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Integrated techno-economic and environmental assessment of an amine-based capture

Simon Roussanaly[a,]*, Amy L. Brunsvold[a], Erik S. Hognes[a], Jana P. Jakobsen[a]
and Xianping Zhang[b]

[a]SINTEF Energy Research, Sem Sælandsvei 11, NO-7465 Trondheim, Norway
[b]Dept. of Energy and Processing Engng., Norwegian Univ. of Science and Technology, NO-7491 Trondheim, Norway

Abstract

A systematic methodology for integrated techno-economic and environmental assessment of CCS value chains is presented and applied to assess the impact of the CO_2 concentration on an amine-based post-combustion CO_2 capture process. In this methodology, the technical assessment, economic evaluation, and environmental assessment (focusing on the global warming effect) are integrated in order to avoid the unilateral understandings obtained when these assessments are performed separately. Seven cases with CO_2 concentrations between 2.5 and 20.5% (mol) are investigated in terms of energy consumptions, the overall costs, as well as the climate impact of the capture process. The process simulation is performed with Aspen Plus®, and the techno-economic evaluation using Aspen Process Economic Analyzer®. A hybrid life cycle assessment approach is used to estimate the climate impact of the capture based on the results of techno-economic assessment. The CO_2 avoided capture cost, which reflects both the techno-economic and environmental performances, is used to assess the comprehensive impact of the CO_2 concentration on the capture process.

Keywords: Carbon Capture and Storage (CCS); Integrated assessment; Amine capture; CO_2 concentration.

1. Introduction

Carbon Capture and Storage (CCS) is considered to be one of the most promising alternatives for reducing anthropogenic greenhouse gas (GHG) emissions, and is forecasted to account for 20% of the reductions in man-made GHG emissions in 2050 [1]. To bring CCS closer to commercial realization, the viability of CCS value chains must be explored. For a commercial CCS chain to be successful, it must be

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* Corresponding author. Tel.: +47-735-93-767; fax: +47-735-97-250.
E-mail address: simon.roussanaly@sintef.no .

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sustainable and therefore take into account the three pillars of sustainability: profitability, planet, and people [2]. To ensure the critical evaluation of the viability of a CCS chain with respect to multiple criteria, a consistent and transparent methodology was developed and published [2]. The value of such a methodology is in the support it provides to decision makers to select the most viable alternatives for the CCS chains.

In this work, we focus in particular on the assessments of techno-economic and environmental impact of an amine-based CO_2 capture process for different CO_2 concentrations. In a CCS value chain, CO_2 capture is considered as the main challenge because it accounts for the major part of the energy consumption and costs of the chain. Thus, a systematic assessment of the CO_2 capture process with regard to different CO_2 concentration is important to understand the potentials and issues of the deployment of CO_2 capture technology for different industries, such as power plants, steel plants, cement production and so on [3, 4]. In this work, a general methodology for the integrated assessment of CCS value chains is presented and applied to assess the impact the CO_2 concentration on the capture process. In this methodology, the technical assessment, the economic evaluation, and the environmental assessment (focusing on the global warming effect) are integrated in order to avoid the partial understandings obtained when these assessments are performed separately [4, 5].

MacDowell et al. [5] comprehensively reviewed capture technologies and listed advantages and disadvantages of each technology, including the chemisorption techniques, the carbonate looping technology, and the oxyfuel process, as well as some emerging technologies. Hammond et al. [6] investigated the techno-economic appraisal of power plants with CCS, focusing on the six indicative options based on PC (Pulverized Coal), NGCC (Natural Gas Combined Cycle) and IGCC (Integrated Gasification Combined Cycles) power stations. Sipöcz and Tobiesen [7] performed the techno-economic evaluation with the simulated results by the extended MEA process integrated into the NGCC with exhaust gas recirculation (EGR). Considering environmental impacts of CCS, a great variety of life cycle assessment (LCA) of power plants with CCS has been conducted [8-14]. For example, Koornneef et al. [10, 11] assessed the environmental impacts of a pulverized coal power plant with CCS to disclose environmental trade-offs and co-benefits due to CCS. They indicated that CCS, indeed, on one hand decreases the climate impact of fossil fuel based electricity production, but on the other hand, leads to the increase of toxic impacts. Singh et al. [12, 14] assessed and compared the environmental impacts of electricity generation from coal and natural gas with and without different CCS technologies with a hybrid LCA approach. It also revealed that the CCS systems achieve a significant reduction of greenhouse gas emissions but have multiple environmental trade-offs depending on the technology.

However, among the large amount of papers on the assessment of carbon capture which had been published, only few of them use a consistent and transparent integrated assessment method as presented in this paper.

2. Methods

2.1. Integrated assessment method

The integrated assessment method is illustrated by Fig. 1 showing the relationships between the different assessments and their integration. The system integrated assessment includes mass and energy flow, capital investments (CAPEX), operating expenses (OPEX), and climate impact from the point where the raw gas enters the capture process until pure CO_2 is delivered to the conditioning, transport and storage chain. First, the process

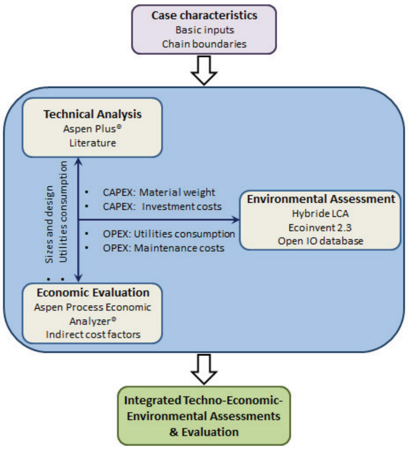

Fig. 1. Framework of integrated method

simulations are performed with Aspen Plus® estimating all the technical data, including mass flows and energy flows of the process, as well as the characteristics of different units. Then the economic evaluations are performed using Aspen Process Economic Analyzer® and a factor-based method for the investments, and utilities consumptions and maintenance for the operating costs estimates. Finally, a hybrid LCA approach is applied to estimate the climate impact by combining physical process data from the technical assessment with economic data from the techno-economic assessment. The results from the integrated techno-economic and environmental assessments are presented by means of the CO_2 avoided capture cost.

2.2. Case description and process models

The flowsheet of a MEA-based CO_2 capture process is shown in Fig. 2. The raw flue gas is pressurized using blowers to overcome the pressure drop of passing through the system. It is then cooled and washed by water to the temperature required for absorption. The cleaned flue gas enters in contact the MEA solvent in a packed absorber, and then the purified sweet gas leaves the top of the absorber after the recovery of MEA traces. The rich solvent is removed from the bottom of the absorber and enters a hot-cold exchanger to be preheated by the regenerated lean solvent, before being regenerated in the stripper. The CO_2 is stripped and dried, before being sent to conditioning, transport, and storage.

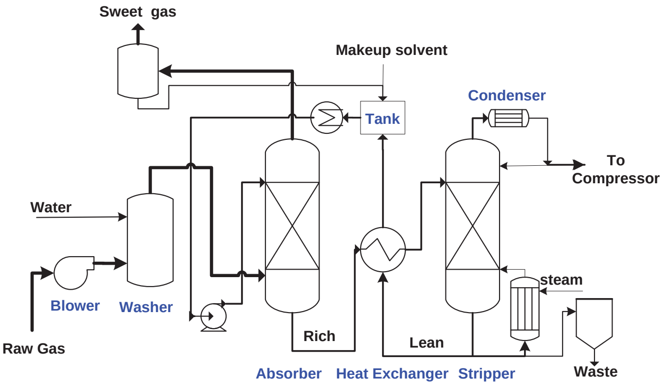

Fig. 2. Basic flowsheet of a CO_2 capture process with a MEA-based system

The parameters for each unit and stream are set based on literature [3, 15, 16]. The amines property package in Aspen Plus® is used to model the vapor-liquid equilibrium of this electrolyte system. Considering the low efficiency of the CO_2 absorption, the absorber is modeled with equilibrium stages with a Murphree efficiency[†] of 27% while the stripper is simulated with the RadFrac[‡] model. Seven CO_2 concentrations (mol %) in the raw flue gas, from 2.5 to 20.5 are considered. The same amount (2 $MtCO_2$/y) of CO_2 is captured for the different cases. The CO_2 capture ratio is 90% and the purity is higher than 95% (mol). The MEA concentration of the lean solvent is 28.3% (wt) while the load is close to 0.206 mol CO_2/mol MEA. The solvent flow rate is calculated based on the assigned capture ratio and CO_2 purity. The number of real stage and the height of packed beds are estimated based on the total column efficiency and the property of the selected packing material. The section of the column is estimated based on the column loading, transport properties and packing characteristics.

[†] Murphee efficiency represents the deviance of the system compare to the ideal separation equilibrium.

[‡] Radfrac is a rigorous tray to tray model for simulating multistage liquid-vapor fractionation equilibrium.

In a MEA-based capture process, a major issue is the degradation of the solvent through irreversible side reactions with CO_2 and other flue gas components, which leads to solvent loss, pollution by emitted MEA, and products degradation. Estimating MEA loss exactly is a key point for the technical assessment [11, 17, 18], the MEA losses are assumed to be mainly from emissions with the sweet gas, oxidative degradation, heat stable salt, polymerization, and reclaimer waste [13]. The losses with the sweet gas are estimated through simulations while the ones caused by degradations are based on the reaction rates [19].

2.3. Costs evaluation methodology

A factor estimation method is used to estimate the investment costs of a CO_2 capture plant where the estimated equipment costs are multiplied with direct (includes erection, piping, secondary equipments, civil work, insulation, steel and concrete costs) and indirect (includes engineering, administration, commissioning, and contingencies costs) cost factors to obtain the investment costs. Equipment costs and direct costs of carbon steel equipment are estimated using Aspen Process Economic Analyzer®, based on results from the process simulations. Direct costs of components in carbon steel are adjusted to reflect the cost of applied stainless steel. This is adjusted by multiplying direct costs with a material factor of 1.3 for machined equipments (pumps and blowers) and 1.75 for welded equipments (columns and heat exchangers) [20]. The investment cost for given equipment is then calculated by multiplying the component specific direct cost with the appropriate indirect cost factor (Table 1). The total investment cost is then determined by summarizing the estimated investment cost for all components within defined system boundaries.

The operating cost is split into fixed and variable operating costs. The fixed operating cost depends of the capture capacity and covers maintenance, insurance, and labor costs. The variable operating cost which is a function of the amount of CO_2 captured covers consumption of utilities: electricity, steam, cooling water, and MEA make up. The annual fixed operating cost is assumed to be 7% of total investment costs, while the annual variable operating costs are estimated using the utilities consumptions given by process simulations and utility costs given in Table 2. The steam required by the stripper is assumed to be extracted prior to a low pressure turbine (5 bar, 150°C) [24] with a steam quality to produce electricity of 23% [25].The Net Present Value (NPV) of project costs, equal to the sum of discounted cost flows during the project, is used as the key performance indicator to measure the overall costs of the CO_2 capture. The net present values are estimated assuming a real discount rate, i.e. inflation free, of 8% and project duration of 25 years.

Table 1. Indirect Cost factor as function of Direct Cost [20]

Total Direct Cost lower limit (k€)	0	15	51	211	367	624	1,428	> 3,620
Total Direct Cost higher limit (k€)	15	51	211	367	624	1,428	3,620	
Indirect Cost Factor	2.23	1.86	1.71	1.65	1.63	1.59	1.58	1.50

Table 2. Utility costs

Utilities	Costs
Electricity [17] (€/MWh)	55
Natural Gas [17] (€/MWh)	23
Water [21] (€/m^3)	0.02
Pure MEA [15] (€/t)	1,300

2.4. Climate impact model

The climate impact is assessed with a hybrid-LCA approach that estimates the global warming potential by calculating the sum of GHG emission from the CCS chains, and their supporting production systems, by combining physical data (materials and energy flows) from the process modeling with economic data (operating and capital expenses) from the economic assessment. Climate impact from materials- and energy flows is calculated with data from the life cycle inventory database Ecoinvent 2.3 (Table 3) [22], while the climate impact from the economic expenses is modeled with data from the environmentally extended input-output database "Open IO database, beta 1.5" [23], which is a web-based database with data from the US economy from 2002[§] (Table 4).

The production of steam is an important source of climate impact. Here, the steam, being extracted prior to a LP turbine that would have produced electricity, is attributed with the climate impact from the electricity produced by the European grid to compensate this steam extraction.

The climate impact assessment method Recipe [24] is used to calculate the different emission to air into CO_2 equivalents according to the guidelines given by IPCC [25]. All results are given as kilo CO_2 equivalents per ton CO_2 captured.

Table 3. Overview of Ecoinvent process used to model the physical flows [22]

OPEX/CAPEX	Climate impact	Unit
Steel for capture equipment	4.502	$kgCO_2/kg$
Ceramics for packing in columns	2.34	$kgCO_2/kg$
Cooling water	2.43×10^{-5}	$kgCO_2/kg$
MEA start- and make up	3.438	$kgCO_2/kg$
Electricity	0.502	$kgCO_2/MWh$
Steam modelled by electricity loss	0.115	$kgCO_2/MWh$

Table 4. Overview of entries in the Open IO database used to model the monetary flows [23]

OPEX/CAPEX	Climate Impact ($kgCO_2/\$_{2002}$)
Production of capture equipment	0.870
Capture facility construction	0.404
Fixed operating expenses	0.657

2.5. The CO_2 avoided capture cost

In order to integrate the results of these three assessments, the CO_2 avoided capture cost [€/t] is here used as a key performance indicator to measure the impact of the CO_2 concentration on the capture cost [26] including the climate impact [18]. The CO_2 avoided capture cost approximates the average discounted carbon credit per tonne transported over the project duration that would be required as income to match the net present value of capital and operating costs for the project. It is equal to the annual costs

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[§] The IO data is for the American economy in 2002 and to convert it into 2009 equivalents in euros a conversion factor of 0.74 EUR_{2009}/USD_{2002} was used for capital investments and 0.92 EUR_{2009}/USD_{2002} for operating expenses.

divided by the annualized amount of CO_2 avoided by the capture (equal to amount captured minus the climate impact), as shown in equation (1).

$$CO_2 \text{ Avoided Capture Cost} = \frac{\text{Annual OPEX} + \text{Annualized investment}}{\text{Annualized } CO_2 \text{ avoided}} \qquad (1)$$

3. Results and Discussion

Results shown in Fig. 3 indicate that the specific reboiler heat duty decreases exponentially with the increase of CO_2 concentration, leveling off for concentrations higher than 15% (mol). The same trend occurs with the electricity consumed by the flue gas compression. It is well known that the high energy consumption for the MEA-based system is mainly caused by the solvent regeneration in the stripper. A possible way to reduce this high heat consumption could be to reduce the water concentration in the solvent; for example, some solvents commercially available, which contains higher MEA concentration, were reported as reducing the steam consumption of 25% compared a conventional system [27].

The total MEA losses caused by the sweet gas emissions and the oxidative degradation decreased with the increase of the CO_2 concentration. The losses with the sweet gas emissions decreases as the volume of the raw flue gas decreases exponentially, while the MEA losses caused by the oxidative degradation decrease relatively slowly since it mainly depends on the solvent volume. Indeed, as the amount of captured CO_2 is fixed, only slight changes in the solvent flow rate are observed. It is worth noting that for lower CO_2 concentrations, the MEA losses are mainly caused by sweet gas emissions, while for higher concentrations, both causes are equivalent.

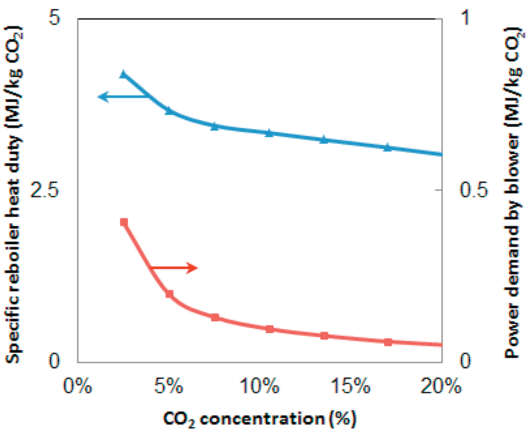

Fig. 3. Influence of CO_2 concentration on energy consumptions

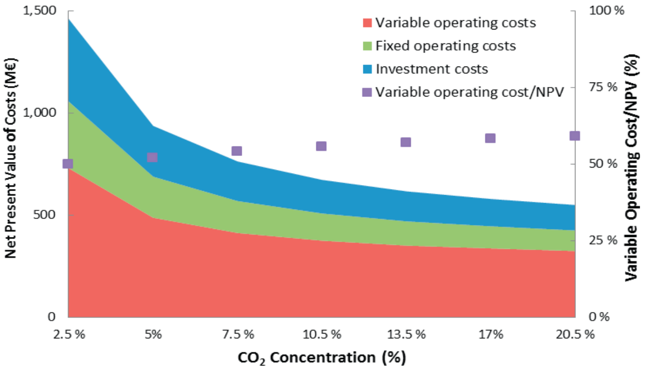

Fig. 4. Capture costs as function of CO_2 concentration

Fig. 4 shows that capturing CO_2 from flue gases at atmospheric pressure increases exponentially as the CO_2 concentration drops. Indeed, the net present value of cost is more than halved when the CO_2 concentration goes from 2.5% to 20.5% for the chosen capture capacity of 2 $MtCO_2/y$. Two thirds of this decrease is due to the reduced investment costs and the fixed operating costs (proportional to investment cost). Hence the relative share of variable operating costs increases with an increase in the CO_2 concentration. The costs evaluation also shows that between 50 and 65% of investment cost are allocated to the packing material and steel used for the four columns of the capture process (gas washer, absorber, MEA recovery unit and stripper). The annual operating cost exhibits a non-linear drop when the CO_2 concentration increases. This is dominated by a reduced fixed operating cost, derived from the investment cost profile. The variable operating cost components experience a more marginal decrease, due to the reduced power demand by the feed gas blower and the lower stripping energy penalty for higher CO_2 concentrations. The difference in costs structure influences the relative importance of potential cost reductions efforts on the total capture cost. A source with a CO_2 concentration of 2.5% would require over a 20% reduction in steam consumption to achieve similar reduction in total capture cost as by reducing investment cost by only 10%. For higher concentration sources the relative importance of steam consumption increases, whereas for a source with CO_2 concentration of 20.5% a 10% reduction in investment cost is equivalent to 8% reduction in steam consumption.

The climate impacts for each CO_2 concentration, expressed in kilogram of CO_2-equivalents per tonne of CO_2 captured, is shown in Fig. 5. The results lead to a similar trend than the costs assessment. The total climate impact per tonne of CO_2 captured is more than 40% lower for a CO_2 concentration of 20.5% than a CO_2 concentration of 2.5 %. Heat for producing the steam is the main driver of GHG emissions from the capture process. The other utilities consumptions (electricity for blowers, cooling water and MEA make up) are also important contributors.

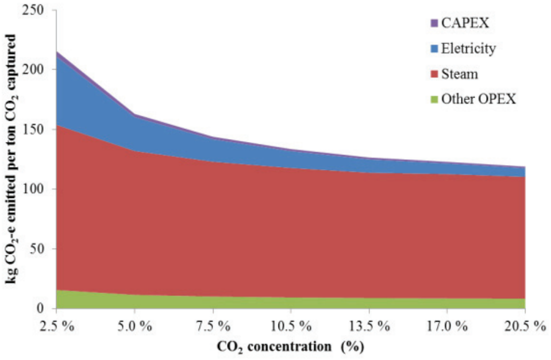

Fig. 5. Contribution of CAPEX and OPEX to climate impact

Fig. 6 shows, for the different CO_2 concentrations, the CO_2 avoided capture cost which approximates the average discounted carbon credit required to overcome the capture costs including the climate impact contribution. Due to the addition of the climate impact effect, the accentuation of the observed drop [**] in the CO_2 avoided capture cost emphases the motivation to capture CO_2 from sources with high CO_2 concentration. This is reflected in efforts to increase CO_2 concentration in low concentration sources. Based on these results, the selection of sources can be a way to decrease the cost of CO_2 capture and therefore CCS. In addition, Fig. 6 stresses the importance of including GHG emissions to estimate the costs. Indeed, not integrating it would lead to considering only a part of the costs and therefore underestimate the average discounted carbon credit required to overcome the capture costs.

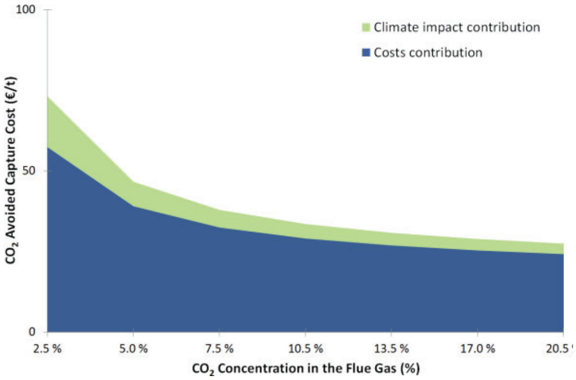

Fig. 6. CO_2 avoided capture costs

[**] It s worth noting that for low concentration, climate impact contributes up to one fourth of the CO_2 avoided capture cost decrease.

4. Conclusions

A systematic methodology for integrated assessment of CCS value chains is presented and applied in order to assess the impact of the CO_2 concentration on an amine-based post-combustion CO_2 capture process. In this methodology, the technical assessment, economic evaluation and environmental assessment (focusing on the global warming effect) are integrated in order to avoid the partial understandings obtained when these assessments are performed separately, and provide support to decision makers in order to select the best alternatives for the CCS chains. The different assessments show that both costs and climate impact drop non-linearly when increasing the CO_2 concentration. Indeed, both the NPV and the climate impact are more than halved when the CO_2 concentration goes from 2.5% to 20.5%. Due to the addition of the two effects, through the CO_2 avoided capture cost, the integrated techno-economic and environmental assessment emphases the motivation to capture CO_2 from sources with high CO_2 concentration. This work contributes to highlight the importance of including GHG emissions to estimate CCS costs and the relative importance of CO_2 concentration. The results obtained from the techno-economic and environmental analysis in this work will be important for the CCS deployment for the different industries with different CO_2 flue gas resource concentrations in the future.

To ensure a critical evaluation of the viability of a CCS chain, consistent and transparent multi-criteria analyses, as presented here, shall be performed. The value of such a methodology is in the support it provides to decision makers to select the best alternatives, bringing CCS closer to realization and enabling the development of CCS infrastructure.

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