

Process engineering method for systematically comparing CO₂ capture options

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Abstract

In the context of greenhouse gas emissions mitigation, CO₂ capture and storage is regarded as a promising alternative for fossil fuel fed power plants. In order to design and evaluate the competitiveness of such complex integrated energy conversion systems, a systematic comparison including thermodynamic, economic and environmental considerations is necessary. From a process engineering perspective, it is important to evaluate the impact of CO₂ capture not only on the efficiency but also on the costs and on the environmental impacts, and to assess the trade-offs. This paper presents the development of a systematic thermo-environmental optimisation strategy for the consistent modelling, comparison and optimisation of fuel decarbonisation options. In particular, it is highlighted how the economic scenario influences the competitiveness and hence the optimal process design.

Keywords: CO₂ capture, Multi-objective optimisation, Process design, Power plant

1. Introduction

To meet the CO₂ reduction targets and to ensure a reliable energy supply, the development and wide scale deployment of cost-competitive innovative low-carbon energy technologies is necessary. Carbon capture and storage (CCS) in power plants is considered as such a promising measure. Three major concepts for CO₂ capture in power plants can be distinguished: post-, pre- and oxyfuel-combustion. The thermo-economic competitiveness of these CO₂ capture options depends on the power cycle, the resources, the capture technology and the economic scenario. Several studies have investigated the penalty of CO₂ capture in terms of efficiency and costs (ZEP (2011), Metz et al. (2005), Figueroa et al. (2008), Finkenrath (2011)). By applying process modelling and simulations, different process configurations have been evaluated in Cormos et al. (2011), Berstad et al. (2011) and Kvamsdal et al. (2007). These studies mainly focus on the thermodynamic performance without including detailed heat and power integration. Economic aspects are considered in Kanniche et al. (2010), whereas economic and environmental aspects are taken into account by Viebahn et al. (2007). None of these studies combines extensive flowsheeting with thermodynamic, economic and environmental considerations simultaneously to make a comprehensive comparison of CO₂ capture options in power plants applications.

This paper applies a systematic methodology to make a consistent comparison of different post- and pre-combustion process options for electricity generation with CO₂ capture. For each process option the same design and performance evaluation principles are applied and the same assumptions are made, which allows to make a thorough

competitiveness assessment on a common basis. Through multi-objective optimisation the trade-off between efficiency, CO₂ capture rate and costs is assessed. The potential process improvement of CO₂ capture process integration by internal heat recovery and valorisation of waste heat for combined heat and power generation is identified. Taking into account the sensitivity of the economic performance to the carbon tax, resource price, operating time, investment and interest rate, it is revealed how the optimal process design is influenced by the economic scenario.

2. Methodology

The presented approach combines flowsheeting and energy integration techniques with economic evaluation and life-cycle assessment in a multi-objective optimisation framework previously presented in Gassner and Maréchal (2009), Gerber et al. (2011) and Tock and Maréchal (2012c). The advantage of including the process integration model in the design process is that the influence of the design and operation is reflected on the thermo-environmental performance of an energy balanced system. This allows to make a systematic comparison of CO₂ capture options in power plants applications.

3. Process description

To show the need of comparing process options with regard to energetic, economic and environmental considerations, different natural gas and biomass fed power plants configurations with pre- or post-combustion CO₂ capture are investigated. Figure 1 summarises the studied options. The different process units are modelled as previously described in Tock and Maréchal (2012a,b,c,d). In a similar way, coal and oxy-fuel combustion concepts can be analysed.

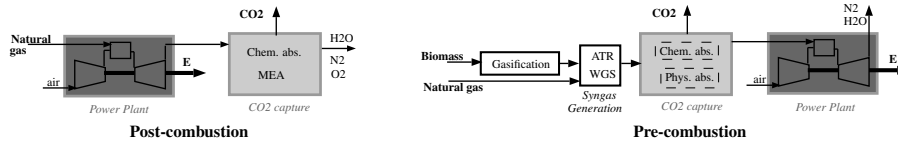


Figure 1: Investigated CO₂ capture options.

4. CO₂ capture options comparison

The competitiveness is evaluated by the energy and cost penalty and the environmental benefit of capturing CO₂ in power plants. The environmental benefit is expressed by the local CO₂ emissions and the overall life cycle impacts assessed for different impact methods for a functional unit of 1GJ of electricity produced. A conventional natural gas combined cycle (NGCC) power plant without CO₂ capture is considered as a reference. The CO₂ avoidance costs ($\frac{COE_{CC} - COE_{ref}}{CO_{2,emit,ref} - CO_{2,emit,CC}}$) are calculated with regard to this reference. The economic performance is expressed by the capital investment and the operating costs evaluated for the base case economic scenario defined in Table 2. The energy efficiency and CO₂ capture rate are maximized by multi-objective optimisation. Based on Pareto results, such as the ones presented in Figure 2, compromise process

configurations with 90% of CO₂ capture are selected for natural gas fed processes and with 60% of capture for biomass processes. The performance results are summarised in Table 1.

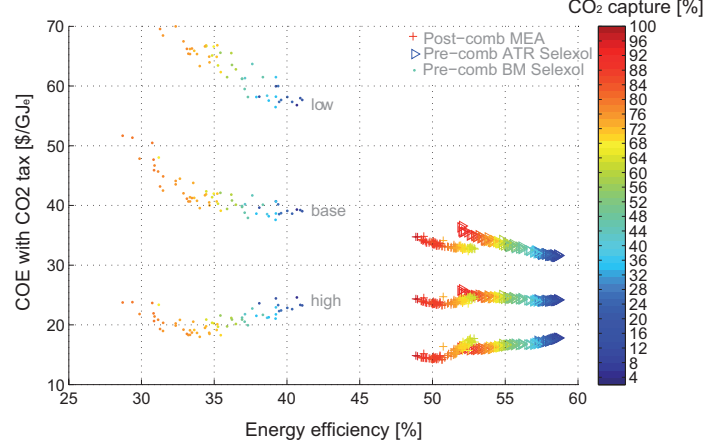


Figure 2: Multi-objective optimisation results: Performance of power plants with CO₂ capture for different economic scenarios defined in Table 2.

4.1. Thermo-environomic performance

Pre-combustion capture reveals to perform slightly better in terms of energy efficiency than post-combustion capture (Table 1). In pre-combustion processes the energy demand for CO₂ capture is lower, however the capital investment is larger because of the more complex installation. The specific annual investment costs are similar since the higher productivity balances the additional investment. Consequently, the electricity production costs, in which the resource purchase accounts for up to 80%, are comparable and highly dependent on the natural gas and biomass market price evolution.

Table 1: Performance results for different power plant options with CO₂ capture.

| System | NGCC no CC | Post-comb MEA | ATR TEA | ATR Selexol | SMR TEA | BM TEA | BM Selexol |
|--|---------------|------------------|------------|----------------|------------|-----------|---------------|
| Feed [MW_{th}] | 559 | 587 | 725 | 725 | 725 | 380 | 380 |
| CO ₂ capture [%] | 0 | 89.5 | 89.7 | 89.1 | 89.3 | 59 | 59 |
| ϵ_{tot} [%] | 58.75 | 49.6 | 56.8 | 52.6 | 53.3 | 34.8 | 34.8 |
| Net electricity [MW_e] | 333 | 296 | 412 | 381 | 386 | 132 | 132 |
| Power steam network [MW_e] | 113.4 | 101 | 82.5 | 67.7 | 55.6 | 45.7 | 45.7 |
| Power GT [MW_e] | 219.5 | 227 | 368 | 369 | 350 | 132 | 132 |
| COE [$\$/\text{GJ}_e$] | 18.31 | 23.17 | 22.67 | 24.5 | 24.1 | 66.1 | 49.5 |
| Annual Invest. [$\$/\text{GJ}_e$] | 1.1 | 2.1 | 2.2 | 2.4 | 2.3 | 21.4 | 11.2 |
| Avoidance cost [$\$/\text{t}_{CO_2,avoid}$] | - | 53.8 | 45.8 | 66 | 61.9 | 173.6 | 113.3 |
| CO ₂ emissions [$\text{kg}_{CO_2}/\text{GJ}_e$] | 105 | 14.9 | 10.1 | 11.5 | 11.2 | -170.4 | -170.4 |
| IPCC GWP [$\text{kg}_{CO_2,eq}/\text{GJ}_e$] | 120 | 34 | 30 | 31.9 | 36.1 | -139.6 | -134.2 |
| EI99 [pts/GJ_e] | 7.48 | 7.7 | 7.7 | 8.1 | 9.0 | 6.2 | 6.1 |
| EI99 Resources Contr.[%] | 78.41 | 89.22 | 82.35 | 83.36 | 79.49 | 17.44 | 17.23 |
| EI99 Health Contr.[%] | 19.30 | 9.25 | 13.67 | 13.36 | 14.95 | 6.65 | 6.95 |
| EI99 Ecosystem Contr.[%] | 2.29 | 1.53 | 3.99 | 3.28 | 5.56 | 75.92 | 75.82 |

Biomass processes yield lower efficiencies and higher costs, but have the advantage

of capturing biogenic CO_2 which leads to a negative CO_2 balance. In addition, the introduction of a carbon tax will shift the competitiveness of CO_2 capture processes.

4.2. Influence of economic scenarios on the competitiveness

The economic performance of CO_2 capture highly depends on the introduction of a carbon tax and on the resource purchase price. Based on sensitivity analysis and multi-objective optimisation it is shown how different process options become competitive under specific economic scenarios.

4.2.1. Sensitivity analysis

The variation of the electricity production costs with the resource purchase price and the introduction of a carbon tax is studied by sensitivity analyses in Figure 3. When a carbon tax of $35\$/\text{t}_{\text{CO}_2}$ is introduced, the economic benefit of a conventional NGCC is reduced and scenarios with 90% of CO_2 capture become competitive (Figure 3 left). The break even natural gas price for which post-combustion CO_2 capture becomes competitive is around $6\$/\text{GJ}_{\text{NG}}$ for a carbon tax of $35\$/\text{t}_{\text{CO}_2}$. Under the base case economic conditions, the break even carbon tax is around $50\$/\text{t}_{\text{CO}_2}$ for post-combustion capture with MEA and around $62\$/\text{t}_{\text{CO}_2}$ for pre-combustion capture with Selexol as shown in Figure 3 (right). Due to the benefit of capturing biogenic CO_2 , CO_2 capture in biomass fed power plants becomes competitive with natural gas fed processes for a carbon tax of $62\$/\text{t}_{\text{CO}_2}$. In these analyses, the CO_2 capture rate and thus the process design are fixed. However, it is evident that there is a trade-off between the economic performance and assumptions, and the process design, in particular the CO_2 capture rate, as seen based on multi-objective optimisation in Figure 2.

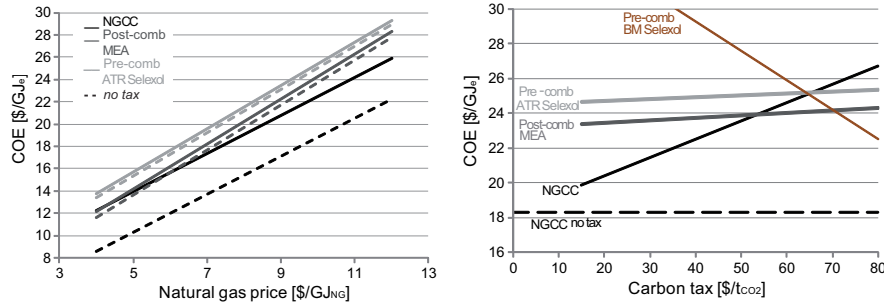


Figure 3: *Left*: Influence of the natural gas purchase price on the electricity production costs without (---) and with (—) the inclusion of a carbon tax of $35\$/\text{t}_{\text{CO}_2}$. *Right*: Influence of the carbon tax on the electricity production costs without and with CO_2 capture for a natural gas price of $9.7\$/\text{GJ}_{\text{NG}}$ and a biomass price of $5\$/\text{GJ}_{\text{BM}}$.

4.2.2. Economic scenario influence

The influence of the economic scenarios, defined in Table 2, is studied for three different capture options based on the optimisation results clearly revealing the trade-off between energy efficiency and CO_2 capture in Figure 2. For these economic scenarios the COE including the carbon tax becomes $27.5\$/\text{GJ}_e$ (*low*), $22\$/\text{GJ}_e$ (*base*) and $17\$/\text{GJ}_e$ (*high*) respectively for the reference NGCC plant. The results in Figure 2 reveal that the choice of the optimal process configuration is highly affected by the economic scenario. For part load operation, high resource prices and low carbon tax (*low*)

Table 2: Definition of the economic scenarios.

| Scenario | Base | Low | High |
|--|------|------|------|
| Resource price [\$/GJ _{res}] | 9.7 | 14.2 | 5.5 |
| Carbon tax [\$/t _{CO2}] | 35 | 20 | 55 |
| Yearly operation [h/year] | 7500 | 4500 | 8200 |
| Expected lifetime [years] | 25 | 15 | 30 |
| Interest rate [%] | 6 | 4 | 8 |

CO₂ capture is not beneficial, while for medium load operation, low resource price and high carbon tax (*high*), configurations with high CO₂ capture rates are favored. For the economic scenario *low*, post-combustion CO₂ capture performs best for each capture rate with regard to the electricity production costs. For the base case assumptions, pre- and post-combustion CO₂ capture in natural gas power plants perform equally in terms of COE for capture rates between 60 and 75%, whereas biomass based processes are more expensive. While for the economic scenario *high*, biomass processes generating green electricity become much more competitive. For natural gas fed power plants, pre-combustion CO₂ capture is advantageous with regard to COE for capture rates below 75% and post-combustion capture for higher capture rates. With the economic scenario *high*, the electricity production costs clearly decrease with increasing CO₂ capture rates, due to the profit from the carbon tax. This leads to negative CO₂ avoidance costs for capture rates above 40% in pre-combustion and above 65% in post-combustion CO₂ capture in NGCC plants. For high capture rates post-combustion CO₂ capture in NGCC plants seems to perform best with regard to the electricity production costs, while pre-combustion CO₂ capture in natural gas power plants is advantageous with regard to the energy efficiency, and CO₂ capture in biomass based power plants is beneficial with regard to the environmental performance. Consequently, there is a competition between the different processes. The production priority and scope defines the decision that has to be taking.

5. Conclusion

The comparison between pre-combustion and post-combustion CO₂ capture in natural gas fed power plants reveals that pre-combustion CO₂ capture capturing 90% of the emissions by physical absorption with Selexol yields a 5.6% higher efficiency than post-combustion CO₂ capture by chemical absorption with MEA yielding an efficiency of 49.6%. However, the economic performance is comparable with 24.5 and 23.2\$/GJ_e respectively for a natural gas price of 9.7\$/GJ_{NG}. With regard to a conventional NGCC plant (58.7% efficiency, 18.3\$/GJ_e), the economic competitiveness of these options highly depends on the introduction of a carbon tax and on the natural gas price. A reduction of the resource price to 7.8\$/GJ_{NG} leads to about a 25% lower break even CO₂ tax. When a high carbon tax is introduced, high CO₂ capture rates become attractive and negative CO₂ avoidance costs can be reached. Due to the advantage of capturing biogenic CO₂, biomass fed power plants become also competitive from an economic and environmental point of view, even if the efficiency is only around 35%. With regard to the economic performance, post-combustion CO₂ capture in NGCC plants seems to perform best at high capture rates, while pre-combustion CO₂ capture in natural gas power plants is advantageous with regard to the energy efficiency, and CO₂ capture in

biomass based power plants is beneficial with regard to the environmental performance. Consequently, there is a competition between the various process options and the different objectives. The choice of the optimal process configuration is hence defined by the production scope and the priorities given to the different aspects. This shows that the proposed process engineering method is a powerful tool to compare systematically different process options, assess trade-offs and support decision-making under different economic scenarios.

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