Cost-optimal CO_2 capture ratio for membrane-based capture from different CO_2 sources

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Abstract

This paper investigates the impact of lower CO_2 capture ratios (CCR) on membrane-based CO_2 capture and the identification the optimal CCRs for different membranes, depending on the CO_2 concentration in the flue gas. In order to investigate this opportunity for cost reduction, a numerical model based on the Attainable Region approach is used to optimise and assess the cost of membrane-based processes for CO_2 capture from post-combustion flue gases containing 10 to 35% CO_2, analysing five membranes and CO_2 capture ratios from 50 to 90%.

The results show that partial CO_2 capture can significantly reduce the CO_2 avoided cost of membrane-based CO_2 capture from post-combustion processes varying from 11% cost reduction in the case with 10% CO_2 to 55% cost reduction in the case of a flue gas containing 35%CO_2. The impact of the CCR varies with membrane properties and CO_2 concentration. Considering these different behaviours, the potential benefits of a membrane process based on two different membranes is investigated while considering the impact of CCR. Finally, the impact of the transport cost on the optimal CCR is then discussed through four industrial cases (a refinery, a coal-fired power plant, a cement plant and a steel plant). Overall, these cost evaluations demonstrate that membrane-based CO_2 capture can significantly benefit from lower CCRs and that considering lower CCRs could enable early deployment of CCS despite low carbon emission cost.

Keywords: Carbon Capture and Storage (CCS); Membrane separation; CO_2 capture ratio; Post-combustion capture; Techno-economic optimisation.

Abbreviations: CAPEX, capital expenditures; CCR, CO_2 capture ratio; CCS, carbon capture and storage; CEPCI, chemical engineering plant cost index; EBTF, European Benchmarking Task Force; FSC, fixed site carrier; GHG, greenhouse gas; IPCC, Intergovernmental Panel on Climate Change; NOAK, n^{th} of a kind; OPEX, operating expenditures; STP, standard temperature and pressure; TDC, total direct costs.

1 Introduction

Carbon Capture and Storage (CCS) is required to reduce anthropogenic greenhouse gases emissions from both the energy and industrial sectors and reach the 2ºC target in a cost efficient manner [1]. While several routes are possible to capture CO_2 emissions, the post-combustion route appears to be the most promising, as it enables retrofit of CO_2 reduction technologies on already operating plants. This feature facilitates CCS to be implemented in a short-term perspective.

Post-combustion solvent-based CO_2 capture is the most mature capture technology and is currently being demonstrated at several facilities around the world [2-5]. However, other emerging technologies, despite their lower maturity, are expected to cut future capture costs [6, 7]. Permeation membrane technology is the most mature of these emerging technologies, and is considered to have one of the strongest cost-reduction potential [6, 8]. In the power generation industry, however, membrane based capture processes have a challenge to energy- and cost-competitive compared to solvent-based capture due to the low driving forces involved [9, 10]. Complex process configurations are employed to overcome this challenge and meet the system constraints (product purity and capture ratio). This results in multiple complex design

decisions in order to minimize the CO_2 capture cost. Loosening the constraints on CO_2 product purity and capture ration can have an effect of CO_2 capture costs and is dependent on the separation technology employed for capture. CO_2 product purity is set by transport and storage requirements, thus leaving CO_2 capture ratio[1] (CCR) as a parameter to vary in order to explore options for cost reduction. Reducing the cost of CO_2 capture could enable early deployment of CCS despite low carbon emission cost. While technology expertise shows that a CCR of 90%, or higher, is cost-effective for solvent technologies, limited number of studies considering the impact of CCR on membrane-based capture have been published [8, 9, 11]. It is therefore interesting to determine whether lower CCRs could be more cost-effective in the case of membrane-based CO_2 capture.

In order to investigate this opportunity for cost reduction, a numerical model based on the attainable region analysis proposed by Lindqvist et al. [12-14] incorporated in SINTEF Energy Research's iCCS tool [15, 16], is used to quantify the impact of lower CCRs and identify the optimal CCRs depending on the CO_2 concentration in the flue gas for different membrane alternatives. In addition to the identification of cost-optimal CCRs and the cost benefit from lower CCRs, specific power generation and industry cases are investigated in order to identify the cost-optimal membrane and CCR combination in each case. The CO_2 captured is eventually transported through a CO_2 transport infrastructure that benefits from economies of scale. The CCR selected for the capture process thus affects the CO_2 transport design and cost. The impact of the inclusion of the CO_2 transport infrastructure in the CCR cost-optimisation is investigated and discussed to overcome the limitations of sub-system optimization.

2 Methodology

2.1 Study concept and system boundaries

This paper investigates the potential of lower CO_2 capture ratio (CCR) in order to reduce the cost of membrane-based CO_2 capture to facilitate early implementation of CCS despite low carbon prices. Thus, the influence of the CCR on the design and cost of a post-combustion membrane-based CO_2 capture process is investigated to identify the cost-optimal design. The exhaust flue gases generated by a power plant or an industrial plant have a wide range of CO_2 concentrations, depending on the type of industry, the industrial technology and characteristics considered [17]. To get a good overview of the effect of CCR on membrane-based post-combustion capture, exhaust flue gases containing between 10 and 35% of CO_2 content are considered in this study. This range of CO_2 concentrations is selected to be representative of the exhaust gas from refineries, coal-fired power plant, cement and steel production plants [17-19].

The membrane-based capture process is therefore optimised and evaluated for the CO_2 concentrations suggested above (10-35%) with CCRs ranging from 50% to 90%. The capture process is designed for five membranes selected to represent a mix of state-of-the-art and potential future development. These results will enable the cost-optimal CCR to be identified for each flue gas CO_2 concentration and membrane. The benefits and disadvantages of lower CCR will be quantified and the impact of the CCR on the membrane process design will thus be better understood. Finally, as significant economies of scale are achievable in the CO_2 conditioning and transport infrastructures, the influence of transport costs on the overall chain cost-optimal CCRs will be identified and discussed on an industrial case-study basis.

The system considered follows the steps shown in Figure 1. First, the cleaned exhaust flue gas from the CO_2 source is sent to the membrane-based CO_2 capture unit. The captured CO_2, available at 1 bar with a minimum purity of 95% [20], is conditioned to meet the pipeline transport requirements (pressure of 150 bar [21, 22]), while the remaining exhaust flue gas after CO_2 capture is vented. Finally, the CO_2 is transported via a pipeline for delivery to an offshore storage.

Two sets of system boundaries are analysed to study the effect of the entire chain on the optimal capture ratio. In the first, only the membrane-based CO_2 capture unit is included in order to identify the cost-optimal CCR for the capture process itself. The second set of system boundaries includes the CO_2 capture, conditioning and transport steps in order to quantify the influence of the economies of scale of the conditioning and transport on the cost-optimal CCR of the chain on a case-study basis.

[1] Defined as the amount of CO_2 captured over the amount of CO_2 in the flue gas.

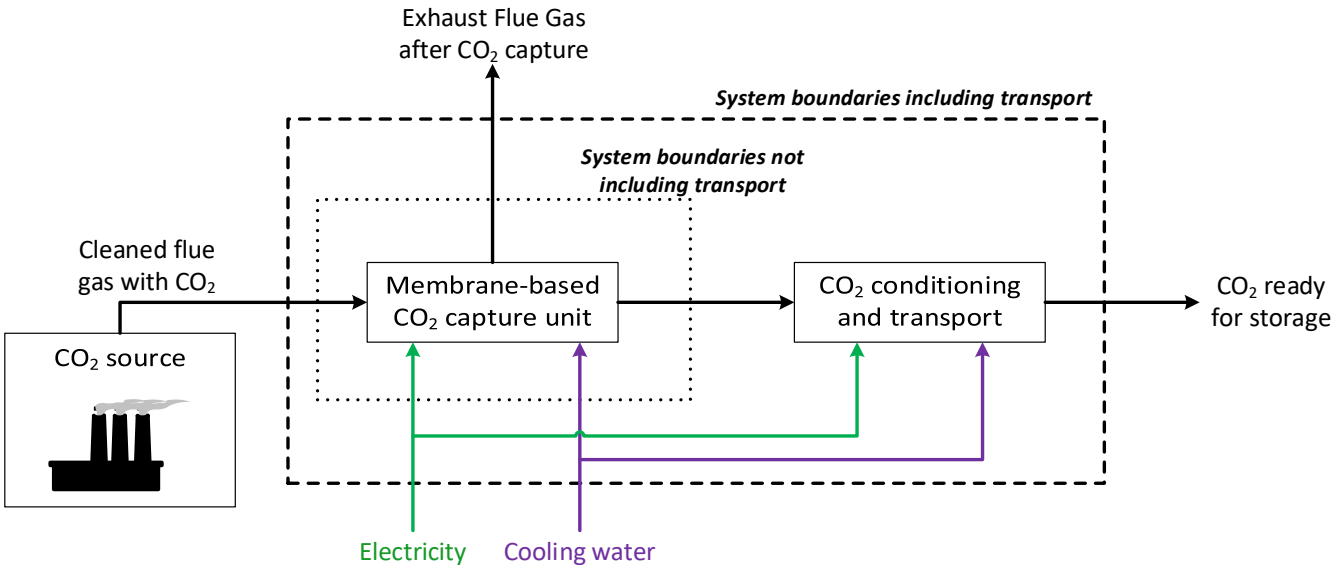


Figure 1: Schematic view of the CO_2 capture, conditioning and transport and the system boundaries

2.2 Technical modelling of the CO_2 capture, conditioning and transport

2.2.1 Membrane-based CO_2 capture

2.2.1.1 The attainable region approach

A graphical methodology, called the attainable region approach, has been developed for systematic design of membrane-based post-combustion capture, illustrated and detailed by Lindqvist et al. [12-14, 23]. This methodology was developed for stage-wise membrane separation processes that are typical in post-combustion capture applications to achieve 95% CO_2 purity requirements with the membranes available or under development.

A numerical model based on this approach, incorporated in SINTEF Energy Research's iCCS tool[15, 16, 24], is used in this work. Based on the system characteristics (CO_2 concentration in the flue gas, CCR...) and membrane properties, the numerical model optimises the membrane-based process, with simple[2] multi-stage configurations (up to three stages), to minimise costs using the approach presented in Figure 2 [23]. Thus, although process configurations with lower number of stages may be feasible, in some cases a configuration with a high number of stages may be selected due to its lower cost. For each considered designs, the process characteristics (pressures, power requirements and area) are evaluated in order to assess and optimise the system costs.

Details of the membrane model are provided in Roussanaly et al. [23].

[2] Without advanced process features, such as retentate recycles or sweep gas. Membrane processes with these advanced process features have been presented in literature and have been shown to reduce cost of capture. However, no systematic method of process design is available to design and compare such membrane processes, particularly for the case with sweep gas. It is expected that the results presented here will provide an insight into the trends that would be similar for processes with complex configurations.

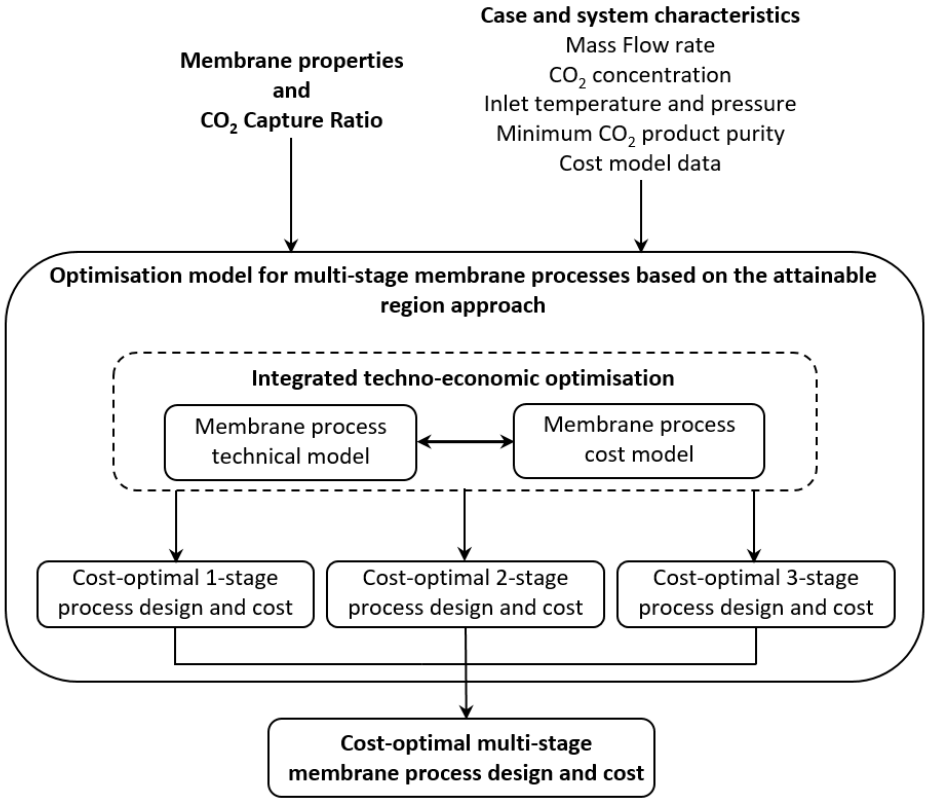


Figure 2: Optimisation approach used to select and assess cost-optimal membrane designs

2.2.1.2 Membranes considered in the study

Many potential materials for post-combustion membrane CO_2 capture are been developed and tested at different scales [25-35]. In this work, five membranes with the characteristics reported in **Table 1** are considered.

The first one, referred to as membrane A, is the second generation Polaris^{TM} polymeric membrane developed by MTR [36]. This membrane is regarded as being at an advanced stage of development and testing [9-11, 36-38], and is considered the reference membrane in several studies [36, 39]. The second membrane, referred to as membrane B, is a theoretical membrane with an improved permeance to reach the R&D targets for improved Polaris^{TM} membranes [39]. This membrane is considered to have a selectivity of 50 and a permeance of 13.9 $m^3_{(STP)}m^{-2}h^{-1}bar^{-1}$. The third membrane, referred to as membrane C, is a theoretical diffusion-based membrane based on Robeson upper bound [40]. In this case, the membrane is selected to have the highest selectivity that can be achieved without violating the upper bound for a membrane with a permeance equal to the Polaris^{TM} membrane and assuming a minimum thickness of 50 nm [41, 42]. The fourth membrane, referred to as membrane D, corresponds to the Fixed Site Carrier (FSC) membrane developed by NTNU [43, 44] and tested at the Norcem Brevik cement plant in Norway [45]. Although FSC membranes are characterised by their high selectivity, they often lead to low permeance (below 1 $m^3_{(STP)}m^{-2}h^{-1}bar^{-1}$) which limit their interest. However, the membrane developed by NTNU has already been reported to reach 2 $m^3_{(STP)}m^{-2}h^{-1}bar^{-1}$ [43] and are theoretically able to reach permeances as high as 5 $m^3_{(STP)}m^{-2}h^{-1}bar^{-1}$ [46]. Therefore, in addition to membrane D with its previously confirmed characteristics, a membrane E with a theoretical improved permeance compared to membrane D is also considered.

Table 1: Characteristics of the membrane modules considered in this study

Membrane	Membrane	Selectivity [-]	Permeance [$m^3_{(STP)}m^{-2}h^{-1}bar^{-1}$]
A	2nd generation Polaris™ membrane developed by MTR	50	5.94
B	Improved R&D target permeance Polaris™ membrane	50	13.9
C	Theoretical membrane-based on Robeson upper bound for a selectivity of 5.94	79	5.94
D	FSC membrane developed by NTNU	135	2
E	Theoretical improved FSC membrane	135	4

2.2.2 CO_2 conditioning and transport

CO_2 conditioning and transport are evaluated using the CO_2 transport modules of the iCCS value chain tool [15], which has been presented in detail by Roussanaly et al. [22, 47].

To reach the requirement at the inlet of the pipeline, conditioning is required and consists of four inter-cooled compression stages, with a pressure ratio around 3 for each compression stages, followed by pumping [48, 49]. While the CO_2 is delivered at 150 bar at the inlet of the onshore pipeline, it is assumed that the CO_2 after transport and reconditioning is delivered at 200 bar to an offshore pipeline to store the CO_2 offshore [22].

Pipeline diameters are selected, among diameters ranging from 6"5/8 to 44", on a case-to-case basis to minimize cost. In each case, the pipeline characteristics are designed to meet the minimal wall thickness requirements [50] in the recommended API specification 5L [51] . The pressure drops along the pipeline are evaluated based on the Fanning equation [52], and the number of reboosting stations is determined to ensure a minimum pressure of 90 bar along the pipeline as shown in Figure 3.

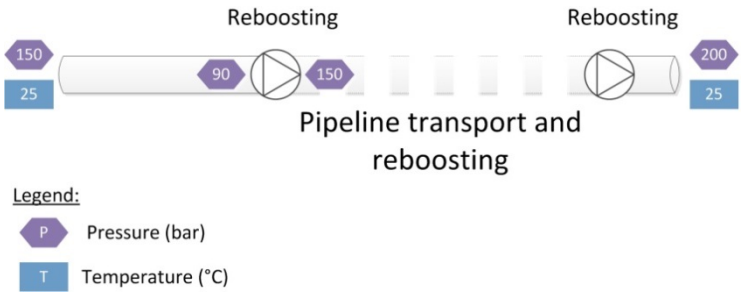


Figure 3: Schematic drawing of the pipeline export [22]

2.3 Cost evaluation of CO_2 capture, conditioning and transport

The cost evaluations are performed on a NOAK (N^{th} Of A Kind) basis and do not take into account the higher costs expected from pilot and demonstration projects before the technologies considered are fully matured and commercial.

All costs are reported in $€_{2014}$ values. If investment costs are not directly available in 2014 prices, they are corrected based on the Chemical Engineering Plant Cost Index (CEPCI) [53], while the cost of utilities are updated based on inflation [54].

2.3.1 Investment costs

The investment costs of the CO_2 capture process are estimate based on a factor estimation method. In this approach, the investment costs are obtained by multiplying the direct cost of each equipment by an indirect costs factor. Direct costs functions ($€_{2014}$) has been regressed for each equipment based on evaluations performed in Aspen Process Economic Analyzer® as shown in Table 2. However, the membrane module and framework costs are assessed based on literature. While the membrane module is evaluated based on the cost adopted by Zhai and Rubin [10], the membrane framework is assessed based

on the costs suggested by van der Sluijs et al. [55] and modified by Roussanaly et al. [13, 23]. Finally, the CO_2 capture investment cost is obtained by multiplying the sum of direct costs by an indirect cost factor of 1.31 [56].

Table 2: Direct cost of membrane module, rotating equipment and heat exchanger [23]

Type of equipment	Cost
Membrane module [10] [€/m^2]	40
First stage of compressor (outlet pressure below 4.1) [€/kW]	920
Second stage of compressor (inlet pressure above 4.1 bar) [€/kW]	510
Expander [€/kW]	570
Vacuum pump [€/kW]	800
Cooler [€/m^2]	370

The CO_2 conditioning and transport investment costs are calculated using the transport modules of the iCCS tool [15, 22, 47, 57]. In these modules, as documented previously [22], the conditioning module estimates the investment cost as a function of the CO_2 capacity while the transport investment cost is determined based on 53,100 €$_{2014}$/inch/km estimate based on costs suggested by Mikunda et al. for North-West European location [58].

2.3.2 Operating costs

The annual fixed operating cost (maintenance, insurance, labour and periodic replacement) is set to 6% of the investment costs of the CO_2 capture and conditioning processes [59], while the annual pipeline fixed operating costs are set to 7,000 €$_{2014}$/km [58]. In addition, the cost associated with periodic replacement of membrane module is taken into account based on a yearly replacement over 5 years [60, 61] and a 8 \$$_{2014}$/m^2 replacement cost [10].

The annual variable operating costs of the CO_2 capture, conditioning and transport systems are evaluated based on utilities consumption (electricity and seawater cooling) obtained from the system design and the utility unitary costs shown in Table 3.

No CO_2 emission penalty cost is considered in the present study as the aim of the study is to investigate how lower CCRs could enable cheaper CO_2 capture and therefore enable implementation of CCS despite low carbon pricing.

Table 3: Cost of utilities for the CO_2 capture, conditioning and transport processes

Utilities	Cost
Electricity [€$_{2014}$/MWh] [62]	80
Seawater cooling [€$_{2014}$/m^3] [63]	0.039

2.3.3 CO_2 avoided cost

The CO_2 avoided cost [64] is here used as a key performance indicator in order to optimise the membrane process and identify the cost-optimal CO_2 capture ratio.

The CO_2 avoided cost (€/t$_{CO2,avoided}$) approximates the average discounted CO_2 credit over the project duration to overcome the costs associated with CO_2 capture, conditioning and transport. It is equal to the annualised investment and operating costs divided by the annualised amount of CO_2 avoided, as shown in equation (1). The annualised amount of CO_2 avoided is defined as the amount of CO_2 captured minus the direct emissions associated with the electricity consumption [62][3] of the CCS infrastructure.

The CO_2 avoided cost is evaluated an 8% discount rate, a 25 years economic lifetime and a three years construction period [56].

$$\text{CO}_2 \text{ avoided cost} = \frac{\text{Annualised investment} + \text{Annual OPEX}}{\text{Annualised amount of CO}_2 \text{ avoided}} \quad (1)$$

[3] The climate impact factor of electricity is considered to be 0.435 kg/MWh.

3 Results

3.1 The influence of the capture ratio on the CO_2 avoided cost

The CO_2 avoided cost of the membrane-based capture process[4] for the five membranes considered at 90% CCR and at their respective cost-optimal CCR are presented in Figure 4 for CO_2 concentrations in the flue gas ranging from 10 to 35%. In addition, the curves collecting the best membrane option among the five membranes analysed for each CO_2 concentration are also plotted in Figure 5 for the 90% CCR and the cost-optimal CCRs.

The results show that the best 90% CCR membrane-based process using the cost-optimal membranes leads to CO_2 avoided cost from 64 to 15 €/t$CO_{2,avoided}$ for flue gases with CO_2 concentration ranging from 10 to 35%. For the case with 10% CO_2 in the flue gas, the selection of the cost-optimal membrane leads to a reduction in CO_2 avoided cost of up to 18%. However the benefit of selecting the cost-optimal membranes decreases to the point of almost disappearing at a CO_2 concentration of 35%, as shown in Figure 5. Furthermore, the results show that the membranes E and C appear to be the best membrane options for CO_2 concentrations in the flue gas up to 20%, while membranes C and B appear to be the best options above 20%.

When considering CCRs lower than 90%, the case evaluations show that the membrane-based process considering the cost-optimal membranes lead to CO_2 avoided cost from 57 to 7 €/t$CO_{2,avoided}$. Figure 5 also shows that the selection of the cost-optimal membrane is more important in the case of partial capture, as it allows the capture cost to be reduced by 17% at 10%CO_2 and 43 % at 35 %CO_2. In term of optimal membrane, the cost results show that membrane B is the best option for CO_2 concentration in the flue gas from 15% to 25%, while membrane B and C appear to be the best options at 10 %CO_2. Finally, the membranes D and E are the best option for the 30 and 35%CO_2 cases when considering partial CO_2 capture.

The comparison of the 90% CCR data with the optimal CCR results emphasize that partial CO_2 capture can significantly reduce the CO_2 avoided from membrane-based CO_2 capture from post-combustion processes. It is worth noting that the cost-optimal membrane is not always the same for the optimal CCR and the 90% CCR. While the benefit of lower CCR is rather limited for low CO_2 concentrations in the flue gas (11% cost reduction in the 10%CO_2 case), this benefit increases with CO_2 concentration, to reach a 55% cost reduction in the case of 35%CO_2 in the flue gas. An intuitive explanation of this is that membrane-based separation is a physical separation driven by the difference in partial pressure between the two sides of the membrane. Lower CCRs limit the CO_2 concentration decrease on the feed side of the membrane, which enables a strong separation driving force to be maintained along the membrane fiber. This helps to lower the compression work required and the membrane area, and therefore the CO_2 avoided cost of the membrane-based capture process. However, it is important to note that depending on the membrane and the flue gas CO_2 concentration, the benefit of lower CCRs can vary greatly, and can even become negative.

[4] Not including conditioning and transport.

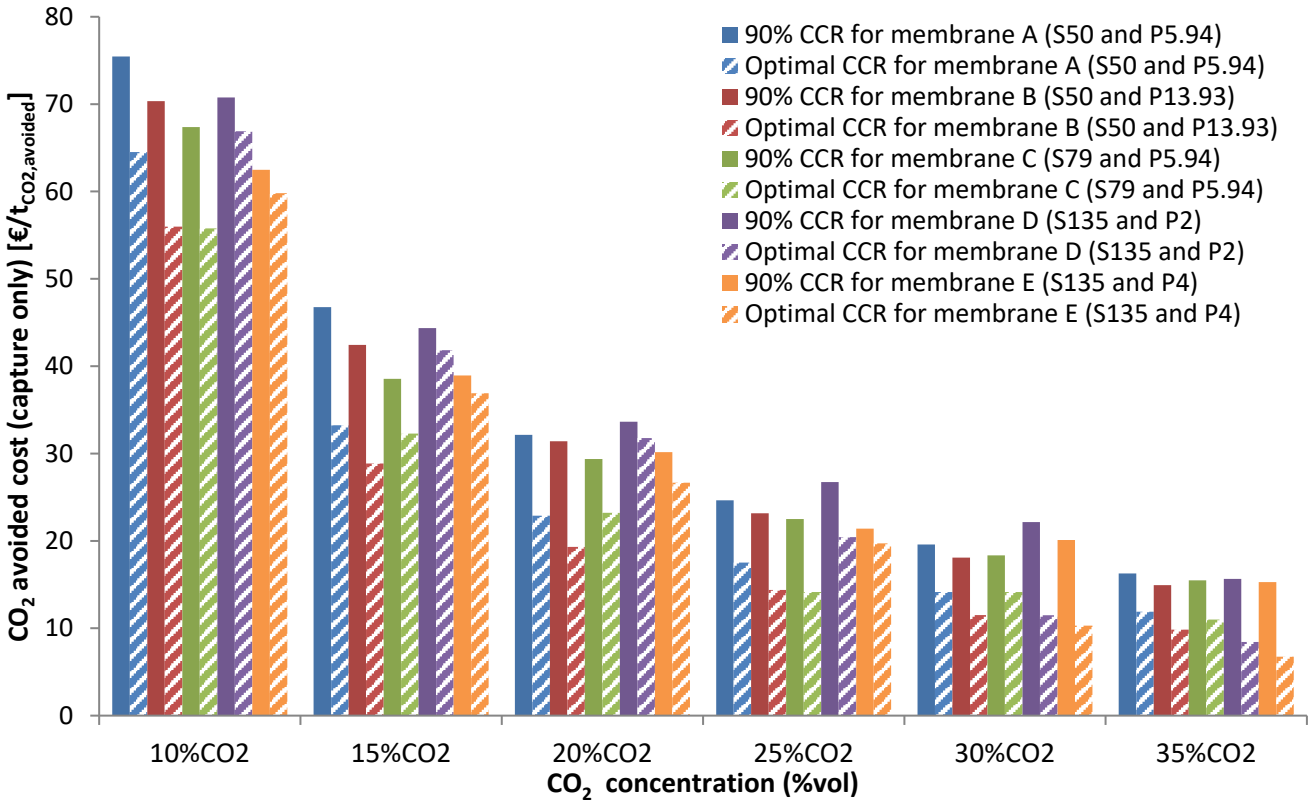


Figure 4: CO_2 avoided cost of the 90% CCR and the optimal CCR of the membrane capture process for the membranes and CO_2 concentration analysed

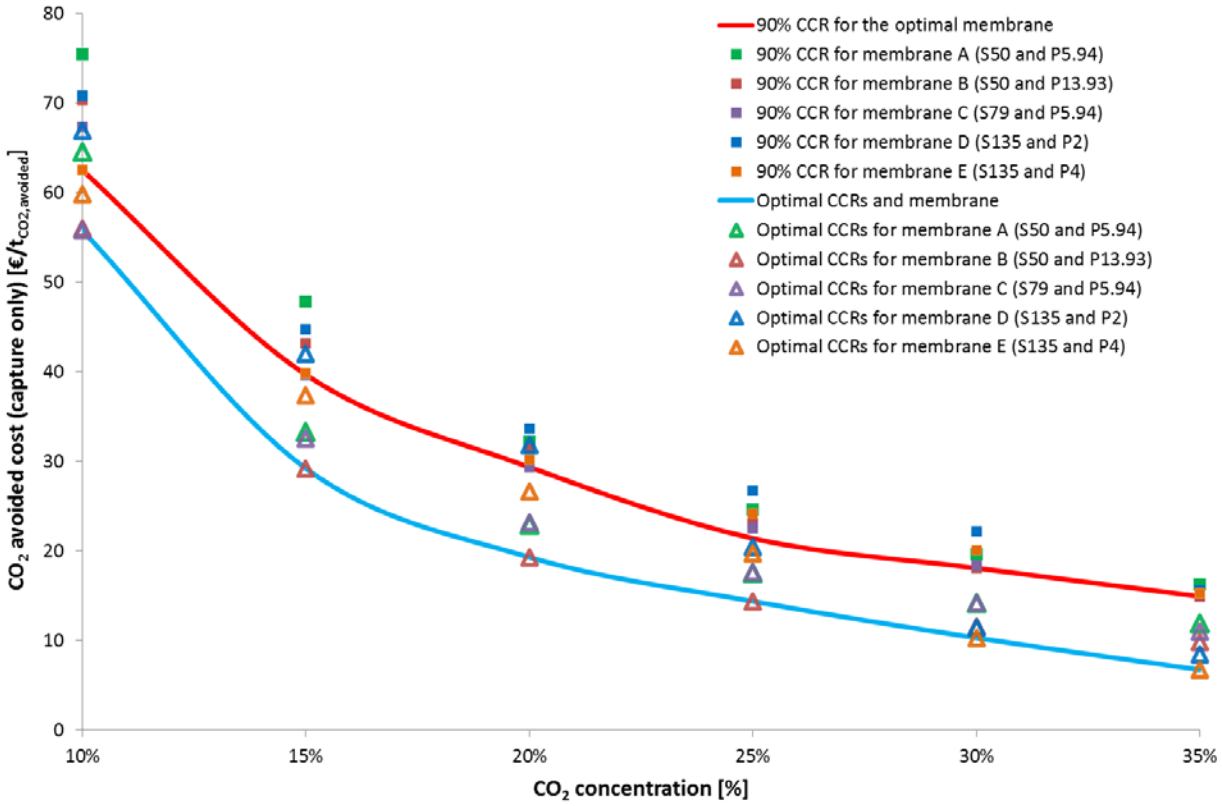


Figure 5: CO_2 avoided cost of membrane-based capture for the five membranes and the overall optimum curves at 90% CCR and their respective optimal CCRs for CO_2 concentrations from 10 to 35%

3.2 The impact of partial capture on the process design and cost

The CO_2 avoided cost depending on the CO_2 capture ratio for the five membranes evaluated is presented in Figure 6(a) to (f) for post-combustion CO_2 capture from a flue gas containing (a) 10%CO_2 (b) 15%CO_2 (c) 20%CO_2 (d) 25%CO_2 (e) 30%CO_2 (f) 35%CO_2.

In the 10%CO_2 case, the evaluation shows that several membranes benefit significantly from lower CCR. Indeed, as shown in Figure 6(a), CO_2 capture ratios of 50 and 60% lead to a cost reduction of up to 21% for membranes A, B and C. This enables membranes B and C to outperform the membrane E, which is the best membrane in terms of cost for a 90% CCR. However, in the case of the membrane D and E, a CCR below 80% can lead to a significant increase in the CO_2 avoided cost. The higher the selectivity of a membrane, the larger is the required driving force and thus pressure differential. This leads to higher specific energy consumption for membranes D and E, mainly due to the compression work required before the first membrane stage. Lowering the CCR does not decrease the compression work before the first stage but has an effect of reducing membrane area. Thus, the specific work of the process and finally the CO_2 avoided cost of the membrane capture process increases in the case of membranes D and E. It is worth noting that in practice, a better way to reduce the amount of CO_2 capture with membrane D and E would be to by-pass part of the flue gas in this case.

In the 15%CO_2 case, the benefit of lower CCR is more significant for membranes A, B and C than in the 10%CO_2 case and provides up to 34% cost reduction. Membranes D and E show a similar trend to the 10%CO_2 case. However, here there is a slight improvement in the relative performance of the membrane at 50% CCR compared to the 90% CCR. This is due to the fact that compared to the 10%CO_2 case lower pressure ratio across the membrane is required as there is a driving force gain with increasing concentration for membranes D and E, and the effect of increasing feed CO_2 concentration will result in reducing the effect of high selectivity on pressure ratio and thus specific energy consumption in subsequent cases. Membranes A, C and especially B outperform membranes D and E. Note that in this case, membrane B outperforms membrane C at lower CCRs.

In the 20%CO_2 case, CCRs from 50 to 70% allow a cost reduction of the membrane capture process for membranes A, B, C and E. However, the relative benefit of partial CCR varies. Indeed, membrane-based processes based on membranes A, B, C and E can lead to costs that are respectively up to 30, 40, 20 and 12% lower for partial CCR than at 90% CCR. However membrane D still has a limited benefit from partial CO_2 capture (less than 5%). As a result, membrane B, with a lower CCR, outperforms membranes C and E which are the cost-optimal options at 90% CCR.

For CO_2 concentration in the flue gas higher than 25%, all the membranes evaluated benefit significantly from the partial CO_2 capture ratio. Indeed, for almost all cases and membrane combinations, the cost-optimal CCR is 50%. Partial capture leads to cost reductions of 29 and 38% compared to 90% CCR for membranes A and B, while it leads to a CO_2 avoided cost of around 20% lower than the 90% CCR for membranes C, D and E. This allows membrane B at lower CCRs to outperform membrane C, which is the cost-optimal option at 90% CCR. For the 30%CO_2 case, lower CCRs have an even stronger impact especially for membranes D and E which can halve their CO_2 avoided when considering a CCR of 50% while membranes A, B and C can decrease their costs by 23 to 37%. Finally, the 35%CO_2 case follows the same trends and benefits as the as the 30%CO_2 case.

Finally, it is important to note that these results are also dependent on the assumptions considered for the case evaluation. For instance, Jakobsen et al. [65] have shown that membrane D was a very good option for CO_2 capture from cement plants when low-cost electricity is available .

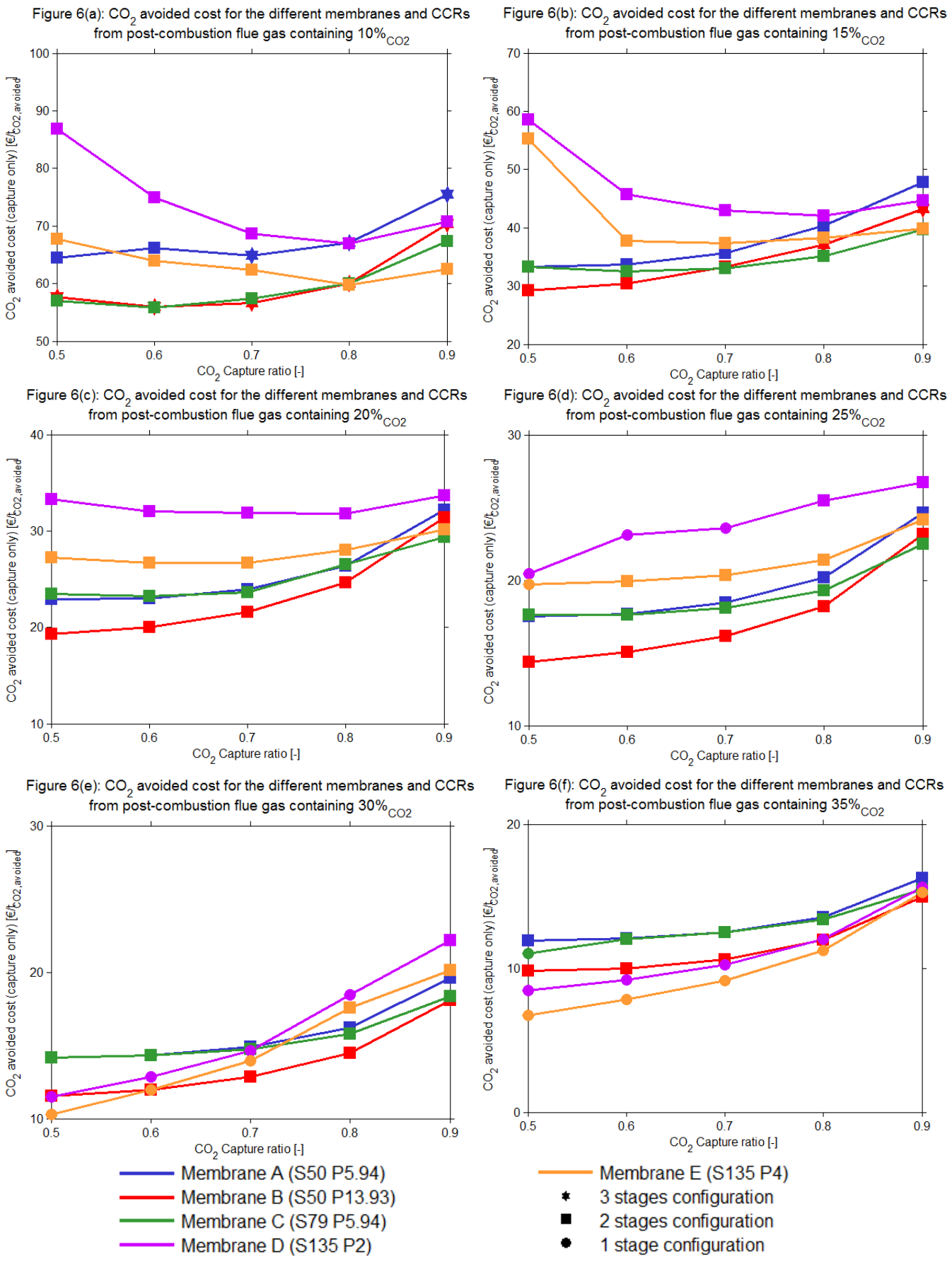


Figure 6: CO_2 avoided cost for the different membranes and CCRs from post-combustion flue gas containing (a) 10%CO_2 (b) 15%CO_2 (c) 20%CO_2 (d) 25%CO_2 (e) 30%CO_2 (f) 35%CO_2

3.3 Opportunities for combined membrane processes

The discussions in the previous section clearly indicates that for lower CCRs moderate selectivity and high permeance membranes (A, B and C) appear to be best suited for CO_2 capture from low CO_2 concentration flue gas and that high selectivity membranes (D and E) are cost-efficient for higher CO_2 content. The question that arises is what would be the effect of having a membrane process with a both categories of membranes. This section aims to identify the opportunity for cost reduction of post-combustion capture membrane processes by utilizing two membrane types.

For the purposes of this work, one membrane from each category has been selected for analysis. The selected membranes are membrane A, the 2nd generation Polaris™ membrane developed by MTR, and membrane D, FSC membrane developed by NTNU.

Figure 7 and Figure 8 show the attainable regions of membranes A and D for 90% CCR with stagewise membrane system design for 10% CO_2 case. As can be seen from the plots, the first stage cost of both the membrane designs are similar, while the case with membrane A requires an additional 2 stages to achieve the desired purity, the design with membrane D only requires 1 additional stage. This is thus reflected in the final CO_2 avoided cost of the two processes.

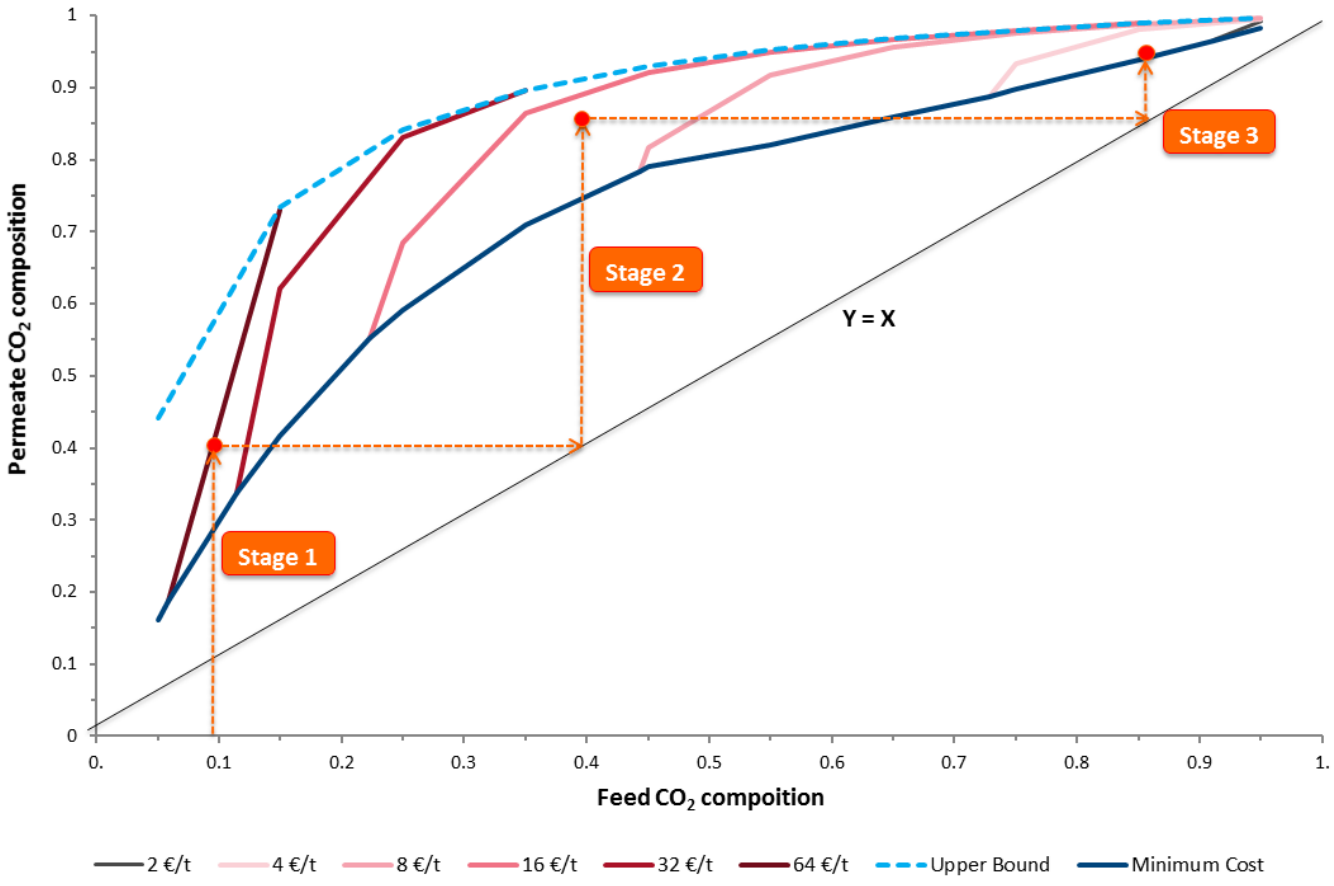


Figure 7: Attainable region for Membrane A - 90% CCR with optimal design for 10% CO_2 case

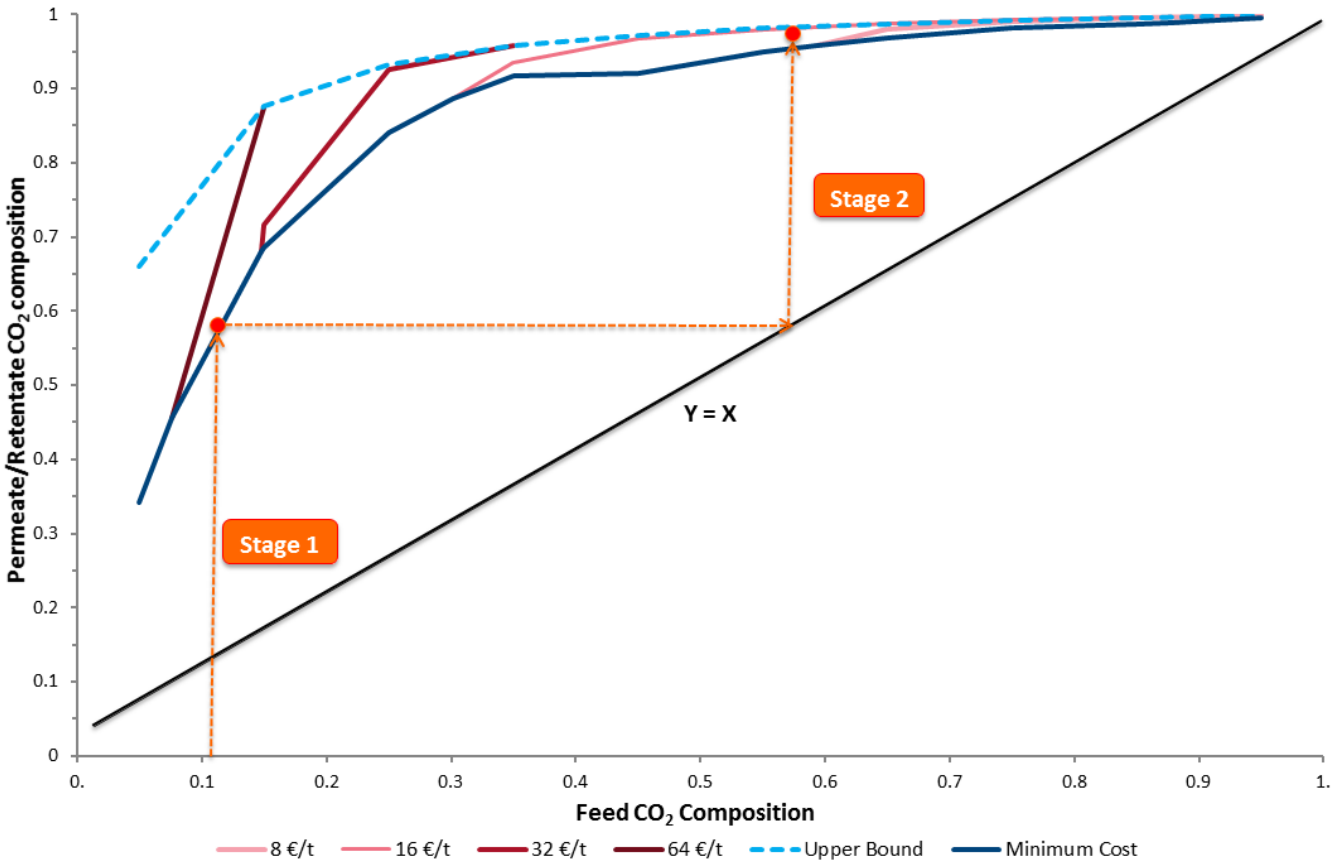


Figure 8: Attainable region for Membrane D - 90% CCR with optimal design for 10% CO_2 case

Figure 9 shows the attainable regions of membrane A and D for 90% CCR case in a single plot with stagewise membrane system design for 10% CO_2 case. In the combined membrane case, the permeate purity from the first membrane stage utilizing membrane A is lower than the design where membrane A is used in all stages resulting in a reduction in capture cost. There is a slight increase in cost for the second stage compared to the case with membrane D only. This is however, more than off-set by the reduction in cost of the first stage process. The combined membrane process design results in a CO_2 avoidance cost of 65.8 €/$t_{CO2,avoided}$ compared to 75.5 €/$t_{CO2,avoided}$ and 70.8 €/$t_{CO2,avoided}$ for processes designed with membranes A and D respectively. Thus the combined membrane system shows a 7% improvement over the best single membrane system design in this case.

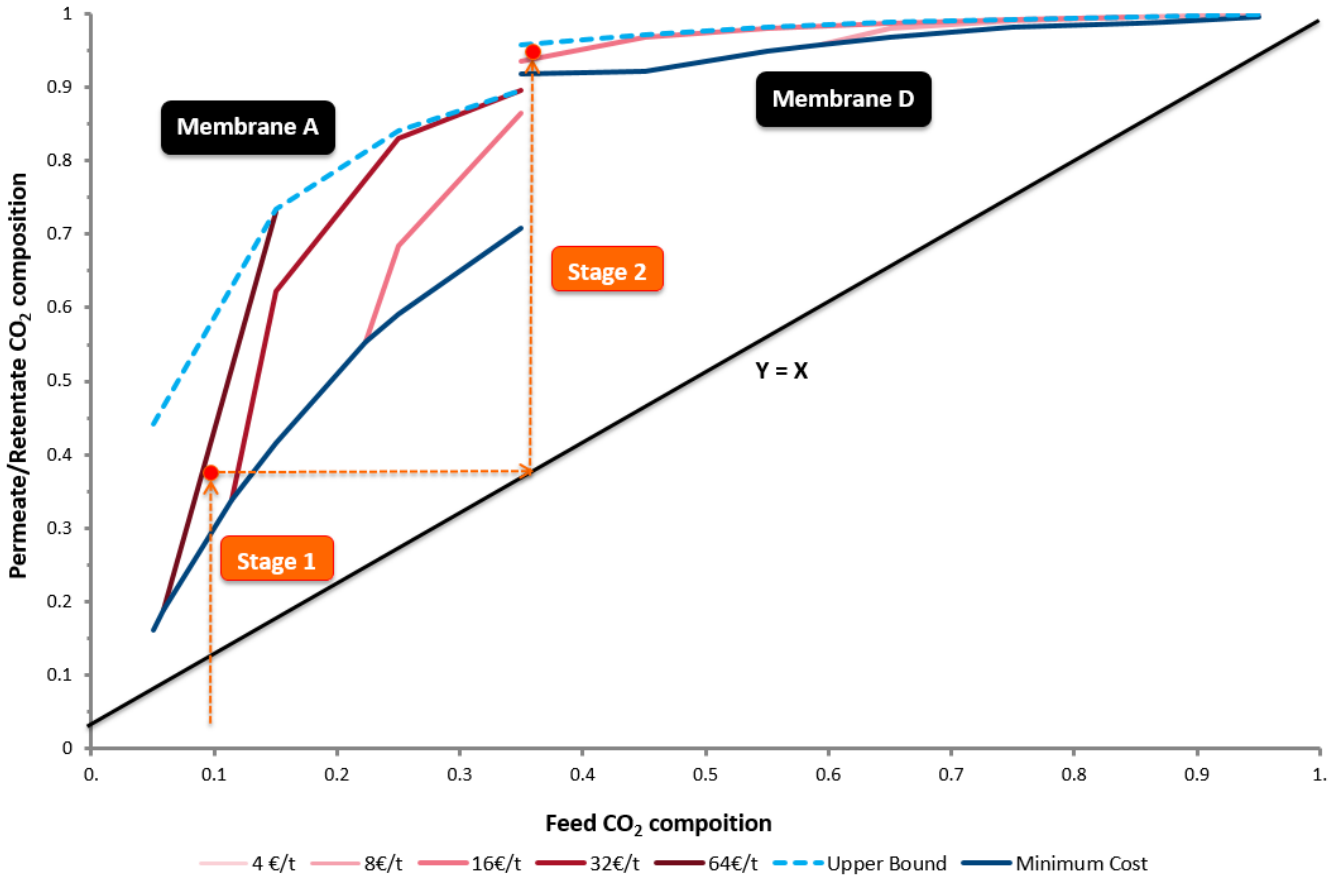


Figure 9: Attainable region for Membrane A and D - 90% CCR with optimal design for 10% CO_2 case

Figure 10 shows, for different CCRs and CO_2 concentrations in the feed stream, the cost reduction of a two-stage process based on membranes A and D compared to the best multi-stage membrane process based solely on membrane A or D as considered in section 3.2.

For the 10% CO_2 case, the combined membrane system results in lower CO_2 avoidance cost than the individual membrane cases for all CO_2 capture ratios. This is because the membranes A and D are not individually suited for 10% CO_2 case. Membrane A is hindered by the higher costs accrued beyond the first stage, while membrane D can achieve the required CO_2 purity using a 2 stage process in a cost-efficient manner. Thus switching to a combined membrane system helps as the cost of the first stage with membrane A is lower than that with membrane D and similar to one of the process based solely on membrane A, while it is possible to achieve the required purity in the second stage using membrane D in a cost-efficient manner.

For the 15% CO_2 case, the combined membrane system is better than the individual cases for CCRs of 70-90%, and performs worse for lower capture ratios. As the capture ratio is decreased, the minimum cost line in the attainable region curve moves higher. In other words, it is easier to achieve higher purities and the optimal purity at the outlet of stage 1 is closer to the minimum cost curve. Thus, the combined membrane process results in a process with a first stage very similar to the one obtained when considering a multi-stage membrane process based solely on membrane A, resulting therefore in very limited cost reduction in the first stage. Meanwhile, the cost of capture in the second stage increases and thus the overall CO_2 avoided cost increases.

Due to the same reason as indicated for the 15% case, the combined membrane system in the 20% case performs better only for the 90% CCR case. However, the gain is lower as with increasing CO_2 concentration in the flue gas the attainable purity at minimum cost increases reducing the potential for improvement.

While not shown in Figure 10, the trend is similar for the 25% CO_2 case as the 20% CO_2 case. However, for the 30% and 35% CO_2 case, the individual membranes are always better than the combined membrane

system. This is primarily due to the fact that at these high flue gas CO_2 concentrations membrane D has an optimal design with a single stage membrane process that results in a lower CO_2 avoided cost.

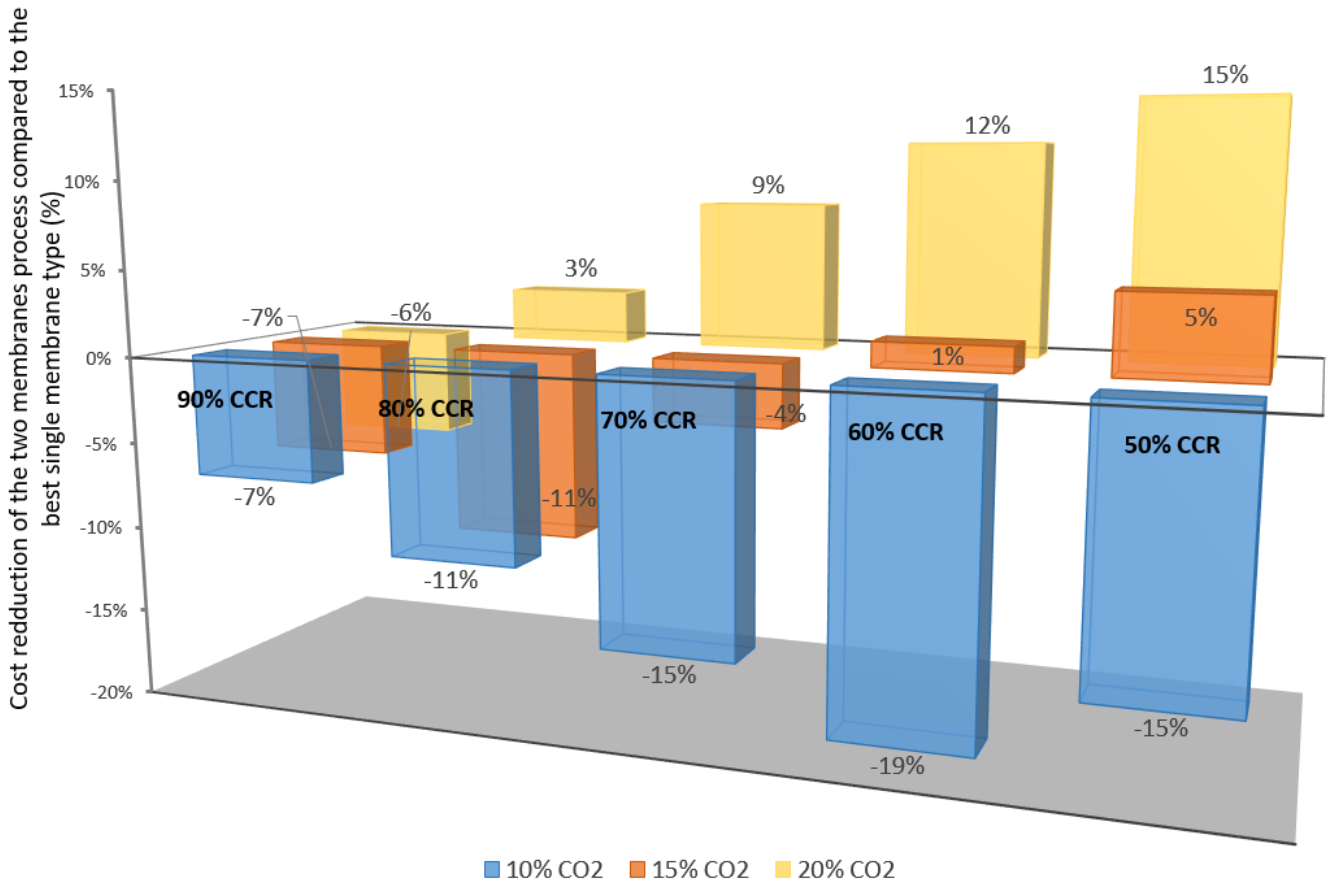


Figure 10: Cost reduction of a two-stage process based on membranes A and D compared to the best membrane process based on solely either membrane A or D for different CCRs and CO_2 concentrations in the feed stream

4 Discussions

CO_2 transport benefits from strong economies of scale that depend on transport capacity, especially for capacities below 5 $MtCO_2/y$, while the CO_2 transport cost correlates fairly linearly with distance [22, 47, 50, 66]. It is therefore expected that CO_2 transport from individual emitters over long distances may be relatively inefficient, especially in the case of partial CO_2 capture from a plant. For this reason, it is important to understand how the optimal CCRs obtained, in section 3.2, change when considering CO_2 capture, conditioning and transport as a whole. In other words, the focus is on optimising the complete system rather than only on the CO_2 capture subsystem as evaluated in earlier sections.

In order to further quantify how the optimal CCR may be affected by the transport distances and capacities, four industrial cases relevant to post-combustion CO_2 capture using membranes are considered: a refinery, a coal-fired power plant, a cement production plant and a steel plant. As the CO_2 concentration in the flue gas from these industries is relatively process- and location-specific, Table 4 presents a summary of typical ranges of CO_2 concentration and the characteristics considered in the four case evaluations. In each case, the membrane process is optimised and evaluated for the five membranes and CO_2 capture ratios, using the methodology presented above. However, it is important to note that due to its specificity[5], the CO_2 avoided cost from the coal power plant is evaluated as suggested by Rubin [64], and the power plant cost methodology presented by Roussanaly et al. [23].

[5] Indeed, the electricity consumed by the capture facility decreases the net power output of the power plant which lead to a different methodology requiring the assessment of the coal power plant costs.

Table 4: Characteristics of the industrial cases considered

Industry considered	Refinery	Coal power plant	Cement production plant	Steel plant
Typical range of CO_2 concentration [%]	8-13 [17]	13-16 [17]	14-33 [17]	16-44 [17]
Selected CO_2 concentration [%]	10	15	20	30
Annual CO_2 emissions without capture [Mt_{CO2}/y]	0.88 [67, 68]	4.28 [56]	0.72 [14, 62]	2.76 [67, 69, 70]

First, in order to understand the contribution of transport to total costs, Figure 11(a) to (d) presents the CO_2 avoided cost (including capture, conditioning and transport) for the chain cost-optimal CCRs in function of the transport distance for the five membranes and four cases taken into account. The impact of including transport in the cost-optimal CCRs, depending on the transport distance and the membrane used is shown on a case-to-case basis in Figure 12(a) to (d).

For the refinery case, Figure 11(a) shows that transport can lead to a significant increase, due to the "limited" CO_2 emissions from the refinery plant (e.g. up to 50% increase when the transport distance is 250 km). As a result of this increase, considering the transport costs can be expected to have an impact on both the selection of the optimal CCRs and the selection of the cost-optimal membrane. This is confirmed in Figure 12(a), as the increase in the share of the transport in the CO_2 avoided cost leads to a significant increase the overall cost-optimal CCR due to the economies of scale of the transport infrastructure. At the same time, it is important to note that this increase in the cost-optimal CCR depends on the relative impact of the CCR on both the capture and the transport costs and is therefore specific to each membrane. Indeed, as discussed in section 3.2, membranes A, B and C benefit significantly from a reduction in the CCR in the case of CO_2 capture from a refinery, while higher CCRs are more beneficial for membranes D and E. Due to these different trade-offs, the inclusion of transport in the selection of the cost-optimal CCR can also lead to the selection of both a different membrane and CCR compared to the case in which only capture is taken into account. This can be observed in the 250 km case in which membrane E at an 80% CCR is the cost-optimal membrane option, while membranes B and C with a CCR of 60% are the cost-optimal options when CO_2 capture alone is taken into account.

For the coal-fired power plant case, Figure 11(b) shows that the increase in the CO_2 avoided cost with distance is lower than in the refinery case, both in absolute and relative[6] terms, as the coal power plant is a relatively large source of emission. Due to this smaller increase, the transport economies of scale have a limited to zero impact on the cost-optimal CCR of each membrane, as Figure 12(b) shows, and therefore have no impact on the selection of the cost-optimal membrane option as shown in Figure 11(b).

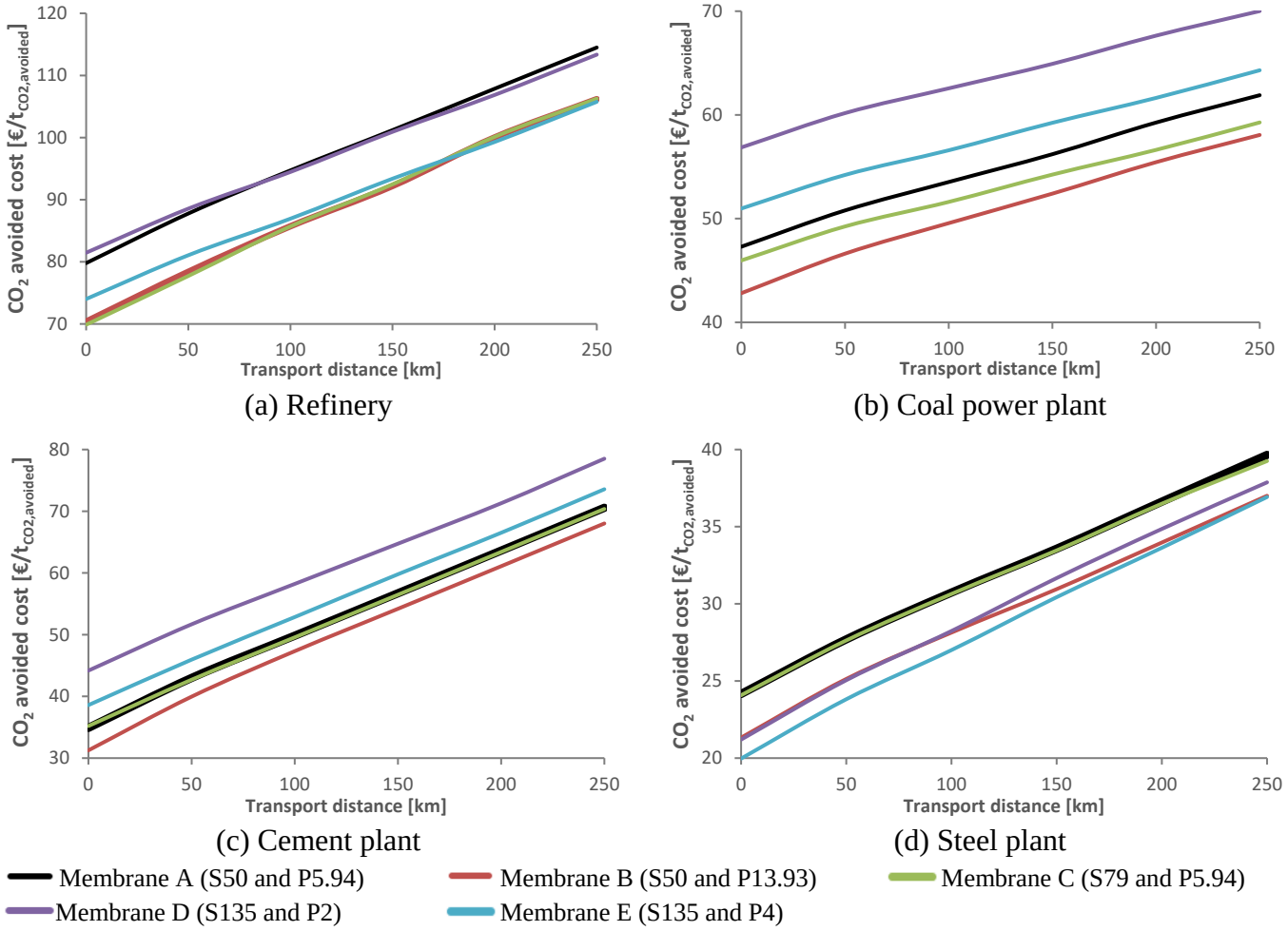
In the case of the cement plant, Figure 11(c) shows that the absolute increase in the CO_2 avoided cost with distance is rather similar to that of the refinery, as the CO_2 emissions from both plants are similar in size, which leads to transport having a similar impact on the cost-optimal CCR. However as the cost of the capture process is close to halved in the cement plant case compared to the refinery, transport has a greater impact on the cost-optimal CCR, as shown in Figure 12(c). Despite this impact on the optimal CCR, the inclusion of transport does not seem to influence the membrane selection in this case.

Figure 11(c) shows that the steel plant case benefits from both a low CO_2 capture cost and rather low CO_2 avoided cost increases, in absolute terms, with the transport distance, due to the fairly large emissions from such plants. This leads to cases in which the transport costs are either smaller or comparable with the capture costs. As a result, a moderate impact of the inclusion of the CO_2 transport and transport distance on the selection of the cost-optimal CCR is observed in Figure 12(d). The variations in these trade-offs among the five membranes can result in changes in the cost-optimal membrane, in the case of long-distance transport as shown in Figure 11(c).

Although the evaluations show that transport can have a significant impact on the cost-optimal CCR, it is important to note that the above results refer to a stand-alone transport infrastructure. However if the cases

[6] It is however worth noticing as the CO_2 avoided cost (considering only capture) is also lower in the power plant case than the refinery case, the relative increase in the CO_2 avoided cost varies between 20 and 35% when comparing the 250km and the 0km costs.

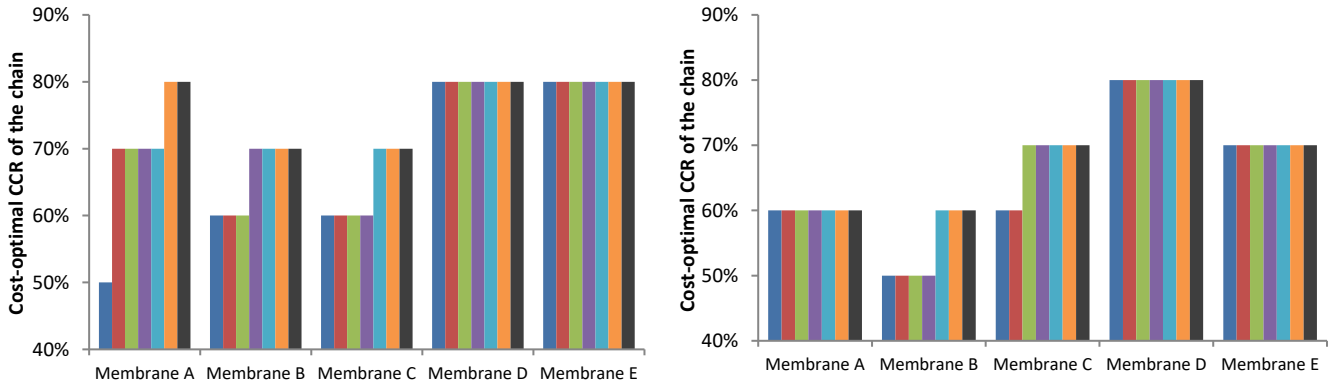
considered can share the transport infrastructure with other sources of CO_2, the impact of transport on the selection of the cost-optimal CCR can be expected to be less significant, leading to a cost-optimal CCR between the one obtained when considering capture only and the one which includes transport on a stand-alone basis. These evaluations thus demonstrate that while membrane-based CO_2 capture can significantly benefit from lower CCRs, the cost-optimal CCR should take the whole chain into account, as it is highly case-specific (industry, CO_2 concentration in the flue gas, membrane considered, transport distance, possibility of combined transport).



(a) Refinery (b) Coal power plant

(c) Cement plant (d) Steel plant

Figure 11: CO_2 avoided cost, (including capture, conditioning and transport) for the chain cost-optimal CCRs in function of the transport distance for the five membranes and for (a) the refinery (b) the coal-fired plant (c) the cement plant (d) the steel plant



(a) Refinery (b) Coal power plant

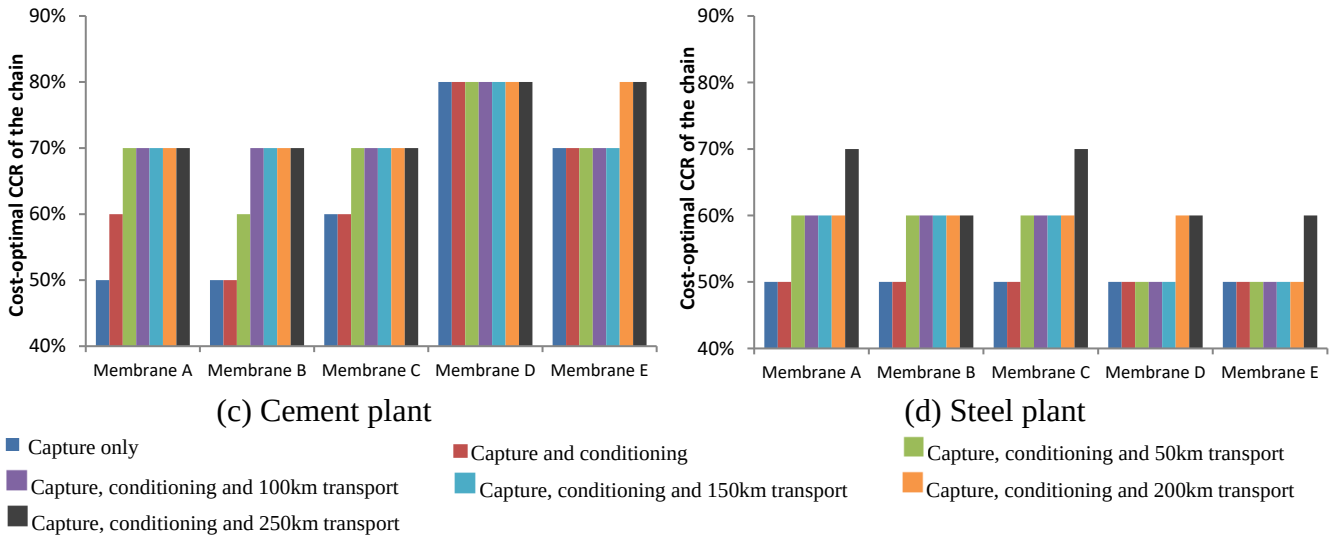


Figure 12: Influence of conditioning and transport on the cost-optimal CCRs of the membrane capture processes for the (a) refinery, (b) coal power plant, (c) cement plant, and (d) steel plant

5 Conclusions

Reducing the cost of CO_2 capture is a critical factor in enabling early deployment of CCS. While 90% CO_2 capture is considered "standard", it is expected that this is not cost optimal for all separation technologies. The cost-optimal CCR will thus depend on the separation technology, its properties and the concentration of CO_2 in the flue gas. Reducing the CCR is thus an option for lowering the CO_2 capture cost.

This paper focuses on the quantification of the impact of lower CCRs on membrane-based CO_2 capture and the identification the optimal CCRs for different membranes, depending on the CO_2 concentration in the flue gas. In order to investigate this opportunity for cost reduction, a numerical version of the Attainable Region approach proposed by Lindqvist et al. [12-14] was incorporated in the iCCS tool [15, 16]. This was used to optimise and assess the cost performance of membrane-based processes for post-combustion CO_2 capture from flue gases containing 10 to 35% CO_2, analysing five membranes and CO_2 capture ratios from 50 to 90%.

The cost performances of processes based on the five membranes are presented and analysed for each of the six feed CO_2 concentrations to quantify the benefit of the cost-optimal CCR compared to the 90% CCR normally considered in literature. The cost assessment shows that partial CO_2 capture can significantly reduce the CO_2 avoided of membrane-based CO_2 capture from post-combustion process (varying from 11% cost reduction in the case 10%CO_2 to 55% cost reduction in the case of a flue gas containing 35%CO_2). The results also show that for CO_2 concentrations up to 25%, the moderate selectivity and high permeance membranes (A, B and C) are the most cost-efficient options and that a CCR lower than 90% can significantly lower their costs. However, the high selectivity membranes (D and E) are not particularly cost-effective and do not benefit strongly from lower CCR, due to the compression work required to pressurise the feed of the first-stage membrane. For CO_2 concentration in the flue gas above 30%, the high selectivity membranes become the most cost-efficient option, given that they can halve the capture cost when considering the cost-optimal CCR. In light of these differences in performances, the benefit of processes that employ the moderate selectivity and high permeance membrane A as their first stage and the high selectivity and moderate permeance membrane D as second stage is investigated. The evaluation shows that the benefits are significant for very low CO_2 concentration and low CCRs, but limited above. While for the 10% CO_2 case there is a possibility to reduce the CO_2 avoidance cost between 7-19%, for concentration above 15%, the improvement is limited (up to 11%) or even negative depending on the CO_2 concentration and CCR considered. However, these results are very dependent on the membranes considered and process configuration with other membranes should be further investigated in order to assess their full potential.

Finally, the influence of transport costs on the selection of the cost-optimal CCR are investigated. The results show that, in the case of small CO_2 emitters (refinery and cement) and long transport distance, the

selection of the cost-optimal CCR may significantly be affected by the inclusion of the transport infrastructure while this impact is reduced for larger CO_2 emitters (coal-fired power plant and steel plant). These cost evaluations thus demonstrate that membrane-based CO_2 capture can significantly benefit from lower CCRs and that therefore considering lower CCRs could, in the case of the post-combustion membrane-based CO_2 capture, enable early deployment of CCS despite low carbon emission cost. However, the identification of the cost-optimal CCR needs to take the entire chain into account, as it is highly case-specific (industry, CO_2 concentration in the flue gas, membrane considered, transport distance, possibility of joint transport). To further identify the potential of membrane-based CO_2 capture processes with lower CCRs, future efforts should compare membrane- and solvent-based CO_2 capture from various industries, in order to identify the relative opportunities of each technology.

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References
[1] International Energy Agency, 20 years of Carbon Capture and Storage: Accelerating future deployment 2016.
[2] SaskPower CCS, The world's first Post-combustion Coal -fired CCS Facilty, 2015. Available from: http://www.saskpowerccs.com/.
[3] D. Thimsen, A. Maxson, V. Smith, T. Cents, O. Falk-Pedersen, O. Gorset, E.S. Hamborg, Results from MEA testing at the CO_2 Technology Centre Mongstad. Part I: Post-Combustion CO_2 capture testing methodology, Energy Procedia 63 (2014) 5938-5958.
[4] E.S. Hamborg, V. Smith, T. Cents, N. Brigman, O.F. Pedersen, T. De Cazenove, M. Chhaganlal, J.K. Feste, Ø. Ullestad, H. Ulvatn, O. Gorset, I. Askestad, L.K. Gram, B.F. Fostås, M.I. Shah, A. Maxson, D. Thimsen, Results from MEA testing at the CO2 Technology Centre Mongstad. Part II: Verification of baseline results, Energy Procedia 63 (2014) 5994-6011.
[5] O. Gorset, J.N. Knudsen, O.M. Bade, I. Askestad, Results from Testing of Aker Solutions Advanced Amine Solvents at CO_2 Technology Centre Mongstad, Energy Procedia 63 (2014) 6267-6280.
[6] IEAGHG, Assessment of emerging CO_2 capture technologies and their potential to reduce costs, 2014/TR4, 2014.
[7] S. Roussanaly, R. Anantharaman, K. Lindqvist, Multi-criteria analyses of two solvent and one low-temperature concepts for acid gas removal from natural gas, Journal of Natural Gas Science and Engineering 20 (2014) 38-49.
[8] E. Favre, Membrane processes and postcombustion carbon dioxide capture: Challenges and prospects, Chemical Engineering Journal 171 (2011) 782-793.
[9] T.C. Merkel, H. Lin, X. Wei, R. Baker, Power plant post-combustion carbon dioxide capture: An opportunity for membranes, Journal of Membrane Science 359 (2010) 126-139.
[10] H. Zhai, E.S. Rubin, Techno-Economic Assessment of Polymer Membrane Systems for Postcombustion Carbon Capture at Coal-Fired Power Plants, Environmental Science & Technology 47 (2013) 3006-3014.
[11] B. Belaissaoui, D. Willson, E. Favre, Membrane gas separations and post-combustion carbon dioxide capture: Parametric sensitivity and process integration strategies, Chemical Engineering Journal 211–212 (2012) 122-132.
[12] K. Lindqvist, R. Anantharaman, A graphical method for the synthesis of membrane systems for CO_2 capture applications, Chemical Engineering Transaction 39 (2014).
[13] S. Roussanaly, K. Lindqvist, R. Anantharaman, J. Jakobsen, A Systematic Method for Membrane CO_2 Capture Modeling and Analysis, Energy Procedia 63 (2014) 217-224.

[14] K. Lindqvist, S. Roussanaly, R. Anantharaman, Multi-stage Membrane Processes for CO_2 Capture from Cement Industry, Energy Procedia 63 (2014) 6476-6483.
[15] J.P. Jakobsen, S. Roussanaly, A. Brunsvold, R. Anantharaman, A Tool for Integrated Multi-criteria Assessment of the CCS Value Chain, Energy Procedia 63 (2014) 7290-7297.
[16] J.P. Jakobsen, S. Roussanaly, M.J. Mølnvik, G. Tangen, A standardized Approach to Multi-criteria Assessment of CCS Chains, Energy Procedia 37 (2013) 2765-2774.
[17] D. Berstad, R. Anantharaman, P. Nekså, Low-temperature CO2 capture technologies – Applications and potential, International Journal of Refrigeration 36 (2013) 1403-1416.
[18] S. Roussanaly, C. Fu, M. Volsund, R. Anantharaman, M. Spinelli, M. Romano, Techno-economic analysis of MEA CO_2 capture from a cement kiln – impact of steam supply scenario, Submitted to 13th International Conference on Greenhouse Gas Control Technologies (2016).
[19] R. Anantharaman, S. Roussanaly, S.F. Westman, J. Husebye, Selection of Optimal CO_2 Capture Plant Capacity for Better Investment Decisions, Energy Procedia 37 (2013) 7039-7045.
[20] IEAGHG, CO_2 Pipeline Infrastructure. 2013/18, 2013.
[21] European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP), The costs of CO_2 transport, Post-demonstration CCS in the EU, 2011.
[22] S. Roussanaly, J.P. Jakobsen, E.H. Hognes, A.L. Brunsvold, Benchmarking of CO_2 transport technologies: Part I—Onshore pipeline and shipping between two onshore areas, International Journal of Greenhouse Gas Control 19C (2013).
[23] S. Roussanaly, R. Anantharaman, K. Lindqvist, H. Zhai, E. Rubin, Membrane properties required for post-combustion CO_2 capture at coal-fired power plants, Journal of Membrane Science 511 (2016) 250-264.
[24] J. Jakobsen, S. Roussanaly, R. Anantharaman, A techno-economic case study of CO2 capture, transport and storage chain from a cement plant in Norway, Journal of Cleaner Production 144 (2017) 523-539.
[25] Y. Chen, D. Lv, J. Wu, J. Xiao, H. Xi, Q. Xia, Z. Li, A new MOF-505@GO composite with high selectivity for CO_2/CH_4 and CO_2/N_2 separation, Chemical Engineering Journal 308 (2017) 1065-1072.
[26] T. Fan, W. Xie, X. Ji, C. Liu, X. Feng, X. Lu, CO_2/N_2 separation using supported ionic liquid membranes with green and cost-effective [Choline][Pro]/PEG200 mixtures, Chinese Journal of Chemical Engineering 24 (2016) 1513-1521.
[27] M.-C. Ferrari, D. Bocciardo, S. Brandani, Integration of multi-stage membrane carbon capture processes to coal-fired power plants using highly permeable polymers, Green Energy & Environment.
[28] H. Rabiee, A. Ghadimi, S. Abbasi, T. mohammadi, CO_2 separation performance of poly(ether-b-amide6)/PTMEG blended membranes: Permeation and sorption properties, Chemical Engineering Research and Design 98 (2015) 96-106.
[29] J.P. Jung, C.H. Park, J.H. Lee, Y.-S. Bae, J.H. Kim, Room-temperature, one-pot process for CO_2 capture membranes based on PEMA-g-PPG graft copolymer, Chemical Engineering Journal 313 (2017) 1615-1622.
[30] L. Liu, W. Qiu, E.S. Sanders, C. Ma, W.J. Koros, Post-combustion carbon dioxide capture via 6FDA/BPDA-DAM hollow fiber membranes at sub-ambient temperatures, Journal of Membrane Science 510 (2016) 447-454.
[31] J.H. Lee, J.P. Jung, E. Jang, K.B. Lee, Y.J. Hwang, B.K. Min, J.H. Kim, PEDOT-PSS embedded comb copolymer membranes with improved CO2 capture, Journal of Membrane Science 518 (2016) 21-30.
[32] V.A. Kusuma, S.R. Venna, S. Wickramanayake, G.J. Dahe, C.R. Myers, J. O'Connor, K.P. Resnik, J.H. Anthony, D. Hopkinson, An automated lab-scale flue gas permeation membrane testing system at the National Carbon Capture Center, Journal of Membrane Science 533 (2017) 28-37.
[33] F. Moghadam, E. Kamio, T. Yoshioka, H. Matsuyama, New approach for the fabrication of double-network ion-gel membranes with high CO_2/N_2 separation performance based on facilitated transport, Journal of Membrane Science 530 (2017) 166-175.
[34] W.S. Chi, S. Hwang, S.-J. Lee, S. Park, Y.-S. Bae, D.Y. Ryu, J.H. Kim, J. Kim, Mixed matrix membranes consisting of SEBS block copolymers and size-controlled ZIF-8 nanoparticles for CO_2 capture, Journal of Membrane Science 495 (2015) 479-488.

[35] N.A. Ahmad, A.N. Mohd Noh, C.P. Leo, A.L. Ahmad, CO_2 removal using membrane gas absorption with PVDF membrane incorporated with POSS and SAPO-34 zeolite, Chemical Engineering Research and Design 118 (2017) 238-247.
[36] L.S. White, X. Wei, S. Pande, T. Wu, T.C. Merkel, Extended flue gas trials with a membrane-based pilot plant at a one-ton-per-day carbon capture rate, Journal of Membrane Science 496 (2015) 48-57.
[37] B. Belaissaoui, G. Cabot, M.-S. Cabot, D. Willson, E. Favre, CO_2 capture for gas turbines: an integrated energy-efficient process combining combustion in oxygen-enriched air, flue gas recirculation, and membrane separation, Chemical Engineering Science 97 (2013) 256-263.
[38] B. Belaissaoui, Y. Le Moullec, D. Willson, E. Favre, Hybrid membrane cryogenic process for post-combustion CO2 capture, Journal of Membrane Science 415–416 (2012) 424-434.
[39] D. Bocciardo, Optimisation and integration of membrane processes in coal-fired power plants with carbon capture and storage, University of Edinburgh, 2015.
[40] L.M. Robeson, The upper bound revisited, Journal of Membrane Science 320 (2008) 390-400.
[41] C. Liu, R. Minkov, S.A. Faheem, T.C. Bowen, J.J. Chiou, High permeance polyimide membranes for air separation, Google Patents, 2013.
[42] National Energy Technology Laboratory, Advanced Carbon Dioxide Capture R&D Program: Technology Update - Appendix B: Carbon Dioxide Capture Technology Sheets, 2013.
[43] X. He, C. Fu, M.-B. Hägg, Membrane system design and process feasibility analysis for CO_2 capture from flue gas with a fixed-site-carrier membrane, Chemical Engineering Journal 268 (2015) 1-9.
[44] X. He, M.-B. Hägg, Hollow fiber carbon membranes: From material to application, Chemical Engineering Journal 215–216 (2013) 440-448.
[45] M.-B. Hägg, CO_2 capture using a membrane pilot process at cement factory, in Brevik Norway - lessons learnt, Trondheim Carbon Capture and Storage conference 8, 17-18 June 2015Trondheim, Norway, 2015.
[46] T.-J. Kim, H. Vrålstad, M. Sandru, M.-B. Hägg, Separation performance of PVAm composite membrane for CO_2 capture at various pH levels, Journal of Membrane Science 428 (2013) 218-224.
[47] S. Roussanaly, A.L. Brunsvold, E.S. Hognes, Benchmarking of CO_2 transport technologies: Part II – Offshore pipeline and shipping to an offshore site, International Journal of Greenhouse Gas Control 28 (2014) 283-299.
[48] L.M. Romeo, I. Bolea, Y. Lara, J.M. Escosa, Optimization of intercooling compression in CO2 capture systems, Applied Thermal Engineering 29 (2009) 1744-1751.
[49] G. Skaugen, S. Roussanaly, J. Jakobsen, A. Brunsvold, Techno-economic evaluation of the effects of impurities on conditioning and transport of CO2 by pipeline, International Journal of Greenhouse Gas Control.
[50] S.T. McCoy, The Economics of CO_2 Transport by Pipeline and Storage in Saline Aquifers and Oil Reservoirs, Carnegie Melon Univerisity, Department of Engineering and Public Policy., 2009.
[51] American Petroleum Institute, Specification for line pipe, American Petroleum Institute1990.
[52] J. Serpa, J. Morbee, E. Tzimas, Technical and Economic Characteristics of a CO_2 Transmission Pipeline Infrastructure, Joint Research Centre Institute for Energy, Petten, 2011.
[53] Chemical Engineering, Economic Indicators: Chemical Engineering Plant Cost Index (CEPCI), 2016.
[54] Trading Economics, Trading Economics database on Euro area inflation rate, 2011.
[55] J.P. Van Der Sluijs, C.A. Hendriks, K. Blok, Feasibility of polymer membranes for carbon dioxide recovery from flue gases, Energy Conversion and Management 33 (1992) 429-436.
[56] R. Anantharaman, O. Bolland, N. Booth, E.V. Dorst, C. Ekstrom, F. Franco, E. Macchi, G. Manzolini, D. Nikolic, A. Pfeffer, M. Prins, S. Rezvani, L. Robinson, D4.9 European best prectice guidelines for assessment of CO_2 capture technologies, DECARBit Project, 2011.
[57] S. Roussanaly, G. Bureau-Cauchois, J. Husebye, Costs benchmark of CO_2 transport technologies for a group of various size industries, International Journal of Greenhouse Gas control 12C (2013) 341–350.
[58] T. Mikunda, J. van Deurzen, A. Seebregts, K. Kerssemakers, M. Tetteroo, L. Buit, Towards a CO_2 infrastructure in North-Western Europe: Legalities, costs and organizational aspects, Energy Procedia 4 (2011) 2409-2416.

[59] A. Chauvel, G. Fournier, C. Raimbault, Manual of Process Economic Evaluation, Editions Technip2003.
[60] B.D. Bhide, S.A. Stern, A new evaluation of membrane processes for the oxygen-enrichment of air. II. Effects of economic parameters and membrane properties, Journal of Membrane Science 62 (1991) 37-58.
[61] C.A. Scholes, M.T. Ho, D.E. Wiley, G.W. Stevens, S.E. Kentish, Cost competitive membrane—cryogenic post-combustion carbon capture, International Journal of Greenhouse Gas Control 17 (2013) 341-348.
[62] K. Koring, V. Hoening, H. Hoppe, J. Horsch, C. Suchak, V. Klevenz, B. Emberger, Deployment of CCS in the Cement industry, 2013.
[63] R. Skagestad, N. Eldrup, Skipstransport av CO_2 fra Østlandet og Midt-Norge, Porsgrunn, 2009.
[64] E. Rubin, G. Booras, J. davison, C. Ekstrom, M. Matuszewski, S.T. McCoy, C. Short, Toward a common method of the cost estimation for CO_2 capture and storage at fossil fuel power plants, Global CCS institute, 2013.
[65] J. Jakobsen, S. Roussanaly, R. Anantharaman, A techno-economic case study of CO_2 capture, transport and storage chain from a cement plant in Norway, Journal of Cleaner Production (2017).
[66] B. Metz, O. Davidson, H.D. Coninck, M. Loos, L. Meyer, Carbon Dioxide Capture And Storage: IPCC Special Report, Cambridge University Press2005.
[67] M.T. Ho, G.W. Allinson, D.E. Wiley, Comparison of MEA capture cost for low CO_2 emissions sources in Australia, International Journal of Greenhouse Gas Control 5 (2011) 49-60.
[68] IEAGHG, CO_2 abatement in oil refineries: fired heaters, in: C. Report no. IEA/CON/99/61, UK, IEA Greenhouse Gas R&D Programme. (Ed.), 2000.
[69] C. Hu, X. Han, Z. Li, C. Zhang, Comparison of CO_2 emission between COREX and blast furnace iron-making system, Journal of Environmental Sciences 21, Supplement 1 (2009) S116-S120.
[70] G. Wingrove, D. Satchell, B. Keenan, C. van Aswegen, Developments in iron making and opportunities for power generation, Proceedings of Gasification Technologies Conference, San Francisco, VSA., 1999.