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Life cycle assessment based process design of CO_2 capture options

Laurence Tock *[a] and François Maréchal[a]

[a]*Industrial Process and Energy Systems Engineering, Ecole Polytechnique Fédérale de Lausanne, Station 9, CH-1015 Lausanne, Switzerland.*

Abstract

In the perspective of mitigating climate change, CO_2 capture and storage (CCS) is considered as a promising option. To evaluate the environmental benefit of capturing CO_2 it is important to make a systematic comparison including the whole life cycle from the resource extraction to the final product (i.e. electricity). Especially when comparing natural gas, coal and biomass fed processes the supply chain differences have to be accounted for. Besides the benefit in terms of greenhouse gas emissions reduction, CCS induces an energy and cost penalty due to the CO_2 separation and compression. The trade-offs between environmental impacts, efficiency and costs are systematically assessed here by combining life cycle assessment (LCA) with flowsheeting, energy integration and economic evaluation in a multi-objective optimisation framework. Post- and pre-combustion CO_2 capture options for electricity generation processes, using fossil and renewable resources, are analysed, compared and optimised. Multi-objective optimisations are performed for various thermo-economic and environmental objectives to highlight the influence on the optimal process design and on the decision making.

Keywords: CO_2 capture, LCA, Multi-objective optimisation, Power plant

1. Introduction

Carbon capture and storage (CCS) is regarded as a promising measure to reduce the greenhouse gas emissions. For CO_2 capture in power plants three different concepts can be distinguished; post-, pre- and oxy-combustion. The competitiveness of these options depends on the power cycle, the resources, the capture technology and the economic scenario. Previous studies have mainly focused on technology and economy (ZEP (2011); Finkenrath (2011)), which is a crucial part but not sufficient for decision making with regard to sustainable development. Few comprehensive comparative evaluations of the environmental impact of CCS are available (Pehnt and Henkel (2009); Singh et al. (2011); Volkart et al. (2013); Viebahn et al. (2007)) and reveal the trade-off between global warming potential (GWP) and other environmental impacts. So far, only reduced multi-criteria assessments were applied to power plants with CCS. If comparisons are made, they are mostly made for a given process design. Multi-objective optimisation of the process design with regard to environmental objectives resulting from a rigorous life cycle assessment (LCA) is rarely performed (Bernier et al. (2010)).

Therefore, the objective of this paper is to systematically compare and optimise different CO_2 capture options taking into account energetic, economic and environmental considerations simultaneously. The process design is optimised in terms of operating conditions and energy integration. In Tock and Maréchal (2013) the systematic methodology for thermo-environomic modelling and optimisation presented by Gerber et al. (2011) has already been applied to assess the competitiveness of CO_2 capture options for natural gas (NG) and biomass (BM) fed power plants. In this optimisation it was focused on the minimisation of the energy penalty

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*laurence.tock@epfl.ch

and of the local CO_2 emissions (i.e. maximisation of the captured CO_2). However, since there is a trade-off between GWP and other environmental impacts (i.e. resources depletion), different life cycle impact objectives will be considered here in order to reveal the influence on the optimal process design and on the decision making.

2. Methodology

With regard to CO_2 emissions mitigation, an assessment of the overall life cycle environmental impacts from the resource extraction along the production chain to the final product, including off-site emissions and construction emissions, is essential. Life cycle assessment (LCA) has been proven to be suitable for this scope. LCA is a well-established method, standardised in ISO 14040 & 14044 (ISO (2006a,b)). The four main stages of LCA are; the goal and scope definition, the life cycle inventory (LCI), the impact assessment (LCIA) and the interpretation. As shown by Gerber et al. (2011), life cycle assessment can be included in the thermo-economic modelling. For this purpose, the LCI is written as a function of the characteristics (i.e. design variables, mass and energy balances, equipment size) of the thermo-economic model. The applied thermo-environomic optimisation approach combines flowsheeting and energy integration techniques with economic evaluation and life cycle assessment (Gerber et al. (2011)) in a multi-objective optimisation framework previously presented (Tock and Maréchal (2012); Gassner and Maréchal (2009)). To assess the trade-offs of the competing objectives an evolutionary algorithm is applied in the optimisation.

The scope of this study being to evaluate power plants with CO_2 capture, 1 GJ_e of net electricity produced is chosen as a functional unit (FU=1 GJ_e). In the LCI phase every flow, crossing the system boundaries as an extraction or an emission, which is necessary to one of the unit processes, is identified and quantified based on the process layouts. The major process steps are resource extraction and transport, heat and power generation and CO_2 removal (Figure 1). The data available from the Ecoinvent database (Ecoinvent 2013) are used to compute the different contributions of the unit processes. Different impact methods are compared to address the influence on greenhouse gas emissions, ecosystem, human health and resources.

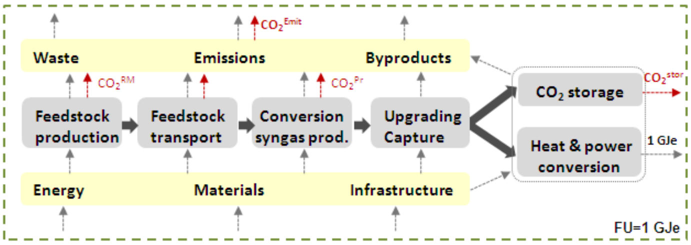

Figure 1: System's boundary for life cycle inventory of pre-combustion CO_2 capture processes.

The IPCC 07 method calculates the global warming potential by using the characterisation factors of different gaseous emissions published by the International Panel on Climate Change in 2007 (IPCC). The global warming potential over 100 years is computed in terms of CO_2 equivalent emissions. It has to be noted that the GWP of fossil CO_2 emissions is standardised to 1, while for biogenic CO_2 emissions the GWP is considered as 0. Storage of fossil CO_2 accounts as zero to GWP, while storage of biogenic CO_2 leads to a GWP of -1. The negative balance is due to the fact that the released CO_2 was previously fixed in the plant as hydrocarbon by photosynthesis. In addition to the climate change impact (CC), the impacts on resources (Res), human health (HH) and ecosystem quality (EQ) are evaluated by the Impact 2002+ method (endpoint categories) and the damage-oriented Ecoindicator99-(h,a) method (hierarchist perspective, single score). In the Ecoindicator99 method climate change is accounted in the human health impact aggregating also carcinogenic, ozone layer depletion and respiratory effects. The respective weighting factors are 40 % HH, 40 % EQ and 20 % Res.

3. Process description

Three representative CO_2 capture options are investigated: 1) Post-combustion CO_2 capture by chemical absorption with monoethanolamine applied to a natural gas combined cycle (NGCC) plant (582 $MW_{th,NG}$) (*NG post-*), 2) Pre-combustion CO_2 capture by physical absorption with Selexol in a natural gas fuelled power plant based on autothermal reforming (725 $MW_{th,NG}$) (*NG pre-*), 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 $MW_{th,NG}$) (*BM pre-*). The biomass plant's scale is limited by the biomass availability and the logistics of wood transport (Gerber et al. (2011)). The different processes have been modelled and analysed previously by Tock and Maréchal (2012,2013). The performance is evaluated by the energy efficiency ε_{tot} defined by the ratio between the net electricity output and the resources energy input (lower heating value basis), the CO_2 capture rate η_{CO2} based on local CO_2 emissions, the life cycle GWP and the electricity production costs (COE), including annual capital investment, operation and maintenance costs and if indicated a carbon tax on local or life cycle CO_2 emissions (i.e. tax CO_2 local / LCA). The competitiveness is compared with a conventional NGCC plant (559 $MW_{th,NG}$) without CO_2 capture yielding an efficiency of 58.8 % (Table 1). The economic assumption are: operation 7500 h/y, lifetime 25 y, interest rate 6 % and resource price 9.7 $/$GJ_{res}$. Figure 2 illustrates the environmental impact of the base case CO_2 capture process options.

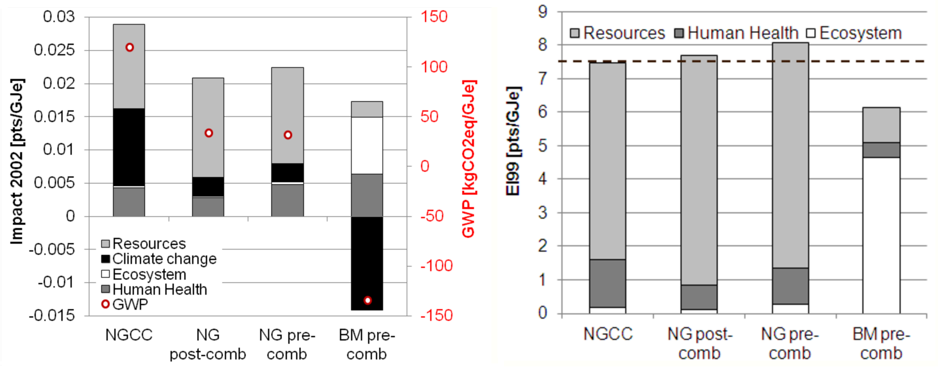

Figure 2: Environmental impacts comparison for base case CO_2 capture process designs.

The benefit of CO_2 capture is clearly revealed with the IPCC and Impact 2002+ method. With a capture rate of 90%, the GWP is reduced to 34 $kg_{CO2,eq}/GJ_e$ with post-combustion CO_2 capture compared to a conventional NGCC plant (120 $kg_{CO2,eq}/GJ_e$). Pre-combustion CO_2 capture (60 %) in biomass fed power plants leads even to a negative balance of -140 $kg_{CO2,eq}/GJ_e$ due to the advantage of capturing biogenic CO_2. However, with the Ecoindicator99 method, the overall impact of CO_2 capture in a NG power plant is 3 % higher than without capture because of the depletion of fossil resources. Due to the energy demand for CO_2 capture and compression, the natural gas consumption is increased to produce 1GJ of electricity compared to a conventional NGCC having a higher productivity. In this method the resources impact overweights the climate change benefit (accounted in HH impact). For CO_2 capture in a biomass fed plant the overall impact is however lower. These results reveal the influence of the choice of the impact method on the evaluation of the CO_2 capture options performance and consequently on the selection of the optimal process design.

4. Multi-objective optimisation

The decision variables for the optimisation are related to the process operating conditions and are mainly temperature, pressure of the different process units and the design of ab-and desorption columns. The objectives of the different multi-objective optimisations are:

- Moo CO_2 capt.: max ε_{tot}, max η_{CO2}
- Moo GWP: max ε_{tot}, min GWP $kg_{CO2,eq}/GJ_e$, min COE
- Moo EI99: max ε_{tot}, min total impact Ecoindicator99, min COE
- Moo Imp.: max ε_{tot}, min total impact Impact 2002+, min COE

The opposite behaviour between the Ecoindicator99 and GWP impact is clearly revealed in Figure 3 for the option of a natural gas fed plant with pre-combustion CO_2 capture. Optimising local CO_2 emissions or the GWP or the total impact assessed with the Impact 2002+ method leads to the same process designs. However, when minimising the Ecoindicator99 total impact, the optimisation leads to solutions with high efficiencies and low CO_2 capture rates (i.e. high emissions) because the increased impact on the resources overweights the decreased impact on the human health (incl. climate change) at high capture rates.

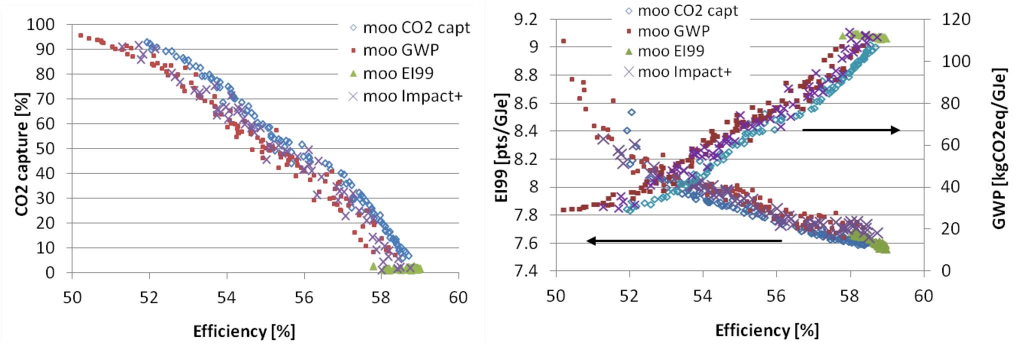

Figure 3: Influence of the objective function on the Pareto optimal solutions for the natural gas fed power plant with pre-combustion CO_2 capture.

To evaluate the economic competitiveness of each process design generated by the optimisation and to support decision making, the impact of the introduction of a carbon tax on the local CO_2 emissions and on the whole life cycle CO_2 emissions is assessed (Figure 4).

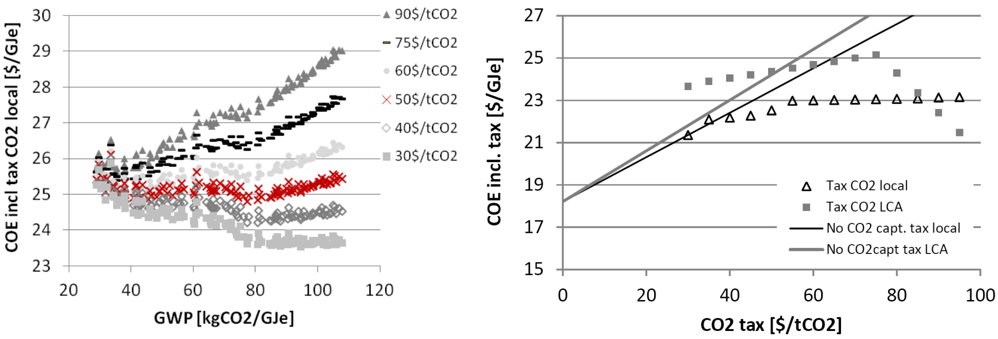

Figure 4: Influence of carbon tax (left) on the COE of the NG power plant with pre-combustion capture and (right) on the COE of the most economically competitive process (right).

Figure 4 (right) reveals that for low CO_2 taxes process designs with high GWP (i.e. low η_{CO2}, high ε_{tot}) lead to the lowest COE, while for taxes higher than 50\$/t_{CO2} process designs with low GWP become profitable. For a given carbon tax, the process design yielding the lowest COE (incl. tax) has been identified from all the generated Pareto optimal solutions and is illustrated in Figure 4 (left) highlighting also the break-even carbon tax for which the CO_2 capture becomes competitive compared to an NGCC plant. The slopes change is related to a switch of the optimal process design with CO_2 capture. The decrease in COE (incl. tax CO_2 LCA) after the maximum is due to a transition of the resource from natural gas to biomass. The performance results of the respective designs are reported in Figure 5 and Table 1.

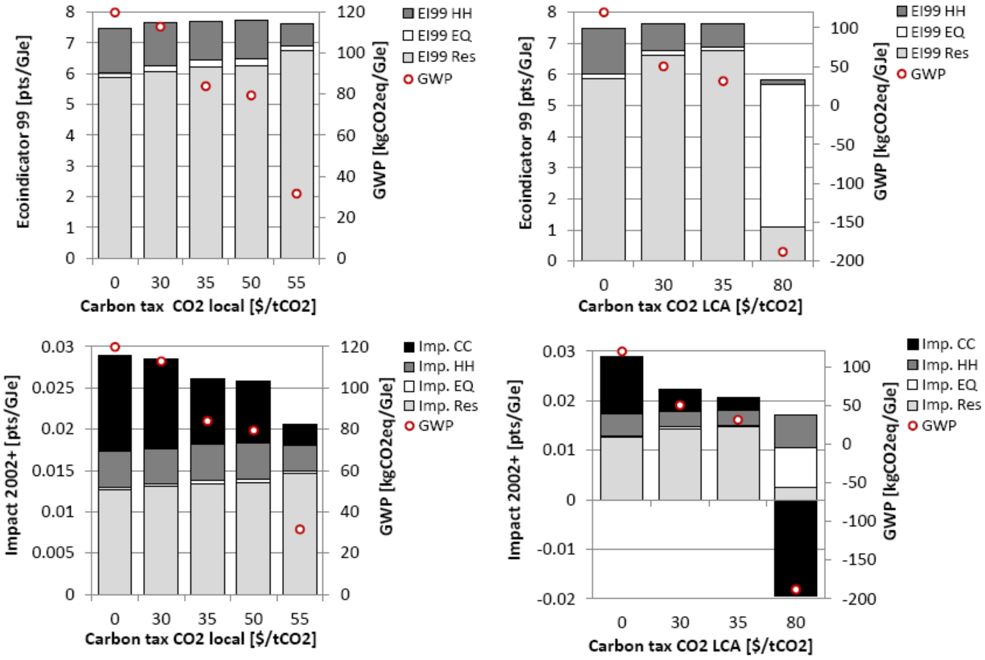

Figure 5: Environmental impact of the process designs with the lowest COE including a tax on the local CO_2 emissions (left) or on the life cyle CO_2 emissions (right) (Table 1).

Table 1: Performance of the optimal process designs yielding the lowest COE (Figure 5).

		tax local CO_2				tax LCA CO_2		
Process	NGCC	NG pre-	NG pre-	NG pre-	NG post-	NG post-	NG post-	BM pre-
Carbon tax [$/t_{CO2}$]	0	30	35	50	55	30	35	80
CO_2 capture rate [%]	0	1.2	33.6	38.8	83.9	76.6	83.9	71.9
Efficiency [%]	58.8	58.2	56.8	56.5	50.6	51.6	50.5	39.3
COE incl. tax [$/GJ$_e$]$]	18.3	21.3	22.1	22.5	23.0	23.7	23.9	24.9

With a tax up to 50 $/t$_{CO2}$ on the local CO_2 emissions, pre-combustion designs with capture rates up to 38 % are competitive, while post-combustion capture with high capture rates becomes interesting for taxes above 55 $/t$_{CO2}$. Figure 5 (left) shows the reduction of the climate change impact with the increasing tax, leading to a lower overall environmental impact evaluated with the Impact 2002+ and IPCC method and a slightly higher one with the Ecoindicator99 due to the resources impact as previously explained. If a tax is introduced on the life cycle CO_2 high capture rates (80 % post-combustion) inducing a climate change impact reduction (Figure 5 right) become already competitive for low taxes 30-75 $/t$_{CO2}$, while for higher taxes biomass processes emerge due to the environmental benefit of capturing biogenic CO_2. These results illustrate the influence of the introduction of a carbon tax on the process design.

5. Conclusion

Different CO_2 capture options using natural gas and biomass resources are systematically compared and optimised in terms of energetic, economic and environmental considerations. By including LCA impacts as an objective in the multi-objective optimisation it is highlighted how the environmental objective influences the decision making. Different impact methods are compared to address the influence on greenhouse gas emissions, ecosystem, human health and resources. With the Ecoindicator99-(h,a) method the environmental impact of power plants with CO_2 capture appears to be worse than without capture because of the larger resources depletion impact, related to the energy penalty, overweighting the climate change benefit aggregated in the human health impact. When the climate change impact is accounted in a separate impact category as in the Impact 2002+ and the IPCC method, CO_2 capture shows a clear environmental benefit. The introduction of a carbon tax favours power plants with CO_2 capture. For a tax on the local CO_2 over 50 $\$/t_{CO2}$ natural gas power plants with 80 % post-combustion capture are the most competitive and allow to reduce the GWP by around 75% to 31 $kg_{CO2,eq}/GJ_e$. Biomass plants become competive with a tax on the life cycle CO_2 emissions around 80 $\$/t_{CO2}$ and lead to a negative GWP of -187 $kg_{CO2,eq}/GJ_e$. Consequently, the optimal CO_2 capture process design highly depends on the chosen impact method to evaluate the environmental impact and on the introduction of a carbon tax.

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