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ScienceDirect

Energy Procedia 114 (2017) 113 – 121

Energy Procedia

13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland

Partial Capture of Carbon Dioxide from Industrial Sources - A Discussion on Cost Optimization and the CO_2 Capture Rate

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Abstract

This work discusses the cost optimal capture rate of absorption based carbon capture processes by a combination of process simulations and cost-estimation. The influence of the quality of the CO_2 source (quantity, continuity and CO_2 concentration) and the availability of low cost heat on the absolute and specific capture cost are highlighted. The results stress that partial capture of CO_2 could lower the specific capture cost (€/ton CO_2) and that the relation between capital expenditure and lowered energy demand should be reconsidered for cases with access to low-cost heat.

Peer-review under responsibility of the organizing committee of GHGT-13.

Keywords: CO2 emissions; Carbon capture; Industrial capture; Partial capture

1. Introduction

The energy intensive process industry has a series of possibilities to reduce their emissions of CO_2, with respect to both process and energy related emissions: increased use of biomass and renewable electricity, energy efficiency measures, and application of carbon capture and storage (CCS). Previous analysis indicate that all these measures are required to reach the emission cuts required to meet near zero emissions, i.e. the reductions in line with a 2-degree-warming-target (see for example the work by Johnsson and Rootzén [1] or the reports by the European

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Peer-review under responsibility of the organizing committee of GHGT-13.
doi:10.1016/j.egypro.2017.03.1154

Commission "Energy Roadmap 2050" [2] and IPCCs 5th "Assessment Report" [3]), which is further enhanced by the outcome from the COP21 meeting in Paris. The importance of CCS has been especially stressed for emissions from the energy intensive industries, including CCS applied to biogenic emissions (BECCS). Although all measures are needed there is a lack of studies assessing what is a cost-efficient mix of mitigation measures for the energy intensive industries. For example, CCS is almost exclusively evaluated as a measure to capture all fossil CO_2 emissions from the plant [4], not considering that a substantial part of the total emissions may be reduced by other measures such as fuel shift and increased energy efficiency. In line with this, this work investigates the concept of partial CO_2 capture with the aim to lower the specific CO_2 capture cost considerably by designing the capture technology specifically for the CO_2 sources most suitable for capture. The concept of partial CO_2 capture includes capturing a lower fraction of CO_2 than the more common target of capturing >90% of the stack emissions (for example to target the capture rate so that only low cost energy could be used), excluding less suitable stacks in a multi-stack facility, and partial capture through a time varying capture rate to consider the spot price of electricity, e.g. using low night-time electricity price.

The possibilities and challenges for carbon capture differs considerably between types of industries (e.g. cement, steel, pulp, or silicon manufacturing). Source characteristics that will influence the carbon capture cost considerably includes the quantity of CO_2, which can vary from a couple up to hundreds of kg CO_2/s, and the quality of the exhaust streams, which may vary from extremely diluted steams with only some percentages of CO_2 concentration to streams that already have a high concentration of CO_2 at the source. Furthermore, the conditions for heat supply differ between industries. Available excess heat that could power the capture unit is of course beneficial, but to what extent excess heat is possible to harvest also depends on what infrastructure is available for steam generation. Access to a steam cycle will have a considerable impact on the capture cost. The conditions for carbon capture at different sites is discussed in detail in a paper by Skagestad et al. [5]. The broad span of conditions will obviously have an impact on the processes possibility to separate CO_2 and that each process will require a specific design of the capture process.

This paper focuses on CO_2 capture through absorption with monoethanolamine (MEA). Although, this capture technology may not be the optimal solution in all cases, MEA is an efficient end-off pipe solution applicable to most conditions. Furthermore, it is frequently used as a benchmark solvent and has a well-documented performance. The aim of the study is to provide a qualitative discussion on how the conditions for CO_2 separation influence the cost to reduce CO_2 emission by CCS.

2. Methodology

The concept of partial CO_2 capture is investigated through cost optimization of the MEA absorption based capture process, considering different capture rates depending on generic plant characteristics such as the number and physical locations of the flue gas stacks (CO_2-sources), CO_2 concentration, possibility for heat supply and available excess heat. In addition, possible effects from an electricity market with volatile electricity prices (e.g. from variable power generation) is discussed. The investigation is based on detailed process simulations with the modelling tool Aspen Plus to design and dimension the capture unit. The process models have been used in several industrial projects on CO_2 capture with good reliability, se for example [6]. The process design is combined in an iterative process with a technical-economic analysis to find cost efficient process designs. The cost estimation is performed with Aspen In-plant Cost Estimator combined with a well proven in-house developed cost factor model [7].

2.1. Absorber Model

The standard chemical absorption process and the rich-solvent split-flow configuration, using MEA as a solvent, were simulated in Aspen Plus V8.8. Simulations of designs and operating conditions are performed to optimize the MEA capture process with respect to energy use, applying a rate-based approach. The performance of the carbon capture process is a result of the combination of stripper pressure, CO_2 loading, solvent concentration and split fraction, which were identified as important design parameters in previous studies [8]. These parameters were optimized with respect to the specific reboiler duty (MJ per unit of CO_2 captured). The stripper pressure is especially interesting when using excess heat to power the reboiler as more excess heat is available at lower temperatures [9]. When optimizing the operating pressure for primary energy consumption it is crucial to consider that high temperatures increase thermal amine degradation and corrosion problems and the upper temperature limit was therefore set to 125 °C.

Table 1 presents the performance and running conditions of the optimized absorption process at reference case conditions with a 90% capture rate. The energy requirement of around 3.2 MJ/kg CO_2 separated is in agreement with what has been previously reported for a MEA process with rich–solvent split flow configuration. The capture rate (i.e. partial capture) may be reduced by only introducing a part of the total flue gas stream to the capture unit with a high capture rate maintained in the absorber, in which the optimization of the running conditions will be the same as for the base case, or by introducing the entire flue gas stream to the absorber and instead reducing the capture rate, in which the optimal running conditions are changed.

Table 1. Running conditions of the optimized absorption process at base case conditions of a 90% capture rate.

Parameter	Value
Column flooding point [%]	80
Stripper height [m]	12
Absorber height [m]	25
Stripper pressure [bar]	2
Stripper diameter [m]	6.7
Absorber diameter [m]	11.2
Washer height [m]	4
Solvent concentration [wt-%]	30
Lean CO2 loading [-]	0.28
Rich CO2 loading [-]	0.53
L/G ratio [-]	4.1
Stage [-]	10
Split fraction [-]	0.7
Flue gas temperature at absorber inlet	40°C
Solvent temperature at absorber inlet	40°C

Table 2. Parameters used as input to cost estimation of the four cases presented in Table 2.

Operating hours	7000 h/a
Interest rate	7.5%
Years in operation	25 y
Location	Generic location (Rotterdam)
Electricity price	55 €/MWh
Steam cost	17 €/ton
Maintenance	4% of CAPEX

2.2. Cost Estimation

The cost estimation is executed by using a detail factor estimation method. The equipment cost is based on an Aspen In-Plant cost database, and the installation factor is from empirical formulas. The capture plant is treated as an extension of the CO_2 source plant. Table 2 gives the basic assumptions used as input to the cost estimation.

The capture rate (CR) of a CO_2 source is defined as the amount of CO_2 captured divided by the amount of CO_2 generated at the source. The capture rate will equal the CO_2 separation rate in the absorber times the part of the flue gas flow treated. The study includes a detailed cost estimation of both of the terms affecting the capture rate. However, in some cases cost is scaled to investigate the effects of certain conditions. In these cases, the fixed cost of the capture plant, including CAPEX, maintenance and personnel cost, (C_{fixed}) designed for 90% capture from the full flow $S^{100\%}$ is scaled to the design load (S) of the capture plant investigated according to:

$$C_{fixed}^{CR} = C_{fixed}^{90\%}\left(\frac{S}{S^{100\%}}\right)^{0.9} \tag{1}$$

The variable cost (C_{var}) is instead scaled to the amount of annually captured CO_2, i.e. the load hours (St) of the capture plant, according to:

$$C_{var}^{CR} = C_{var}^{90\%}\left(\frac{St}{St^{100\%}}\right) \tag{2}$$

2.3. Site conditions

The influence of site specific conditions on the cost for CO_2 capture as a function of the capture rate is illustrated by estimating the fixed costs, which primarily depends on the conditions of the CO_2 source (quantity, quality, and capture rate), and the variable costs, which mainly depend on the heat supply (quantity and quality of excess heat, fuel costs, infrastructure for heat generation, availability of steam cycle, competing uses for heat). The cost is estimated for the four cases presented in Table 3. The CONC and FLOW cases represent capture from CO_2 sources with lower quantities of CO_2, which can be seen as less suitable for CO_2 capture. Together with the SEP case, the FLOW case can be seen as to represent designs for partial capture where the overall capture rate is deliberately reduced by either capturing from a slip stream or reducing the separation rate in the absorber. Note that all cases capture an amount of CO_2 equal to 25% of the amount captured in the reference case. The cases are theoretical and chosen to illustrate the influence of the CO_2 source on the capture cost.

The influence of the heat supply is more complex and will depend on the development of the energy system. Here the influence of the heat supply is discussed by a case that represents an industrial site that has the opportunity to cover parts of its heat demand with low-cost energy. In this case the steam cost is not fixed but given by a step-function as a function of the amount of CO_2 captured according to Table 4.

Finally, the operating conditions of the CO_2 source is investigated. Figure 1 shows the two operational patterns of the CO_2 source investigated in this work. Figures 1a and b show a CO_2 source that constantly operates at full load (7 000 h out of the 8 760 h per year is assumed as full operational time) while Figures 1c and d show a CO_2 source with an even distribution from full to no load over the 7 000 h/a. The blue colored field shows the operation of the CO_2 source and the red colored field indicate how much of the maximum flue gas flow the capture plant is designed for. The overlapping fields indicate how much CO_2 that is captured and the non-overlapping red-field indicate the overcapacity of the capture unit. Thus, Figures 1 a and c show a capture plant designed for 90% capture rate from the full flow and Figures 1 b and d show a partial capture plant (a 90% capture rate from 50% of the flue gas flow).

Table 3. Input data to the simulated cases.

	Quantity (kg FG/s)	Quality (vol.% CO_2)	Capture Rate (% of CO_2)	CO_2 captured (kg/s)
Reference (REF)	200	20	90	36

Low Concentration (CONC)	200	5	90	9
Low Flow (LOW)	50	20	90	9
Low Separation (SEP)	200	20	22.5	9

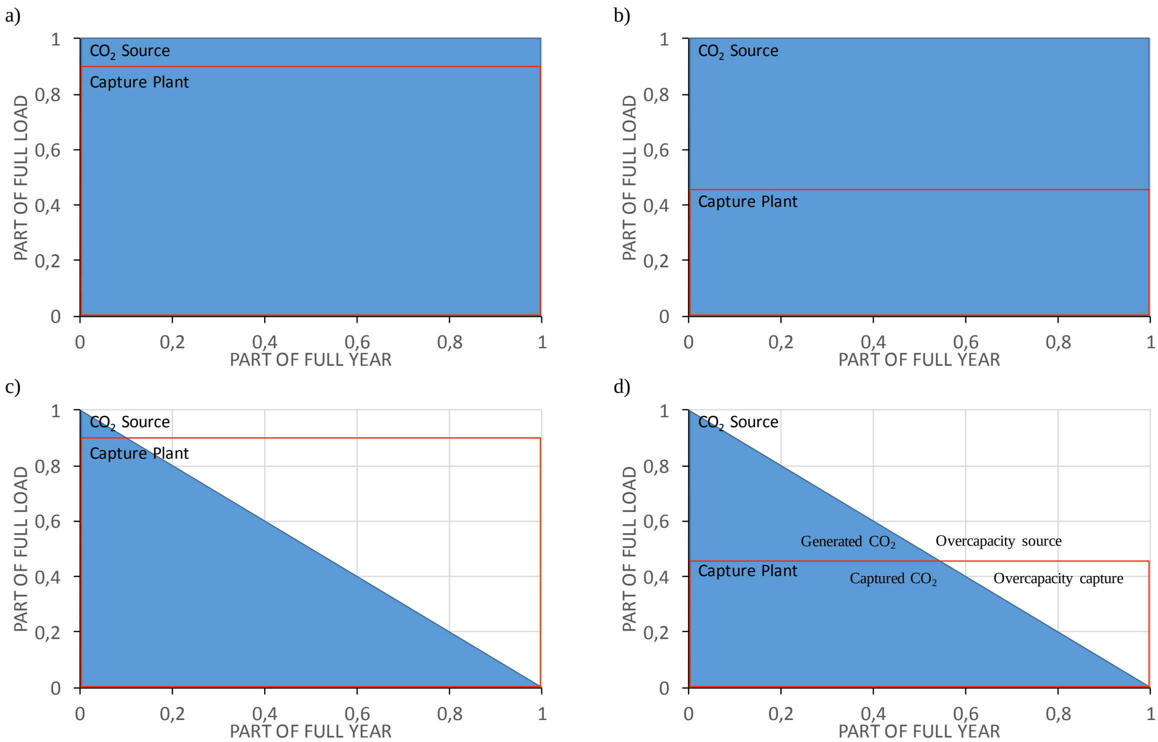

Figure 1. Illustration of scenarios for the operating patterns of the CO_2 source in the present investigation. The blue colored field shows is the operation of the CO_2 source. The red colored field is the part of the maximum flue gas flow the capture plant is designed for. The overlapping field indicate how much CO_2 that is captured. The non-overlapping red-field indicate the overcapacity of the capture unit.

Table 4. Steam costs used to illustrate the influence of the access to low-cost steam on the CO_2 capture cost.

Level	Amount (% of total demand)	Specific cost (€/ton steam)	Example of heat source
LOW	30	0.2	Excess heat
MEDIUM	30	6	Existing energy infrastructure
HIGH	Rest	16.7	New energy infrastructure

3. Results

3.1. Influence of the CO_2 Source

Figure 2 compares the distribution between fixed costs (CAPEX plus maintenance and personnel) and variable costs between the reference (REF), reduced concentration (CONC), reduced flow (FLOW), and reduced separation-rate in the absorber (SEP) cases. The variable cost is divided into cost for steam for the reboiler (STEAM), cooling water (COOLING) and electricity (EL). Starting with the reference case, the total annual cost for the capture plant with the given assumptions is around 50 M€ and the specific cost is around 60 €/ton CO_2 captured. The costs and distribution of the reference case are representative for what has been presented for large scale post-combustion CO_2 capture from a power plant source [10]. For the cases with a reduced amount of CO_2 captured, the total annual cost is around 20, 15, and 18 M€ and the specific cost is around 90, 70, and 80 €/ton CO_2 captured for the CONC, FLOW and SEP case, respectively. Naturally, the total cost is reduced for all cases relative to the reference as the size of the capture plant is reduced. The specific cost is on the other hand increased mainly as the investment cost is increased while the running costs, especially the steam cost, is related to the amount of CO_2 captured. It is seen in Figure 2 that the investment part of the total cost is increased for the cases with reduced capture. Comparing the cases representing less suitable CO_2 sources, the increased importance of the investment is especially obvious for the case with reduced CO_2 concentration. In this case, large parts of the capture plant have to be dimensioned for the same flow as in the reference case plus that the capital intensive heat exchanger must be made larger to operate with low CO_2 concentrations and relatively large solvent flows. The investment in the CONC case is almost double to the FLOW case, although they capture the same amount of CO_2, which illustrates the importance of CO_2 concentration on the capture cost. The steam demand is also increased in the CONC case relative the reference and FLOW cases as the rich loading is decreased.

Comparing the two options for partial capture, the FLOW and the SEP case, it is somewhat beneficial to capture with 90% separation rate from a slip stream rather than reducing the absorber separation rate while capturing from the entire stream (70 vs. 80 €/ton CO_2 captured). It should, however, be noted that this conclusion depends on economic assumptions and site specific conditions as the two approaches to partial capture affect the cost of the capture process in different ways. The FLOW case mainly reduces the investment cost as equipment size can be reduced at lower flows (also the cooling is reduced as a lower flue gas flow needs to be cooled) while the specific steam consumption is the same as for the reference case. The SEP case, on the other hand, has increased specific investment costs but reduced specific steam consumption as the capture process can be made more efficient working with high outlet concentrations of CO_2. Cases with low steam costs will, thus, favor a slip stream approach to partial capture while cases with favorable conditions for investments will favor a reduced capture rate in the absorber approach to partial capture. Another aspect that should be considered is that the approach to reduce the separation rate in the absorber gives a better position for increasing the capture rate in the future if the need for CO_2 emission reduction should change.

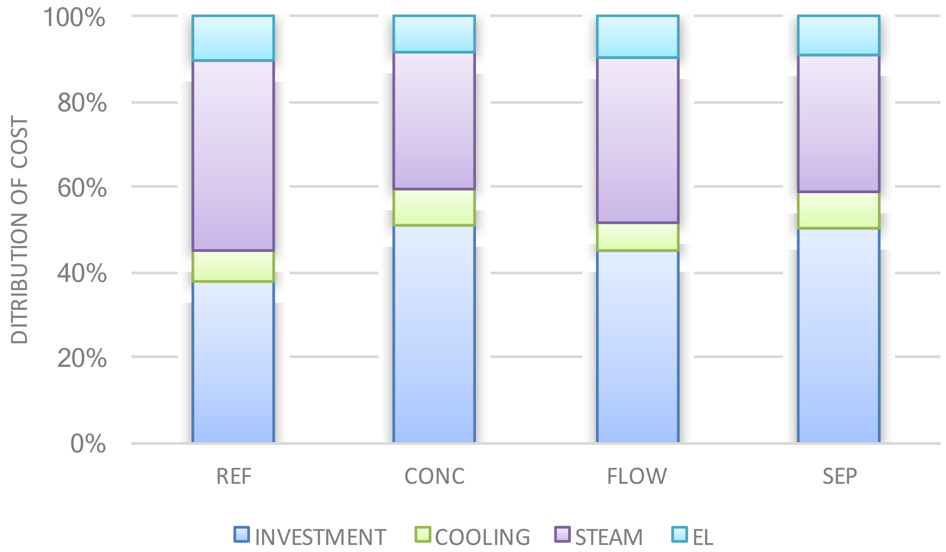

Figure 2. Distribution of the capture cost for the different cases. The total annual cost is around 50, 20, 15, and 18 M€ and the specific cost is around 60, 90, 70, and 80 €/ton CO_2 captured for the reference (REF), reduced concentration (CONC), reduced flow (FLOW), and reduced separation rate in the absorber (SEP) cases, respectively

3.2. Influence of the Heat Supply

The results presented in Figure 2 are based on a fixed steam cost of 17 € per ton of steam. The cost for energy is, however, case specific and the availability of excess heat and time variations in energy prices may influence the steam cost significantly:

1) Excess heat. At industrial sites there is often heat available, which is not possible to use within the main process, but that is still of such quality that it could be utilized in the CO_2 capture unit. The value of this heat is difficult to determine as it is site specific. It may be anything from negative, as you reduce the need for cooling, to the cost for collecting it or to the value it would have to a steam cycle or a district heating system. Secondly there might be options at the industrial site to increase the heat output without the need to invest in new steam capacity. Examples of such options are access to a steam cycle with steam extraction and possibility to increase the output of existing heating equipment. For such options there is a cost associated with the increased heat output, but this cost is considerably lower than if the cost would include new infrastructure.

2) Time varying energy prices. With the increasing share of intermittent wind and solar power in the electricity system the electricity market has become more volatile. This creates an opportunity to run the capture process during periods of extremely low electricity prices when the heat is free and using the heat for electricity production when the prices are high.

Figure 3 shows the results of a case that represents a scenario of an industry that has excess heat available (cost of 0.2€/ton) to cover 30% of the heat required for full CO_2 capture and an opportunity to use existing infrastructure to produce heat to cover another 30% of the total heat demand (cost of 6€ per ton). The remaining 30% to reach a 90% capture rate would thus require new infrastructure for steam generation (cost of 17€/ton). The specific capture cost for 90% capture is decreased to 42€/ton relative to the 60€/ton required for the reference case, which is expected as the cost for steam is reduced. A minimum in capture cost is seen for the excess-heat-only case at 34 €/ton and, maybe as important, the total annual cost is reduced with 80% to around 10M€. The methodology chosen, to represent steam strictly as a running cost, gives the linear increase between operating points. For future partial capture studies, it would be recommended to represent steam cost by both an investment cost and a running cost. Such a representation would generate a step-like response to a switch in energy supply. It would, however, not change the optimum operating position. It is also obvious from Figure 3 that in the case of access to low-cost heat the investment dominates the capture cost and focus should rather be on reducing the size and complexity of the process than on reducing the energy requirement of the regeneration process.

3.3. Influence of Variable Load

The effect of low utilization of the CO_2-source and, thus, of the capture unit on the capture cost is exemplified by a case with an even distribution between load levels from full to no load during 7 000 h, which is the utilization in the base case, and with the plant standing still for the remaining time of the year (1 760 h), as shown in Figure 1. The results are illustrated in Figure 4. Relative to the reference case the specific capture cost is increased from around 60 €/t CO_2 to around 80 €/ton CO_2. In difference to the reference case there is a clear profit in designing the capture plant for 50% of the full flow with this utilization profile – the specific capture cost is decreased by 12 €/ton CO_2. If the steam cost is decreased with 70% relative to the reference case (two right-hand bars in Figure 4), which will increase the relative importance of the investment cost, it is even more beneficial to design the unit for parts of the full flow - the specific capture cost is decreased by 14 €/ton CO_2. The optimal design of capture unit for a variable CO_2 source will, thus, depend on the utilization profile of the CO_2 source as well as the steam price of the specific plant.

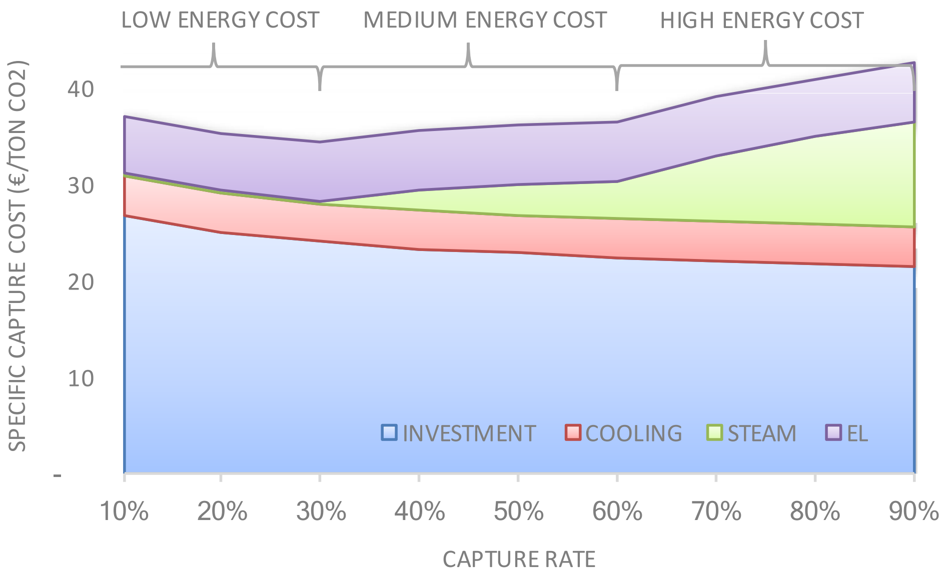

Figure 3. Specific capture cost at different capture rates for a scenario with an industry with heat cost of 0.2€/ton steam up to 30% capture, 6€/ton between 30%-60% capture, and 16.7€/ton above 60%.

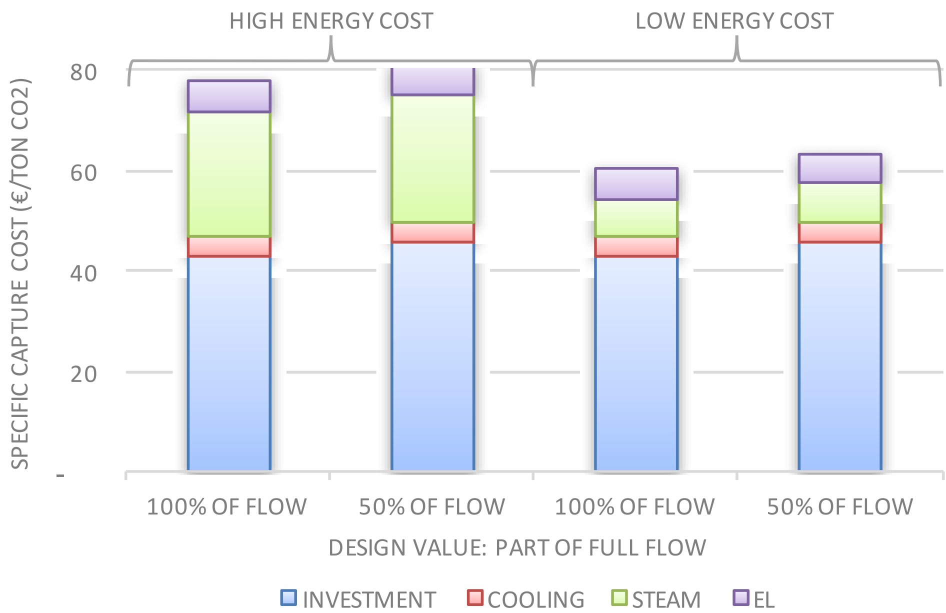

Figure 4. Specific capture cost when the number of full load hours (load*operating hours) of the CO_2 source is decreased with 50% depending on the size of the capture plant. The two left-hand bars have full steam cost and the two right hand bars have reduced steam costs with 70%. The specific capture cost of the reference case with full utilization was around 60 €/ton CO_2 (not shown).

4. Conclusion

This work discusses the influence of the quality of the CO_2 source (quantity, load hours, and CO_2 concentration) and the availability of low cost heat on the absolute and specific capture cost and on the cost optimal capture rate of absorption based carbon capture.

The work emphasizes that there are several scenarios for both industrial and power based CO_2 sources where partial capture heavily reduces the absolute as well as the specific capture cost. These scenarios include sources with access to low-cost heat that could power parts of the capture process, sources with low utilization and varying load, and sources with several CO_2 containing streams of varying quality. Furthermore, the optimal relation between the fixed operating costs, dominated by the investment cost, and the variable operating cost, dominated by the heat demand should be investigated for partial capture schemes. For the conventional capture case the heat demand typically dominates the capture cost. However, for many of the partial capture cases discussed above the energy cost is a minor share and the capture cost is dominated by the investment. In such cases, increased investments to lower the energy demand are not motivated.

Future work should, thus, map the possibilities for low-cost partial capture schemes in specific case studies for efficient and low-cost CO_2 mitigation. Furthermore, the influence of the economic assumption and the optimum between investment and energy cost of absorption based carbon capture should be analyzed to further lower the capture cost of partial capture schemes.

Acknowledgements

The authors wish to acknowledge Annabelle Berlinger (MSc student at Chalmers University of Technology) for her valuable contribution to the process modelling as well as the research partners in the CO2stCap project for discussions and input on the conditions for CCS in their specific industries. The project is funded by The Swedish Energy Agency, the Norwegian CLIMIT-Demo program via Gassnova, and participating industries and research partners.

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