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Decision support for CO_2 capture process options under uncertain market conditions using multi-objective optimisation

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Abstract

To meet the CO_2 reduction targets and ensure a reliable energy supply, the development of cost-competitive innovative low-carbon energy technologies is essential. Switching to renewable resources and CO_2 capture and storage in power plants, are regarded as promising alternatives. Post-, oxy- and pre-combustion CO_2 capture concepts are applicable for power plants using natural gas, coal or biomass as a feedstock. A systematic thermo-environomic optimisation strategy including thermodynamic, economic and environmental considerations is applied for the consistent modelling and optimisation of CO_2 capture options. The environmental benefit and the energetic and economic costs of CO_2 capture are assessed and optimised. The economic competitiveness appears to be strongly determined by the economic conditions such as the resource price and the carbon tax which are highly uncertain. A method that takes into account the economic parameter sensitivity to support decision-making based on the Pareto-optimal solutions is proposed here. The selection method aims at identifying the most economically competitive process configuration in terms of the polygeneration of electricity, heat and captured CO_2 in a wide range of market conditions.

Keywords: CO_2 capture, Decision-making, Economic conditions, Multi-objective optimisation, Power plant

1. Introduction

To meet the CO_2 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. The performance of these CO_2 capture options depends on the power plant layout, the resources, the capture technology and the economic conditions. The penalty of CO_2 capture in terms of efficiency and costs has been assessed in several studies (ZEP (2011); Metz et al. (2005); Finkenrath (2011)). The competitiveness of CO_2 capture processes is determined by the economic conditions, especially the resource price and the introduction of a carbon tax. The analysis of the gas and carbon market over the last years, reveals diverse patterns over time and with regard to the geographic location (IEA (2011); EU (2011)). European gas prices are about twice as high as US gas prices and are projected to be 10 \$/GJ in 2020, 12 \$/GJ in 2030 and 16 \$/GJ in 2050 for the *EU 'Reference'* energy scenario (EU (2011)). According to these predictions, the carbon tax prices which drop from around 25 €/t_{CO2} in 2008 to below 10 €/t_{CO2} in the second half of 2011, will for the current policy initiatives scenario rise moderately until 2030 (32 €/t_{CO2}) and then significantly to provide support to low carbon technologies and energy efficiency (51 €/t_{CO2} in 2050). Comparing the costs projections for

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different energy and policy scenarios a large variation of the predictions is found. This highlights the large uncertainty of costs projections and the need to account for different economic scenarios when evaluating the competitiveness of CO_2 capture options to support investment decisions in the power sector.

The influence of the economic conditions is frequently investigated based on extreme scenarios or sensitivity analysis, however no systematic approach taking into account the economic conditions fluctuation for the decision-making based on the optimisation results is applied and process integration aspects and life cycle assessment are not systematically assessed. Based on the systematic optimisation approach for assessing the performance of CO_2 capture options, previously presented by Tock and Maréchal (2012,2013), a method, taking into account the economic parameter sensitivity, to support decision-making based on the Pareto-optimal solutions is proposed here. The influence of the economic scenario on the decision-making is studied by taking into account the sensitivity of the economic performance to the carbon tax, the resource price, the operating time, the investment and the interest rate.

2. Methodology

The applied thermo-environomic modelling and optimisation approach illustrated in Figure 1 combines flowsheeting and energy integration techniques with economic evaluation and life cycle assessment (LCA) (Gerber et al. (2011)) in a multi-objective optimisation framework previously presented (Tock and Maréchal (2012); Gassner and Maréchal (2009)). With regard to the competing objectives, it is a priori not obvious which configuration has to be chosen from the generated Pareto-optimal solutions. Therefore the aim is here to propose a decision support (Figure 1) which allows to identify the optimal process design from the Pareto-optimal solutions taking into account the economic conditions sensitivity.

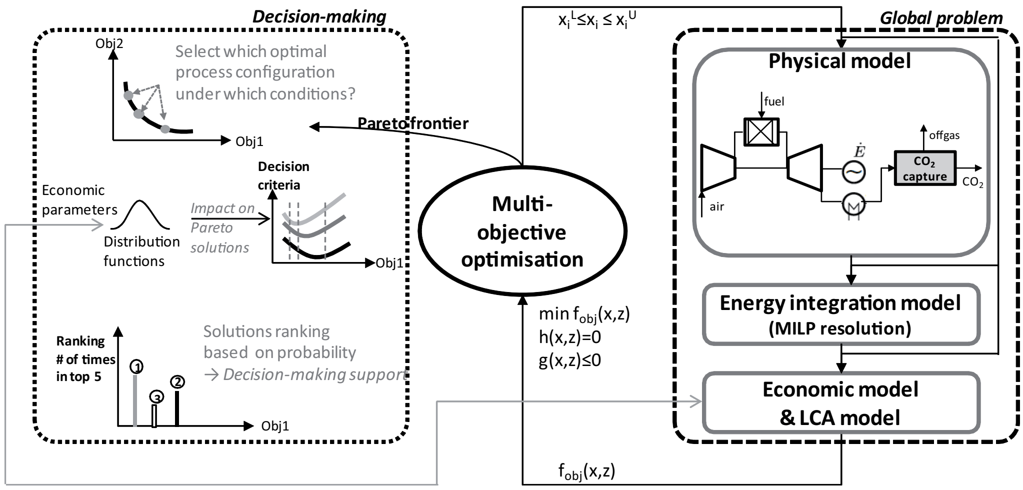

Figure 1: Thermo-environomic optimisation strategy to support decision-making.

In this approach, the economic conditions fluctuation is first described by probability distribution functions, such as the normal, uniform and beta distributions. The key parameters for the economic conditions are reported in Table 1. The lower and upper boundary values are defined from literature projections (IEA (2012); EU (2011); ZEP (2011)). The appropriate distribution function is selected and the characteristic parameters are identified based on the three scenarios values. For the carbon tax the beta distribution is chosen, because it is assumed that the tax price will most probably increase in the future. By applying the distribution functions a series of 1000 economic scenarios is randomly generated.

Table 1: Definition of the economic scenarios and parameters of the distribution functions for the economic assumptions.

	Scenario			Distribution functions parameters			
	Base	Low	High	Distribution	Param. A	Param. B	Param. C
Resource price [$/GJ$_{res}$]	9.7	5.5	14.2	Normal	μ=9.7	σ=2.5	-
Carbon tax [$/t$_{CO2}$]	35	20	55	Beta	a=2	b=1.5	c=100
Yearly operation [h/y]	7500	4500	8200	Beta	a=3.9	b=1.2	c=8600
Economic lifetime [y]	25	15	30	Beta	a=5.8	b=4	c=40
Interest rate [%]	6	4	8	Normal	μ=0.06	σ=0.01	-
Investment cost [%]	-30%	-	+30%	Uniform	a=-0.3	b=0.3	-

For every single economic scenario and for each configuration of the Pareto frontiers the decision criteria is then recomputed. The selected decision criteria is the economic performance that is expressed by the electricity production costs (COE) including a carbon tax. From the Pareto-optimal solutions the five best configurations that yield the best performance with regard to the decision criteria (i.e. lowest COE incl.CO_2 tax) are then identified for each economic scenario. After having identified the five most economically competitive configurations in the wide range of economic scenarios, it can be found out if some configurations are dominating or if some are never part of the best performing ones. To evaluate this quantitatively, the probability to be part of the five best performing configurations is assessed for each point of the Pareto front. The different process configurations are ranked based on this probability. This allows identifying the most economically competitive process configurations in a wide range of economic scenarios.

3. Process description

The approach is illustrated for three representative CO_2 capture options:

1. Post-combustion CO_2 capture by chemical absorption with monoethanolamine (MEA) applied to a natural gas combined cycle (NGCC) plant (582 $MW_{th,NG}$)
2. Pre-combustion CO_2 capture by physical absorption with Selexol in a natural gas fuelled power plant based on autothermal reforming (ATR) (725 $MW_{th,NG}$)
3. Pre-combustion CO_2 capture by physical absorption with Selexol in a biomass fired power plant based on fast internally circulating fluidised bed gasification (380 $MW_{th,NG}$)

The biomass plant's scale is limited by the biomass availability and the logistics of wood transport (Gerber et al. (2011)). The different process options have been modelled and analysed previously by Tock and Maréchal (2012,2013). A multi-objective optimisation is performed with the objective of maximising the energy efficiency ε_{tot} and the CO_2 capture rate η_{CO2} with regard to the process operating parameters. The energy efficiency ε_{tot} is defined by the ratio between the net electricity output and the resources energy input, expressed on the basis of the lower heating value. The economic performance is evaluated by the electricity production costs (COE), including the annual capital investment and the operation and maintenance costs. The competitiveness is compared with a conventional NGCC plant (559 $MW_{th,NG}$) without CO_2 capture characterised by an efficiency of 58.7%, specific CO_2 emissions of 105 kg_{CO2}/GJ_e, COE of 18.3 $/$GJ_e$ without carbon tax and 22 $/$GJ_e$ with a carbon tax for the base case economic conditions reported in Table 1.

4. Multi-objective optimisation and decision-making

The multi-objective optimisation results (Figure 3) reveal the trade-off between energy efficiency and CO_2 capture rate. An increase of the CO_2 capture rate leads to a decrease of the energy efficiency due to the energy consumption for CO_2 capture and compression to 110 bar. Considering only these two performance indicators no evident decision in favour of one specific process configuration can be made; the economic dimension has to be added. CO_2 capture leads to an increase of the COE due to the reduced electricity production and the increased investment costs for the capture equipment. When a carbon tax is introduced the cost penalty is reduced by the benefit from the tax due to the lower emissions. Consequently, there are break even economic conditions for which CO_2 capture becomes beneficial. The economic performance of the Pareto-optimal solutions is illustrated in Figure 2 for the economic scenarios reported in Table 1. Depending on the economic scenario the most economically competitive configuration is different, therefore the proposed approach is applied for decision-making.

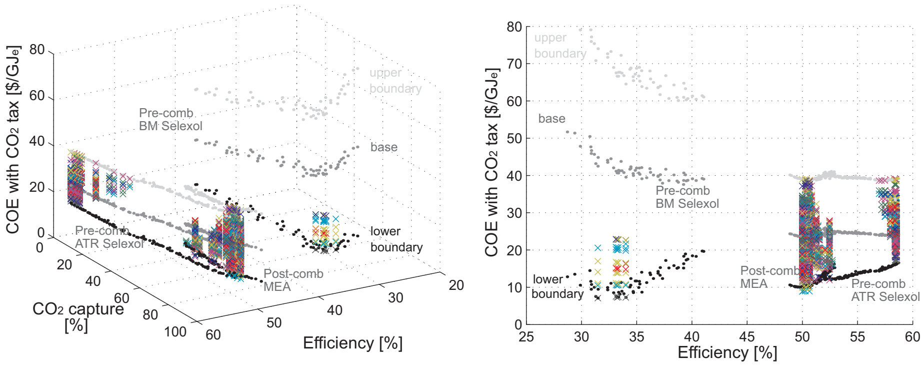

Figure 2: Power plants performance with CO_2 capture: Influence of the economic scenario on the decision-making based on the top 5 configurations yielding the best economic performance. The crosses (x) represent for each economic scenario the 5 selected configurations. Right: 3D-representation, Left 2D-representation.

The configurations yielding the best economic performance are identified in Figures 2&3. Figure 3 illustrates by the black dots how the decision-making along the Pareto-optimal frontier changes. Figure 2 reports the variation of the COE of the most economically competitive configurations identified from the Pareto-optimal solutions between the upper and lower borderline. The crosses represent for each economic scenario the five selected configurations yielding the best economic performance. For the base case economic scenario biomass fed processes are not competitive and post-combustion CO_2 capture performs best for capture rates around 70-85%. When gas prices increase, the natural gas based processes become uncompetitive compared to the base case biomass configurations. These results point out the competition between the processes and the influence of the economic scenario on the decision-making. This competition is highlighted in Figure 4 evaluating the overall competitiveness of each Pareto-optimal solution compared to the most-economically competitive solution. The post-combustion process configuration capturing 83% of the CO_2 emissions yields a relative competitiveness of 1 since this solution is the most economically competitive one in the large range of economic conditions. These results clearly show the close competition between post- and pre-combustion and underline that the CO_2 capture rate is a key factor defining the economic performance. Pre-combustion CO_2 capture configurations, being slightly more expensive for similar capture rates, yield however slightly better efficiencies. Depending on the production scope, this could affect decision-making for the more expensive solution. For some marginal economic scenarios CO_2 capture in biomass fed power plants becomes a competitive alternative. In fact, the benefit from the carbon tax overweights the efficiency penalty for capture rates around 70%. The performance results of the most economically competitive process configurations are compared with the conventional NGCC plant without CO_2 capture and summarised in Table 2.

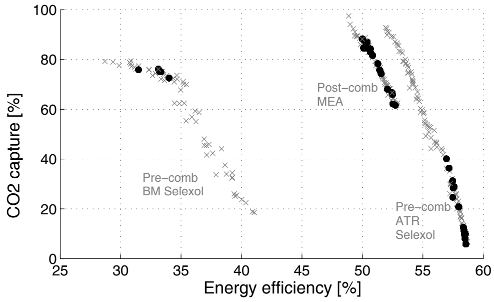

Figure 3: Multi-objective optimisation results.

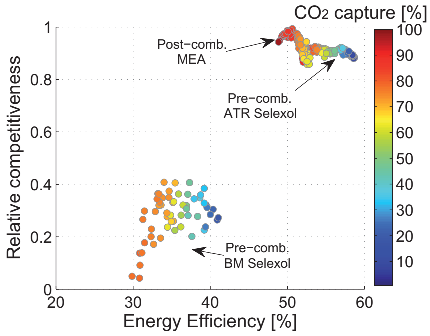

Figure 4: Relative competitiveness.

Table 2: Process performance.

System	NGCC no CC	Post-comb MEA	ATR Selexol	BM Selexol
Feed [$MW_{th,NG/BM}$]	559	582	725	380
CO_2 capture [%]	0	82.98	78.63	69.93
ε_{tot} [%]	58.75	50.65	53.59	35.45
Base case economic scenario (Table 1)				
COE no tax [$/GJ$_e$]	18.31	22.7	23.7	46.1
COE incl. tax [$/GJ$_e$]	22	23.2	24.5	21.1
Economic scenario variation (Table 1)				
COE incl. tax [$/GJ$_e$]	18.3-28.8	9-40	12.8-42	15-69
Environmental Performance (FU=1GJ$_e$)				
CO_2 emit. [kg_{CO2}/GJ_e]	105	13.9	22.2	-198.1
IPCC GWP [$kg_{CO2,eq}/GJ_e$]	120	35.4	42.2	-167

This shows how the most economically competitive process configurations can be identified from the Pareto-optimal solutions by applying the selection approach taking into account the economic conditions fluctuation.

5. Conclusion

This paper presents a selection approach taking into account the economic conditions fluctuation to identify economically competitive process designs from multi-objective optimisation results. The approach is applied to systematically assess CO_2 capture options in power plants. The results reveal that the choice of the optimal plant design is highly influenced by the resource price and the introduction of a carbon tax. By including the economic conditions sensitivity in the decision-making step, it appears that apart of the economic market conditions, the CO_2 capture rate is a key factor defining the economic competitiveness. Post-combustion CO_2 capture reveals to be economically competitive for capture rates between 70 and 80% when a carbon tax is introduced. While pre-combustion CO_2 capture in natural gas fired power plants is advantageous in terms of energy efficiency and CO_2 capture in biomass based power plants is beneficial from an environmental point of view due to the advantage of capturing biogenic CO_2. The various natural gas fed power plants designs with CO_2 capture lead to an average efficiency decrease of 6.5%-points (5-8%). It is shown that for specific economic conditions CCS can become an energy, cost and environmental efficient alternative on the future energy market compared to a conventional NGCC plant.

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