Optimal operation of MEA-based post-combustion carbon capture for natural gas combined cycle power plants under different market conditions

*Xiaobo Luo, *Meihong Wang*

School of Engineering, University of Hull, Cottingham Road, Hull, HU6 7RX, United Kingdom

Meihong.Wang@hull.ac.uk

Abstract

Carbon capture for fossil fuel power generation attracts an increasing attention in order to address the significant challenge of global climate change. This study aims to explore the optimal operation under different market conditions for an assumed existing natural gas combined cycle (NGCC) power plant integrated with MEA-based post-combustion carbon capture (PCC) process. The steady state process models for NGCC power plant, PCC process and CO_2 compression train were developed in Aspen Plus® to give accurate prediction of process performance. Levelised cost of electricity (LCOE) is formulated as the objective function in optimisation studies. Economic evaluation was carried out for the base case of the integrated system including CO_2 transport and storage (T&S). The optimal operations were investigated for the carbon capture level under different carbon price, fuel price and CO_2 T&S price. The study shows that carbon price needs to be over €100/ton CO_2 to justify the total cost of carbon capture from the NGCC power plant and needs to be €120/ton CO_2 to drive carbon capture level at 90%. Higher fuel price and CO_2 T&S price would cause a higher operating cost of running carbon capture process thus a higher carbon price is needed if targeted carbon capture level is to be maintained.

Keywords: CCS, Carbon capture, Process Optimization, Process Simulation, NGCC power plant

1. Introduction

1.1 Background

Using carbon capture and sequestration (CCS) technology to reduce CO_2 emissions from fossil fuel-fired (e.g. coal and natural gas) power generation plays an important role to achieve the target of limiting average global temperature increase to 2°C in 2050 (IEA, 2012). Amine-based post-combustion chemical absorption process is considered as the most likely technology to be commercially deployed (Wang et al., 2011). Currently, 20% of global electricity production capacity is supplied from gas-fired power generation (BP, 2014). This number is expected to increase in the next several decades because of the advent of cheap natural gas and carbon emission mitigation policy. However the cost of electricity will increase from £66 to £144.1 per MWh for NGCC power plant integrated with PCC process (DECC, 2013). Except for an enormous capital investment, the parasitic energy penalty is also significant for NGCC power plant integrated with PCC process (Luo et al., 2015;

Marchioro Ystad et al., 2013). Therefore research efforts are required for potential improvements to reduce both the capital cost as well as the energy penalty to gain a better economic profile of commercial deployment of carbon capture.

One of the most important engineering tools for addressing these cost issues is optimization (Edgar et al., 2001). Optimization of a large process, such as NGCC power plant integrated with PCC process in this study, can involve several levels such as process configurations (Amrollahi et al., 2012; Oyenekan and Rochelle, 2007; Sipöcz and Tobiesen, 2012), features of equipment designs (Agbonghae et al., 2014; Canepa and Wang, 2015), controlled variables of plant operations (Abu-Zahra et al., 2007b; Kvamsdal et al., 2011; Mac Dowell and Shah, 2013) as well as control strategies (Panahi and Skogestad, 2011; Schach et al., 2013).

Most early studies were carried out for the parametric studies for coal-fired power plants. Key variables such as lean solvent loading, liquid solvent and gas flow rate ratio (L/G ratio), MEA concentration in solvent and stripper operating pressure have been investigated. The results show those parameters have big impacts to energy consumptions (Abu-Zahra et al., 2007b) and are highly sensitive to the economic performance of the whole plant (Abu-Zahra et al., 2007a). However their optimal values exhibit a large range in different studies. For example, the optimal value of lead loading is in a wide range of 0.18-0.32 mol CO_2/mol MEA with corresponding special duty at a range of 4.5-3.8 GJ/ton CO_2 (Abu-Zahra et al., 2007b; Mac Dowell and Shah, 2013). Considering PCC process for gas-fired power plant, the range of lean loading is even wider from 0.12 to 0.32 mol CO_2/mol MEA in recent studies (Agbonghae et al., 2014; Luo et al., 2015; Mores et al., 2014; Sipöcz and Tobiesen, 2012). For the design parameters, the diameter and packing height of the absorber and the stripper have large impacts to the capital cost. The optimal values of these design parameters are coupled with other process variables. Their interactions are highly nonlinear based on chemical principles. Then it is hard to make fast cost estimation by simply formatting cost calculation equations.

Another approach to achieve minimal total cost is optimal operation towards market changes such as volatile electricity demand and pricing, fuel price as well as carbon price. In the study of Rao and Rubin (2005), it was founded that the relationship between the cost and carbon capture level is non-linear and venting a fraction of flue gas to keep relatively low capture level less than 75% could achieve a significant cost saving. Mores et al. (2012) found that the total annual cost of carbon capture plant varies linearly for carbon capture level within a range of 70%-80% but it increases exponentially when carbon capture level increases from 80% to 95%. Cohen at al. (2012) investigated the economic benefits of a 500 MW_e coal-fired power plant with CO_2 capture for a carbon pricing from 0 to 200 US$/ton CO_2 and concluded that CO_2 capture investment is unjustifiable at low CO_2 prices. In the study by Mac Dowell and Shah (2013), optimal CO_2 capture level is 95% for £30/ton CO_2 and £90/MWh scenario and is around 70% for £8/ton CO_2 and £55/MWh scenario for a 660 MW_e coal fired power plant integrated with a capture plant. Their result shows that carbon price should be more than £40/ton CO_2 to justify the total cost of carbon capture for an objective of capture level greater than 90% without considering the costs of CO_2 compression, transport and storage.

1.2 Aim of this study and its novelties

Compared with coal-fired power plant, the CO_2 concentration in flue gas is much lower for a gas fired power plant which causes some significantly different features in terms of the economic performance such as bigger equipment size and lower L/G ratio. Thus the optimization results of carbon capture for a coal-fired power plant may not be applied directly to NGCC power plant. This paper aims to explore the optimal operation of an assumed existing MEA-based PCC process for an NGCC power plant by conducting cost optimization based on a steady state first principle process model. This process model consists of a 453 MW_e NGCC power plant integrated with PCC process and CO_2 compression train whilst the cost model was extended to cover the cost of CO_2 transport & storage (T&S) by combining the cost estimate based on process simulation results and the literature data. The novelties of this study are claimed as follows:

(1) In the cost model, the total annual cost of the CO_2 T&S was regarded as an operating expense charged by the operators of the CO_2 T&S infrastructure, which avoids heavy calculations for the CO_2 T&S with many uncertainties. With this method, the cost model was developed to cover the cost of the whole integrated system. Thus the results and insights obtained from this study present the optimal operation for the NGCC power plant equipped with a whole integrated CCS chain.

(2) The optimisations were carried out for the optimal carbon capture level under different carbon price, natural gas (NG) price and CO_2 T&S price. It is found that carbon price, NG price and CO_2 T&S price will greatly affect the decision making about the optimal carbon capture level for operating the PCC process for a NGCC power plant.

2. Methodology

2.1. Process model development

For this large scale plant optimisation, process model is the important part. Process model contains the bulk of parameters, variables and constraints in an optimization problem (Edgar et al., 2001). Accurate process model offers better predictions of process variables in terms of both technical and economic performance. In this study, the process models include those for NGCC power plant, PCC process and CO_2 compression train. In this section, the sub-models were developed using Aspen Plus® based on our previous studies (Luo et al., 2015; Canepa et al., 2013).

2.1.1. Model for NGCC power plant

A 453 MW_e NGCC reference model with a GE 9351FB gas turbine and a triple-level pressures reheat HRSG (IEAGHG, 2012) was developed using Aspen Plus®. Peng-Robinson (Peng and Robinson, 1976) with Boston Mathias modifications (Neau et al., 2009a; Neau et al., 2009b) (PR-BM) equation of state (EOS) is used for the gas cycle and STEAMNBS (Aspen-Tech, 2012) EOS is used for the steam cycle for the calculation of thermodynamic properties.

At the ambient conditions (ambient temperature is assumed to be 9 °C and ambient pressure is assumed to be1.01 bar in this study), fresh air is compressed to mix with nature gas to enter the combustion chamber (See Fig. 1). The hot gas leaves the combustion chamber and enters the turbine to expand to generate a part of electricity. Exhaust gas from gas turbine, through HRSG, provides heating to the steam cycle to generate three kinds of steams at the different pressures of 170bar, 40bar and 5bar, which go to the high pressure steam turbine (HP-ST), the intermediate pressure steam turbine (IP-ST) and the low pressure steam turbine (LP-ST) respectively to generate another part of electricity.

The model parameters are presented in Table 1. The simulation results using this model in Aspen Plus® were compared with the simulation results using another software package GT Pro® in IEAGHG benchmark report (IEAGHG, 2012), in order to make a brief validation. The comparison results of Aspen Plus® and GT Pro® appear to be in good agreement (Luo et al., 2015).

2.2. Models for PCC and compression train

For the reactive absorption process using MEA solvent to absorb CO_2, the rate-based approach model in Aspen Plus® has been proven to be able to provide an acceptable accuracy for the performance prediction of PCC process (Lawal et al, 2009; Zhang et al., 2009). The model for PCC process used in this study is developed in Aspen Plus® based on the previous researches (Canepa et al., 2013; Luo et al., 2015). Electrolyte NRTL (Chen and Song, 2004) property method is used to describe the thermodynamic and physical properties. The simulation results from this model were compared with the experimental data (Dugas, 2006). The validation shows a good agreement of several key design parameters and operational variables such as lean solvent loading, rich solvent loading, capture level and the temperature profiles of both the absorber and the stripper (Canepa and Wang, 2015). After validation with experimental data at the pilot scale, PCC process model was scaled up to match the capacity requirement of the NGCC power plant. Table 2 shows the model parameters of the PCC process after scaling up to match the NGCC power plant. In order to directly use the detailed equipment costs in IEAGHG's benchmark report (IEAGHG, 2012) in Sections 4 & 5 of this paper for cost evaluation and optimization, the design features of the equipment of the PCC process in this study were set to be consistent with those in this benchmark report.

A compression train is needed to pressurize captured CO_2 to reach a high entry pressure, as high as 110-150 bar, for pipeline transport and geologic sequestration. By our previous study (Luo et al., 2014), an optimal option was selected to get a minimum annual cost including annualized capital cost, operating and maintenance cost and energy cost. The optimal configuration compromises 6 stages integrally geared compressor followed by a pump with intercoolers at an exit temperature of 20 ^{o}C, which was also adopted in this study. The key parameters can be seen in Table 3.

2.3. NGCC integrated with PCC and compression train

When the NGCC power plant is integrated with the PCC process and CO_2 compression train, there are several basic interfaces (see Fig. 1) including: (1) Flue gas is lined from HRSG to the capture process after gas processing; (2) Low pressure steam is extracted for solvent regeneration; (3) Steam condensate returns to the steam cycle of the NGCC power plant; (4) the NGCC power plant provides electrical power supply for PCC process and CO_2

compression. Compared with NGCC standalone, carbon capture case has a total 9.58% net power efficiency decrease according to previous study (Luo et al., 2015). The net electricity output is reduced by three factors: 1) steam extraction causes a reduction in steam flow rate through the LP-ST; 2) the power consumption of CO_2 compression train; 3) auxiliary power consumption for the blower and solvent circulation pumps. Out of the three factors, the power reduction due to steam extraction is the main one.

Another process modification for the NGCC power plant integrated with PCC process is to recirculate 38% of the flue gas leaving from the HRSG outlet back to compressor inlet where it is mixed with fresh air (see Fig.1). The CO_2 concentration in the flue gas from NGCC power plant is as low as 3-4 mol% whilst it is 11-13 mol% for a coal fired power plant. Higher flue gas flowrate leads to bigger equipment size and lower CO_2 concentration in flue gas causes lower absorption efficiency of the absorber in the PCC process (Jonshagen et al., 2011). Exhaust gas recirculation (EGR) is an effective solution for lower capital cost and better thermal performance for a NGCC power plant integrated with a PCC process (Luo et al., 2015; Sipöcz and Tobiesen, 2012).

3. Development of cost models

3.1. Cost breakdown

For operating an industrial process plant, the total cost includes capital expenditure (CAPEX) and operational expenditure (OPEX). OPEX can be split into fixed OPEX (operating and maintenance (O&M) cost) and variable OPEX (mainly the energy and utilities cost) (IEAGHG, 2002). CAPEX includes equipment material and installation, labour cost, engineering and management cost and other costs happened during the project contracture and commissioning. Fixed OPEX includes overhead cost, operating and maintenance cost (O&M) and other costs fixed for the plant no matter running at partial or full load or shutdown. Variable OPEX mainly includes fuel cost, energy and utilities costs, and solvent make-up cost. For an NGCC power plant integrated with PCC process, it is noticed that variable cost should also include the emission penalty cost of CO_2 discharged into atmosphere and T&S cost of CO_2 captured.

3.2. Objective function

For techno-economic evaluation or cost optimisation of a power plant integrated with carbon capture process, different economic indexes have been used in different studies, including (a) total annual operating profits; (b) total annualized cost; (c) levelised cost of electricity (LCOE); (d) cost of CO_2 avoided. In this study, LCOE was formulated to be the objective function of the optimization. LCOE was calculated through dividing total annual cost by annual net power output as in equation (1). The total annual cost is a sum of annualized CAPAX, fixed OPEX and variable OPEX as in equation (2).

$$LCOE = \frac{Total\ annual\ cost}{Net\ power\ output} \tag{1}$$

$$Total\ annual\ cost = Annualized\ CAPEX + Fixed\ OPEX + Variable\ OPEX \tag{2}$$

The annualized CAPEX is the total CAPEX multiplying by capital return factor (McCollum and Ogden, 2006). It would be noticed that this study focuses on the optimal operation of NGCC power plant with PCC process. Its CPAEX and fixed OPEX are assumed to be fixed neglecting the tax and labor cost changes. Only the variable OPEX was considered to vary in response to different market situations. In this study, variable OPEX includes fuel cost, cooling utilities cost, solvent make-up cost, carbon emission cost and CO_2 T&S cost.

3.3. CO_2 T&S cost

CO_2 transport and storage are two important sections of whole CCS chain and are also cost-intensive processes. Collecting CO_2 mixture from several emitters into trunk pipelines for geologic storage is more cost-effective than the use of separate pipelines (Chandel et al., 2010; IPCC, 2005). Other companies may operate CO_2 transport and storage infrastructure and charge the emitters for the CO_2 stream entering the network. One example is that National Grid plc. will construct and operate the CO_2 transport pipelines and the permanent CO_2 undersea storage facilities at a North Sea site in the Yorkshire and Humber CCS Project in the UK (National Grid, 2014).

The previous predictions of the costs of CO_2 T&S are in a wide range with high uncertainties. For the pipeline transport cost, IPCC presented to be 9.9-14.9 €/ton CO_2. Luo et al. (2014) conducted a simulation-based techno-economic assessment which shows the transport cost is around €17/ton CO_2. For the CO_2 storage cost, IPCC predicted it to be 0-7.9 €/ton CO_2 for onshore storage and 6-30.8 €/ton CO_2 for ocean storage. DECC of UK (DECC, 2013) issued a report, in which the transport and storage cost accounts for a big part of the increment of LCOE. Under FID 2013, 2020 and 2028 CCS technology scenarios, the CO_2 T&S cost is 49.7, 19.2 and 4.5 €/MWh.

3.4. Optimisation methodology

Optimal operation of such an assumed existing large configuration of plant could include many subtopics such as temperatures, pressures, flow rates of key streams and some operating conditions of main equipment. In this paper, the optimisation study focus on operation strategy of the PCC process for the NGCC power plant. A typical optimization model consists of an objective function supplemented with equality and inequality constraints. LCOE was formulated as the objective function in this study. So this optimization problem can be formulated as follows:

$$\text{Minimize } f(c,d,o) \tag{3}$$

Subject to the process constrains and operation constrains:

$$h(c,d,o) = 0 \tag{4}$$

$$g(c,d,o) \leq 0 \tag{5}$$

Where c is the vector of the coefficients in the objective function and constrains; d is the vector of the design variables (i.e. diameters and packing heights of the absorber and stripper, also the operating pressure and operating temperature of the towers). And o is the vector of operational variables (i.e. CL, capture level, L_{lean}, lean loading, L/G_{ratio}, solvent and flue gas ratio and $H_{reboiler}$, reboiler duty).

In this study, equality constraints relate to the mass balances, reactions and phase balance were formulated by the first principle process models built in Aspen Plus® described in Section 2. For this optimal operation of an assumed existing plant, the design variables such as diameters and packing heights of the absorber and the stripper would not change. The values of key design variables can be seen in the tables in Section 2.

The inequality constraints are imposed in the form of upper bounds for product flow rates for different cases. Those inequality constraints for controlled operational variables in this study are listed in equation (6-10) considering the flexible operation range of packing towers and other equipment.

$$60\% \leq CL \leq 95\% \quad (6)$$

$$0.2 \leq L_{lean} \leq 0.36 \ (mol\ CO_2/mol\ \ MEA) \quad (7)$$

$$0.5 \leq L/G_{ratio} \leq 6 \quad (8)$$

$$0 \leq F_{flood} \leq 0.75 \quad (9)$$

$$0 \leq H_{reboiler} \leq 400 \ (MW_{th}) \quad (10)$$

For the nonlinear programming (NPL) optimisation of such a large scale rate-based process model, high computational requirements and convergence problems often occur although commercial software package AspenPlus® was used. Compromising on those challenges, specific values were considered for two key operational variables although they are continuous in real process. Their value sets were presented in equation (11) and (12) respectively.

$$CL = \{60\%, 70\%, 80\%, 85\%, 90\%, 95\%\} \quad (11)$$

$$L_{lean} = \{0.2, 0.24, 0.26, 0.28, 0.3, 0.32, 0.36\} \ (mol\ CO_2/mol\ \ MEA) \quad (12)$$

4. Techno-economic evaluation of the base case

In this section, the technical performance was evaluated according to the process simulation results. Then the cost of whole chain for capturing carbon from NGCC power plant was evaluated for the base case by combining calculation results and the literature data, in order to give a basis for the optimal operation study in Section 5.

4.1. Technical performance

The base case was set up based on the PCC process described in Section 2.2 with 90% carbon capture level for the NGCC power plant with EGR. The key technical performance parameters of the base case were compared with the reference case of NGCC standalone and were summarized in Table 4.

4.2. LCOE of the base case

For the economic evaluation, CAPEX and fixed OPEX were referred to published benchmark report (IEAGHG, 2012). Variable OPEX was summarized from each sub cost calculated based on the simulation results from process model. To harmonize results for comparison with other studies, the following assumptions were made: 1) all costs are corrected to €2015 using the harmonised consumer price index (HICP) in Europe zone; 2) the captured CO_2 mixture has no economic value; 3) cooling water is sourced from a nearby body of water at the cost of pumping and operation of a cooling tower. Other important cost inputs are provided in Table 5, with the costs given in Euro.

Table 6 shows the comparison of the results between the reference case of NGCC standalone and the base case of carbon capture. In the base case, the annualized CAPEX of PCC process is close to the annualized CAPEX of NGCC power plant and the variable OPEX accounts for 65% of the total annual cost. For the variable OPEX of NGCC standalone, the fuel cost is the biggest part and carbon emission cost is the second largest part. However when NGCC is integrated with PCC process, the fixed OPEX increases obviously because of new expense items such as CO_2 T&S cost and MEA solvent make-up cost.

5. Optimal operation

The economic evaluation of the base case in section 4.2 shows the high capital cost as well as wide range operating cost occurring for carbon capture from the NGCC power plant. For the optimal operation of an assumed existing NGCC power integrated with PCC process, two major questions will be answered: (1) what is the optimal carbon capture level under different market situations? and then (2) what are the optimal values of key operational variables at a specific optimal capture level?

5.1. Optimal capture level under different carbon price

In order to achieve the target of global climate control, carbon tax (also called “allowance”) was set to drive the actions of reducing CO_2 emission. Current carbon price in Europe is around €7/ton CO_2 (FML, 2015) but future carbon price are highly uncertain from 25 US$ to 200 US$ per tonne of CO_2 with different paths (USDOE, 2010). The economic performances with regard to LCOE were examined under different carbon prices of €7, €50, €100 and €150 per tonne of CO_2 in this study.

The results were summarized in Fig. 2. Under low carbon price of €7/ton CO_2 (Fig. 2 (a)), LCOE gets the minimum value of €82.3/MWh with 60% CL at an optimal lean loading of 0.26 mol CO_2/mol MEA. Fig. 2(a) shows LCOE increase obviously with higher CL no matter what the lean loading would be. That trend indicates that the carbon emission penalty cost cannot justify the high operating cost of the PCC process under low carbon price. The optimal operation in terms of minimum LCOE is to vent the flue gas to the atmosphere through bypassing the PCC process. With higher carbon price of €50/ton CO_2, the differences of LCOE of different CLs become smaller as indicated in see Fig. 2(b). For the scenario of carbon price of €100/ ton CO_2, the values of LCOE distribute in a very narrow range (see Fig.

2(c)) which means the carbon emission penalty cost can just justify the extra variable OPEX for carbon capture. With high carbon price of €150/ ton CO_2, the optimal value of LCOE of 90% CL and 95% is very close at a lean loading of 0.26-0.28 mol CO_2/mol MEA whilst LCOE is around €99.5/MWh (see Fig. 2(d)).

The optimal values for key operational variables at different capture levels were displayed in Fig. 3. The economic range of the lean loading was found to be 0.26-0.3 mol CO_2/mol MEA for the capture level in a range from 60% to 95%. It is noticed that this result is different with the optimal values such as 0.158 mol CO_2/ mol MEA in the study of Mores et al. (2014) and 0.2 mol CO_2/ mol MEA in the study of Agbonghae et al. (2014). The reason is that those studies implemented optimisation studies for both design and operation. In that context, lower lean loading required smaller L/G ratio which results in a reduction of the required diameter of the absorber. However the diameter of the absorber is fixed in this study for optimal operation. Therefore the CAPEX is fixed. Here, the optimal operation is to reduce the OPEX only. In this sense, the lean loading doesn't have to be that low.

The trend of the L/G ratio is different from that for the lean loading. The L/G ratio relies more on the amount of CO_2 captured. As shown in Fig. 3, the L/G ratio increases as more solvent is required for absorb more CO_2 at higher capture level. It is also noticed that the required L/G ratio for a same capture level varies for different CO_2 concentration in the flue gas. The range of L/G ratio in mass is from 0.5 to 1.5 for a NGCC power without EGR (4.04 mol% CO_2 content in the flue gas) (Agbonghae et al., 2014) and it is from 1.2 to 2.2 for a NGCC with EGR (7.32 mol% CO_2 content in the flue gas) in this study. As a comparison, It is from 2.0 to 5.0 for a subcritical coal-fired power plant with PCC process (13.5 mol% CO_2 content in flue gas) (Agbonghae et al., 2014).

The special duty was calculated from the reboiler duty dividing by the rate of CO_2 captured. The range of special duty is from 3.25 to 4.35 GJ/ton CO_2 for PCC process for gas-fired power plant in previous studies (Agbonghae et al., 2014; Canepa and Wang, 2015; Mores et al., 2014; Sipöcz and Tobiesen, 2012). Fig. 4 presented that the special duty is from 4.05 to 4.32 GJ/ton CO_2 whilst the reboiler duty increases greatly when the capture level increase from 60% to 95%.

Fig. 5 gives the trend of thermal efficiency of the NGCC with PCC at different capture levels, which is easy to justify because more steam was extracted from the crossover pipe between IP and LP steam turbine of the NGCC power plant for providing heat to the stripper reboiler of the PCC process at the higher capture levels.

5.2. The effect of NG price

In section 4, the economic evaluation results show fuel cost is the largest part of variable OPEX and is a huge expense even compared with annualized CAPEX. It is realized that the uncertain NG price would have big impact to decide the optimal operation strategy.

Fig. 6 shows the results of the optimal capture level under different fuel prices with fixed carbon price of €100/ton CO_2. At the scenario of low NG price at €2/GJ (see Fig. 6(a)), the higher capture level shows a lower LCOE because the CO_2 emission penalty can easily justify the fuel cost. The situation reverses when NG price rises up to €12/GJ (see Fig. 6(c)).

Thus a carbon price higher than €100/ton CO_2 is required to drive the balance back for carbon capture.

Fig. 7 presents the required carbon price for driving the capture level to 90% in response to the changes of fuel price. The result shows a range of LCOE is 63.5-138.0 €/MWh when the NG price rises from €2/GJ to €12/GJ. For the based case point with 90% capture level, the required carbon price is around €107/ton CO_2 with a LCOE of €102/MWh.

5.3. The effect of CO_2 T&S price

The CO_2 T&S cost is a significant part of variable OPEX of running a PCC process for the power plant. DECC of the UK (DECC, 2013) issued a report, in which the transport and storage cost accounts for a big part of the increment of LCOE. Under FID 2013, 2020 and 2028 CCS technology scenarios, the CO_2 T&S cost is 40.7, 15.7 and 3.7 £/MWh. The change of the CO_2 T&S price may affect the optimal operation decision largely. In this section, the optimisations were carried out on three different CO_2 T&S equivalent prices of 102.5, 39.54 and 9.32 €/ton CO_2.

The results were displayed in Fig. 8. With low CO_2 T&S price of is €9.32/ton CO_2 (see Fig. 8(a)), the optimal capture level is 90%-95% compared with 80%-90% at the intermediate price of €39.54/ton CO_2 (see Fig.8(b)). At the high CO_2 T&S price of is €102.5/ton CO_2, the high cost of carbon capture would not be justified (see Fig.8(c)) and a carbon price higher than €100/ton CO_2 is needed to provide driving force for carbon capture. Otherwise bypassing PCC process is the optimal choose.

Fig. 9 presents the required carbon price for driving the capture level to 90% in response to the changes of CO_2 T&S price. The result shows a range of LCOE is 80.4-124.3 €/MWh when the CO_2 T&S cost rises from 0 to €100/ton CO_2. When the CO_2 T&S cost is 0, the carbon price is required to be €55/ton CO_2 for 90% capture level, which is very close to €54/ton CO_2 for the case without considering the CO_2 compression, transport and storage in the study by Mac Dowell and Shah (2013). Comparing the results from Fig. 8 and Fig. 10, it is noticed that CO_2 T&S price has a lower sensitivity than fuel price to LCOE at 90% capture level.

6. Conclusions

In this paper, the optimal operation of large scale NGCC power plant integrated with PCC process was investigated. The objective function to be minimized in the optimization is formulated as LCOE. The techno-economic evaluation was carried out for the reference case and the base case for whole integrated system of NGCC integrated with PCC, CO_2 transport and storage (T&S). It indicates that LCOE increases from €58.1/MWh without carbon capture to €97.7/MWh for carbon capture at 90% level. The optimal operation studies were carried out for the carbon capture level under different carbon price, fuel price and CO_2 T&S price by minimizing LCOE. For an assumed existing 453 MW_e NGCC power plant with whole CCS system, current carbon price of €7/ton CO_2 is too low to drive power generators to run the carbon capture process. Carbon price needs to be risen up to around €120/ton CO_2 to drive carbon capture level to 90%. An economic range of lean loading is 0.26-0.3 mol CO_2/mol MEA for the capture levels from 60% to 95%. This study indicates carbon price, fuel price and CO_2 T&S price will significantly affect the decision making on the optimal capture level for operating the PCC process for a NGCC power plant.

Acknowledgements

The authors would like to acknowledge the financial support from EU FP7 Marie Curie International Research Staff Exchange Scheme (Ref: PIRSES-GA-2013-612230) and 2013 China-Europe small-and medium sized enterprises energy saving and carbon reduction research project (No.SQ2013ZOA100002).

References

Abu-Zahra, M.R.M., Niederer, J.P.M., Feron, P.H.M., Versteeg, G.F., 2007a. CO_2 capture from power plants: Part II. A parametric study of the economical performance based on mono-ethanolamine. International Journal of Greenhouse Gas Control 1, 135-142.

Abu-Zahra, M.R.M., Schneiders, L.H.J., Niederer, J.P.M., Feron, P.H.M., Versteeg, G.F., 2007b. CO_2 capture from power plants Part I. A parametric study of the technical performance based on monoethanolamine. International Journal of Greenhouse Gas Control 1, 37-46.

Agbonghae, E.O., Hughes, K.J., Ingham, D.B., Ma, L., Pourkashanian, M., 2014. Optimal Process Design of Commercial-Scale Amine-Based CO_2 Capture Plants. Industrial & Engineering Chemistry Research 53, 14815-14829.

Alibaba.com, 2015. monoethanolamine price. Available at: http://www.alibaba.com/showroom/monoethanolamine-price.html (Assessed February 2015).

Amrollahi, Z., Ystad, P.A.M., Ertesvåg, I.S., Bolland, O., 2012. Optimized process configurations of post-combustion CO_2 capture for natural-gas-fired power plant – Power plant efficiency analysis. International Journal of Greenhouse Gas Control 8, 1-11.

Aspen-Tech, 2012. Aspen Physical Property System: Physical Property Methods. Aspen Technology, Inc., Burlington, USA, p. 248.

BP p.l.c, 2014. BP Statistical Review of World Energy. Available at: http://www.bp.com/content/dam/bp/pdf/Energy-economics/statistical-review-2014/BP-statistical-review-of-world-energy-2014-full-report.pdf (Assessed September 2014)

Canepa, R., Wang, M., 2015. Techno-economic analysis of a CO_2 capture plant integrated with a commercial scale combined cycle gas turbine (CCGT) power plant. Applied Thermal Engineering 74, 10-19.

Canepa, R., Wang, M., Biliyok, C., Satta, A., 2013. Thermodynamic analysis of combined cycle gas turbine power plant with post-combustion CO_2 capture and exhaust gas recirculation. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering 227, 89-105.

Chandel, M.K., Pratson, L.F., Williams, E., 2010. Potential economies of scale in CO_2 transport through use of a trunk pipeline. Energy Conversion and Management 51, 2825-2834.

Chen, C.C., Song, Y., 2004. Generalized electrolyte ‐ NRTL model for mixed ‐ solvent electrolyte systems. AIChE Journal 50, 1928-1941.

Cohen, S.M., Rochelle, G.T., Webber, M.E., 2012. Optimizing post-combustion CO_2 capture in response to volatile electricity prices. International Journal of Greenhouse Gas Control 8, 180-195.

DECC of UK, 2013. CCS Cost Reduction Task Force: final report, Available at: https://www.gov.uk/government/publications/ccs-cost-reduction-task-force-final-report (Assessed February 2015)

Dugas, R.E., 2006. Pilot plant study of carbon dioxide capture by aqueous monoethanolamine. MSE Thesis, University of Texas at Austin.

Edgar, T.F., Himmelblau, D.M., Lasdon, L.S., 2001. Optimization of Chemical Processes. McGraw-Hill.

Fusion Media Limited (FML), 2015. Carbon Emissions Futures - Dec 15 (CFI2Z5). Available at: http://www.investing.com/commodities/carbon-emissions (Assessed February 2015).

IEA, 2012. Energy Technology Perspectives 2012. International Energy Agency, Paris.

IEAGHG, 2002. Pipeline transmission of CO_2 and energy. Transmission study report. IEA GHG, pp. 1-140.

IEAGHG, 2012. CO_2 Capture at Gas Fired Power Plants. International Energy Agency. Available at: http://www.globalccsinstitute.com/publications/co2-capture-gas-fired-power-plants (Assessed February 2015).

IPCC, 2005. Carbon Dioxide Capture and Storage, UK, p. pp 431

Jonshagen, K., SipÃķcz, N., Genrup, M., 2011. A novel approach of retrofitting a combined cycle with post combustion CO_2 capture. Journal of Engineering for Gas Turbines and Power 133, 011703.

Kvamsdal, H.M., Haugen, G., Svendsen, H.F., 2011. Flue-gas cooling in post-combustion capture plants. Chemical Engineering Research and Design 89, 1544-1552.

Lawal, A., Wang, M., Stephenson, P. and Yeung, H. (2009), Dynamic modelling of CO2 absorption for post combustion capture in coal-fired power plants, *Fuel*, Vol. 88, Issue 12, p2455-2462.

Luo, X., Wang, M., Chen, J., 2015. Heat integration of natural gas combined cycle power plant integrated with post-combustion CO_2 capture and compression. Fuel.

Luo, X., Wang, M., Oko, E., Okezue, C., 2014. Simulation-based techno-economic evaluation for optimal design of CO_2 transport pipeline network. Applied Energy 132, 610-620.

Mac Dowell, N., Shah, N., 2013. Identification of the cost-optimal degree of CO_2 capture: An optimisation study using dynamic process models. International Journal of Greenhouse Gas Control 13, 44-58.

Marchioro Ystad, P.A., Lakew, A.A., Bolland, O., 2013. Integration of low-temperature transcritical CO_2 Rankine cycle in natural gas-fired combined cycle (NGCC) with post-combustion CO_2 capture. International Journal of Greenhouse Gas Control 12, 213-219.

McCollum, D.L., Ogden, J.M., 2006. Techno-economic models for carbon dioxide compression, transport, and storage & Correlations for estimating carbon dioxide density and viscosity, pp. 1-87.

Mores, P., Rodríguez, N., Scenna, N., Mussati, S., 2012. CO_2 capture in power plants: Minimization of the investment and operating cost of the post-combustion process using

MEA aqueous solution. International Journal of Greenhouse Gas Control 10, 148-163.

Mores, P.L., Godoy, E., Mussati, S.F., Scenna, N.J., 2014. A NGCC power plant with a CO2 post-combustion capture option. Optimal economics for different generation/capture goals. Chemical Engineering Research and Design 92, 1329-1353.

National Grid, 2014. Yorkshire and Humber CCS Project. Available at: http://www.ccshumber.co.uk/ (Assessed April 2015).

Neau, E., Hernández-Garduza, O., Escandell, J., Nicolas, C., Raspo, I., 2009a. The Soave, Twu and Boston–Mathias alpha functions in cubic equations of state: Part I. Theoretical analysis of their variations according to temperature. Fluid Phase Equilibria 276, 87-93.

Neau, E., Raspo, I., Escandell, J., Nicolas, C., Hernández-Garduza, O., 2009b. The Soave, Twu and Boston–Mathias alpha functions in cubic equations of state. Part II. Modeling of thermodynamic properties of pure compounds. Fluid Phase Equilibria 276, 156-164.

Oyenekan, B.A., Rochelle, G.T., 2007. Alternative stripper configurations for CO_2 capture by aqueous amines. AIChE Journal 53, 3144-3154.

Panahi, M., Skogestad, S., 2011. Economically efficient operation of CO_2 capturing process part I: Self-optimizing procedure for selecting the best controlled variables. Chemical Engineering and Processing: Process Intensification 50, 247-253.

Peng, D.Y., Robinson, D.B., 1976. A new two-constant equation of state. Industrial and Engineering Chemistry Fundamentals 15, 59-64.

Rao, A.B., Rubin, E.S., 2005. Identifying Cost-Effective CO_2 Control Levels for Amine-based CO_2 Capture Systems. Industrial & Engineering Chemistry Research 45, 2421-2429.

Schach, M.-O., Schneider, R., Schramm, H., Repke, J.-U., 2013. Control Structure Design for CO_2-Absorption Processes with Large Operating Ranges. Energy Technology 1, 233-244.

Sipöcz, N., Tobiesen, F.A., 2012. Natural gas combined cycle power plants with CO_2 capture – Opportunities to reduce cost. International Journal of Greenhouse Gas Control 7, 98-106.

USDOE, 2010. Energy Market and Economic Impacts of the American Power Act of 2010, Washington, DC, USA.

Wang, M., Lawal, A., Stephenson, P., Sidders, J., Ramshaw, C., 2011. Post-combustion CO_2 capture with chemical absorption: A state-of-the-art review. Chemical Engineering Research and Design 89, 1609-1624.

Ycharts, 2015. European Union Natural Gas Import Price. Available at: http://ycharts.com/indicators/europe_natural_gas_price (Assessed February 2015).

Zhang, Y., Chen, H., Chen, C.-C., Plaza, J.M., Dugas, R., Rochelle, G.T., 2009. Rate-Based Process Modeling Study of CO_2 Capture with Aqueous Monoethanolamine Solution. Industrial & Engineering Chemistry Research 48, 9233-9246.