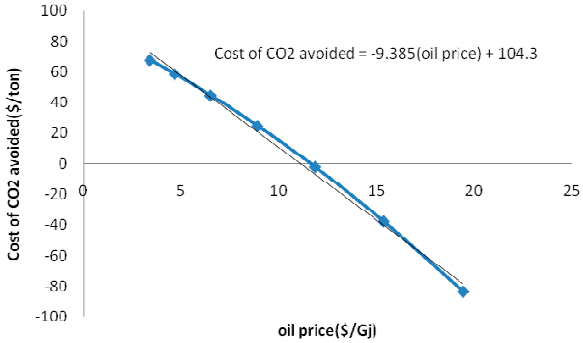

Figure 3 Effect of oil price on the cost of CO_2 avoided.

7. Conclusion

In this paper, oxy-fuel combustion was considered as a capture technology in a gas firing steam cycle. The IECM model is used to compare the performance and economic parameters in both the reference and capture plants. Since the IECM estimates the power requirement for air separation unit and CO_2 purification and compression unit using expressions derived in other studies, these two units were simulated by the Aspen Plus software to compare the results with those of the IECM. The results show that the power requirement evaluations from the IECM performance model and the Aspen Plus software are approximately the same. Since the capture units (air separation unit and CO_2 purification and compression unit) are cost and energy intensive, the cost of electricity generated in capture plant increases drastically. In order to compensate for the cost of CO_2 capture and transport, the captured CO_2 can be injected to oil fields for enhanced oil recovery (EOR). It was shown that at high oil prices ($64/ barrel or higher), EOR revenue can fully compensate for the cost of CO_2 capture and storage.

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