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Targeting membrane properties for end-of-pipe capture

A process systems approach

Rahul Anantharaman, Simon Roussanaly, Karl Lindqvist
SINTEF Energy Research

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Background

Trade-offs

- **Membrane properties:** Permeance vs. Selectivity
- **Specifications:** CO_2 product purity vs. Capture Ratio
- **Cost:** Energy vs. Membrane area

- Multi-stage systems required for post-combustion capture to 95% product purity.
- For multi-stage process the design complexity increases.
- Identifying the “best” configuration and membrane properties is not straight-forward.

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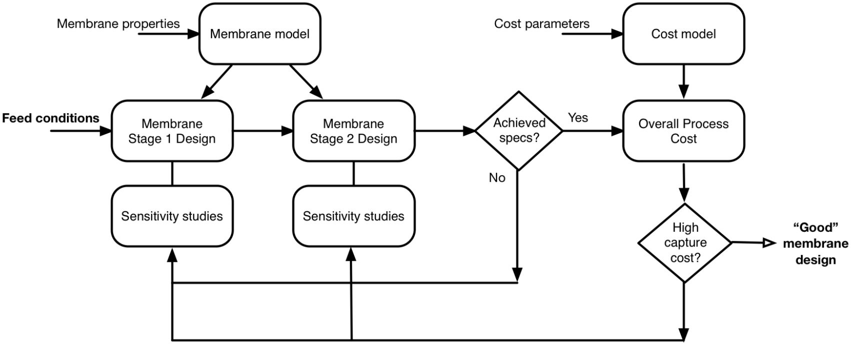
Parametric variation based design



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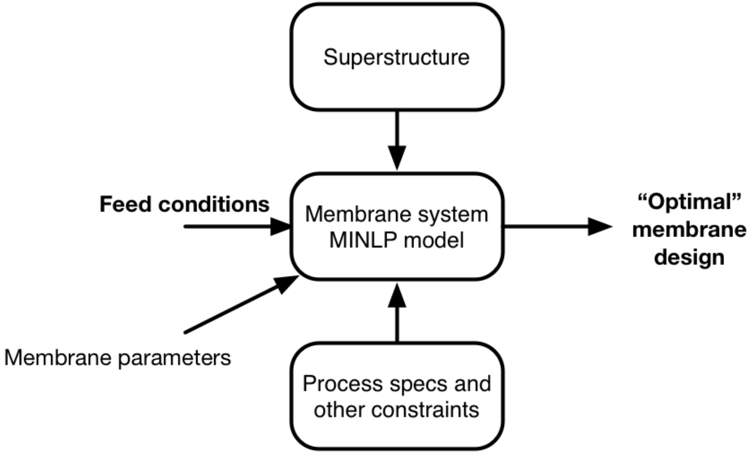
Optimization based design



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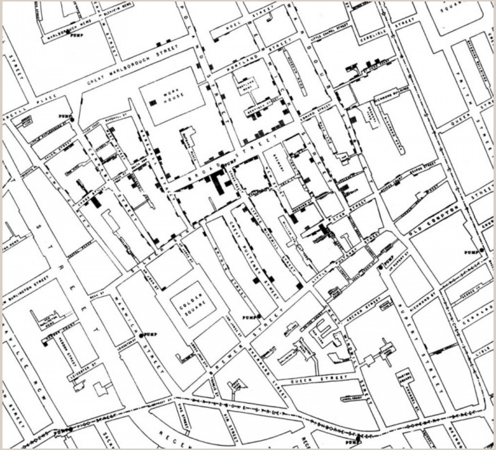
Motivation for new approach

Would it be possible to develop a **visual** design methodology:

- multiple stages can be designed using a single figure?
- indicates the potential of a membrane for different applications?
- visually compare membranes?
- capture cost is incorporated to accurately reflect the area-energy trade-off?

The power of **visual**



John Snow - Cholera “infographic”

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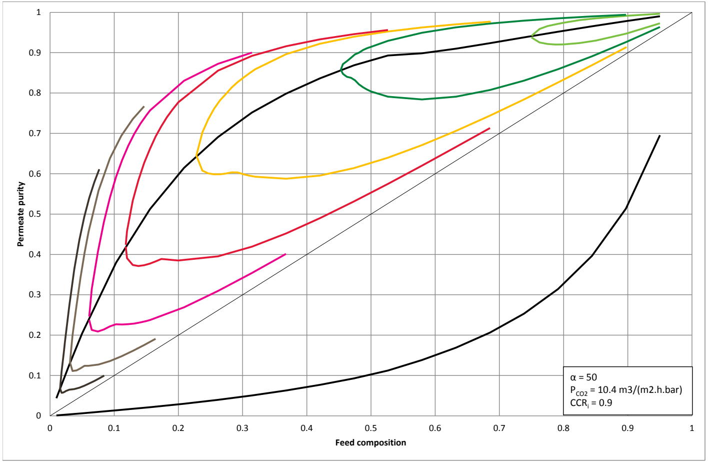
Attainable region - Effect of selectivity



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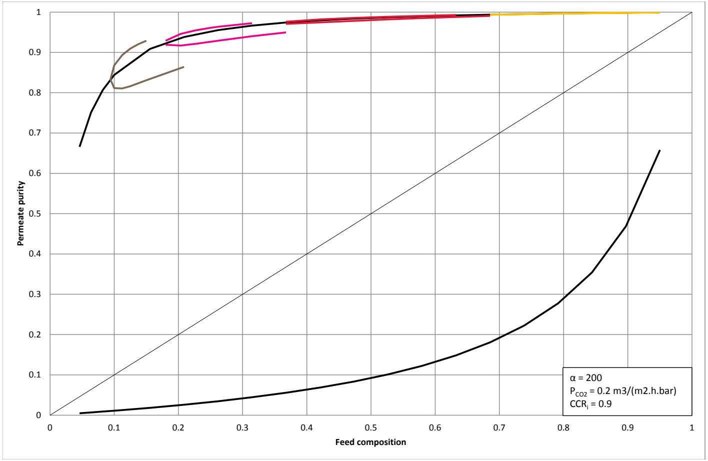
Attainable region - Effect of selectivity



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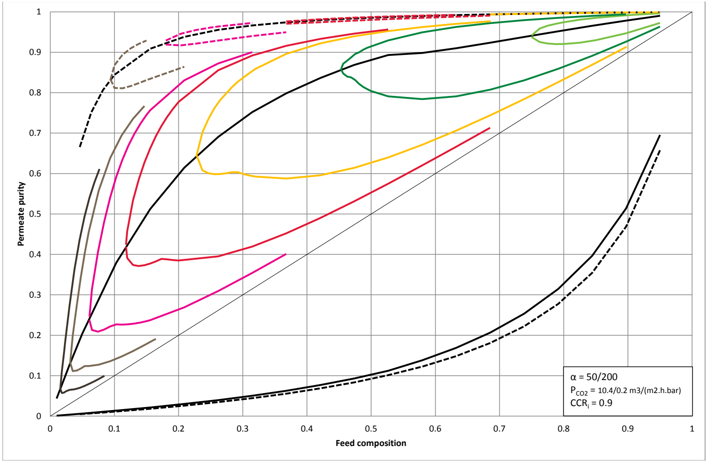

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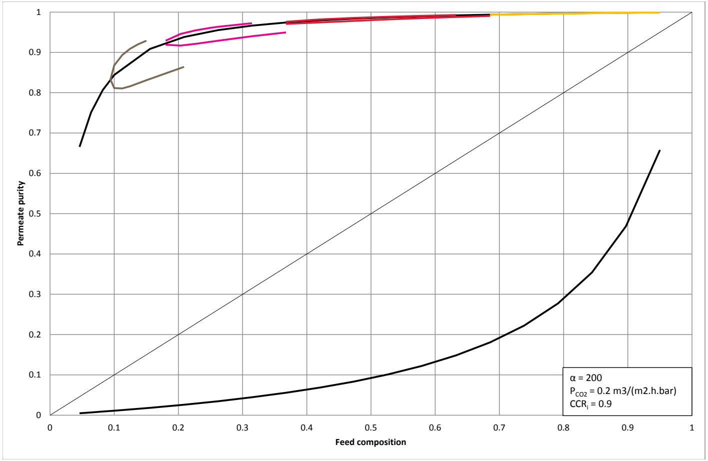
Attainable region - Effect of permeance



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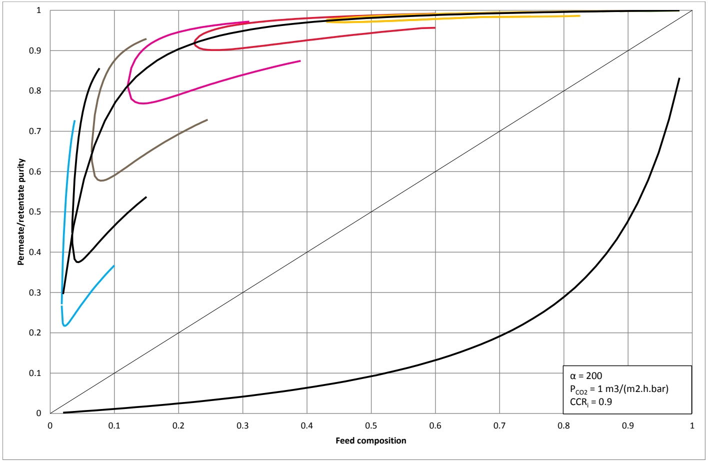

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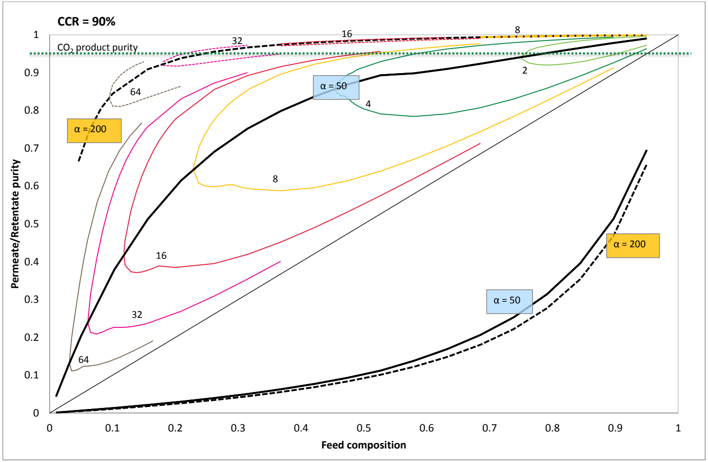
Attainable region - Example



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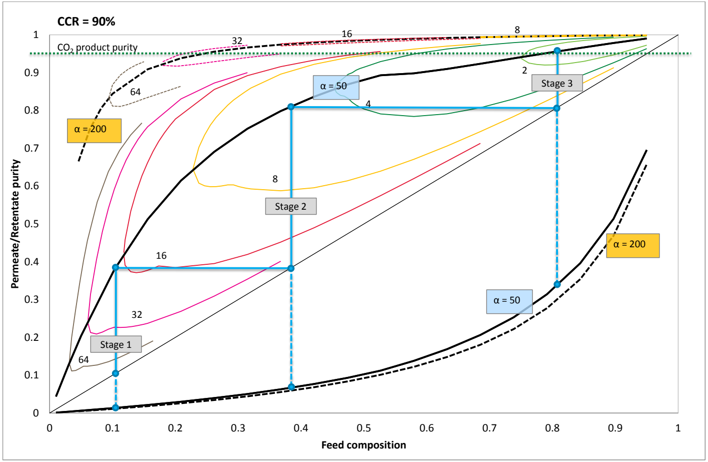
Min Cost Design - Membrane 1



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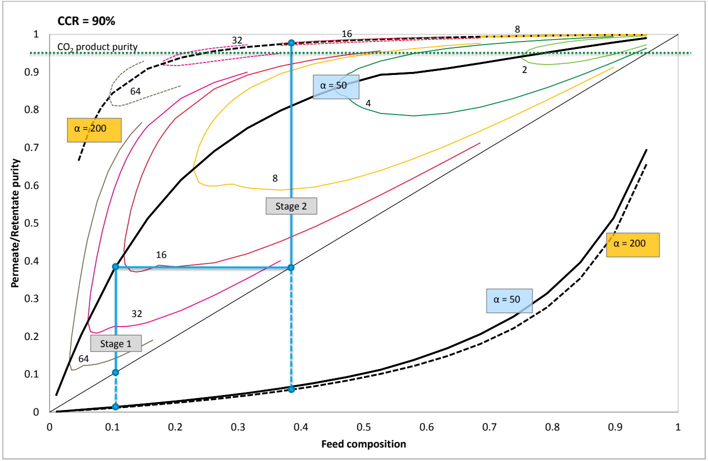
Min Cost Design - Membranes 1 & 2



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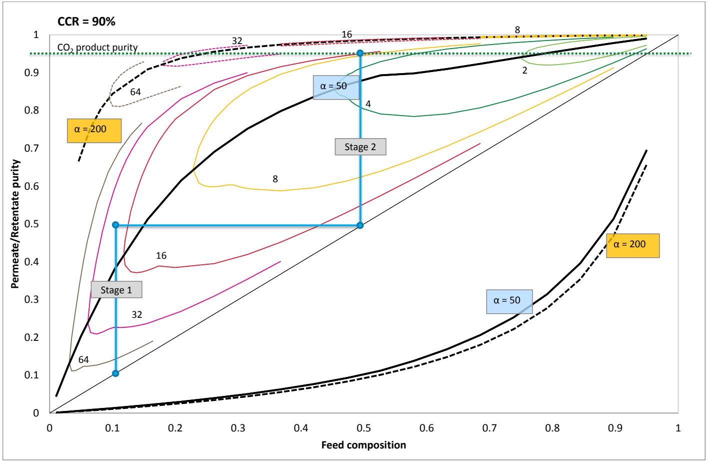
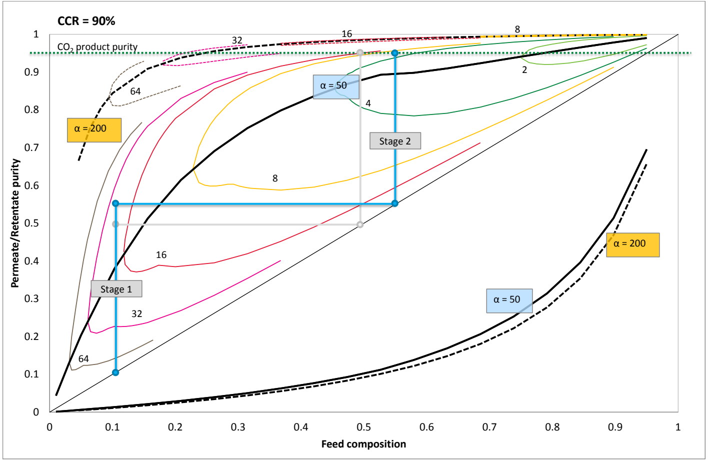
Attainable Region - 2 stage design



Attainable Region - 2 stage design



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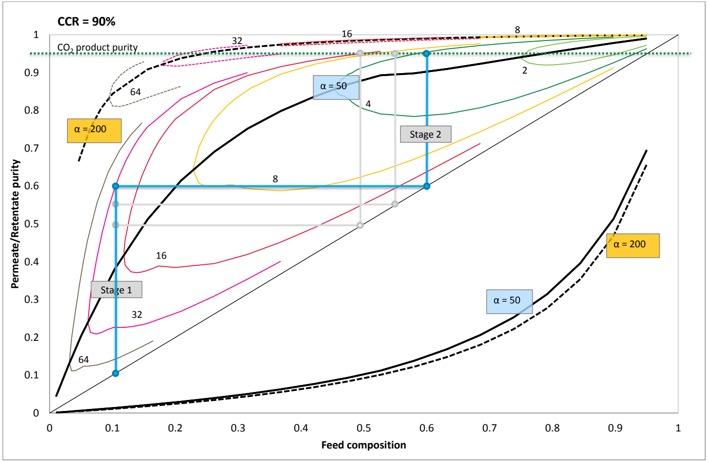
Attainable Region - 2 stage design



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New paradigm of process design

- Current material development strategies
  - Development and further improvement based on ”educated guess” target properties
  - No systematic benchmarking before development
  - Different target properties and material development strategies
- Integrated techno-economic assessment to guide material development
  - Identify target characteristics (properties, costs, etc.)
  - Guide further development of existing materials
  - Benefits
    - Reduction of development cost
    - Faster time to market

The storyline

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A graphical method for the synthesis of membrane systems for CO_2 capture applications

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Gas separation membranes are considered among one of the promising technologies for post-combustion capture and has been studied extensively. Membrane processes are conceptually very simple. However, with existing membrane properties (selectivity and permeability) and other limitations, a single stage membrane process is not feasible to ensure CO_2 purity of 95% and CO2 capture rate of 90% in the case of post-combustion capture. Traditionally membrane design is done using sensitivity analysis on a single separation stage or layout by trial and error, since it is difficult to find a good combination of parameters that achieve the desired target. A novel graphical approach to the design of membrane systems has been developed. Incrorporating the inherent trade-off between installed area and energy consumption in membrane systems, the methodology utilizes the cost of CO_2 removal in the design process. The visual method provides the user with insight such as the attainable region to guide the design process. The method allows comparison and evaluation of different membranes is a clear and consistent manner.

1. Introduction

CO_2 capture and storage from large point sources is expected to be an important aspect of a carbon constrained future energy scenario. Post-combustion capture, where CO_2 is captured in an end-of-pipe scenario, is vital to retrofit the multitude of existing fossil fueled power plants and industrial sources of CO_2 where other capture routes are typically not feasible. Amine-based CO_2 capture plants are considered to be mature post-combustion capture technology. They, however, have a high energy penalty for capture and a large environmental footprint.

Gas separation membranes are considered among one of the promising technologies for post-combustion capture and has been studied extensively. Membrane technology has a few advantages over amine-based solvent systems in that the process has no steam requirement and therefore is far less complicated to retrofit into existing power plants, and it has no environmental impacts caused by solvent losses and degradation. Polymeric membranes are primarily used for post-combustion applications. Brunetti et al. (2010) and He & Hägg (2010) provide an overview of membranes for post-combustion capture.

A single stage membrane process is conceptually very simple. The driving force is the CO_2 partial pressure difference across the membrane. This is manipulated by pressurizing the membrane feed and/or operating the permeate side under vacuum. From a process design perspective, membrane processes are not straight-forward. The main considerations or specifications for separation process are product purity and degree of separtion or capture (commonly referred to as the CO_2 Capture Ratio or CCR for CO_2 capture applications). Membrane processes involve a trade-off between these two specifications – increasing the CCR implies a decrease in CO_2 product purity. The CCR and product purity are adjusted by changing the driving force across the membrane and membrane area. Additionally, they depend on membrane mass transport properties – selectivity and permeance. Selectivity and permeance are not independent and their limits are given by the Robeson plot (Robeson, 2008). The effects of membrane properties and operating conditions are presented in Lowa et al. (2013) and show the trade-off in the selectivity andpermeance of the membrane, operating cost (energy cost of achieving required pressure ratio) and capital cost (installed membrane area). The membrane design process must thus take all the parameters into account. Further, due to the low feed CO_2 concentrations and limitations in the membrane

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The storyline

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Energy Procedia

GHGT-12

A systematic method for membrane CO_2 capture modeling and analysis

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Abstract

This work presents a new systematic methodology for the design and optimization of membrane systems for CO_2 capture integrating both technical and cost models. In this methodology, graphical solutions to the separation problem are generated to design a cost-optimal membrane system (process configuration, operating conditions) that satisfy CO_2 capture ratio and product purity requirements.

The methodology developed is illustrated through the design of a post-combustion CO_2 capture membrane system installed on an ASC power plant and its comparison with a MEA capture unit. This cost-optimal design of the membrane system leads to a levelized cost of electricity (LCOE) of 94 €/MWh which is 58% more expensive than the plant without capture and at the same price level as the reference plant with MEA CO_2 capture. The subsequent CO_2 avoided cost is evaluated to be 53 €/t$CO_{2,avoided}$ for both the membrane and MEA CO_2 capture system.

Finally a comparison between the cost model considered and models available in the literature is performed in order to demonstrate that the competitiveness of the membrane system designed in this paper is due to an improved design and not a possible underestimation of the membrane capture cost.

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Keywords: Carbon Capture and Storage (CCS); CO_2 capture; Post-combustion membrane; Cost evaluation.

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The storyline

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Energy Procedia

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GHGT-12

Multi-stage membrane processes for CO_2 capture from cement industry

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Abstract

Capture conditions for cement plant flue gas differ substantially from other industrial flue gases due to the high partial pressure of CO_2, presenting an opportunity for polymeric membranes to compete with other capture technologies. In this work, two membrane processes are designed by applying a recently developed graphical methodology to identify promising membrane properties, number of stages and operating points for each stage. The net present values of cost and the CO_2 avoidance costs are compared with an MEA based capture unit when applied to a 0.7 Mt_{CO2}/year cement plant. The membrane designs are shown to have a significantly lower investment cost (32.6 M€ vs. 294 M€) and CO_2 avoidance cost (27 €/t vs 55 €/t) than the reference MEA based capture process. The investment cost for turbomachinery and the operating cost for electricity are also shown, in this particular case, to be more important than the membrane investment and replacement costs over the lifetime of the membrane capture plant. The present work underlines the importance of using a cost-based approach to balance the trade-offs in membrane process design.

Peer-review under responsibility of the Organizing Committee of GHGT-12

Keywords: CO_2 capture; Post-combustion capture; Gas separation membranes; Cement; Cost evaluation; Design methodology

1. Introduction

In the transition to a low-carbon society, carbon capture technologies are considered for a range of industrial sectors. Post-combustion gas separation by permeation membranes is a promising alternative that has potential to

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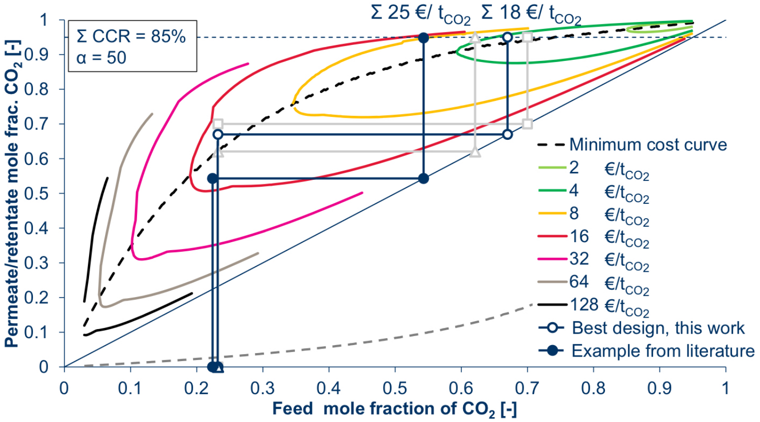
The storyline



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The storyline

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Journal of Membrane Science

journal homepage: www.elsevier.com/locate/memsci

Membrane properties required for post-combustion CO_2 capture at coal-fired power plants

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ABSTRACT

This paper focuses on the identification of membrane properties required to enable cost-competitive post-combustion CO_2 capture from a coal power plant using membrane-based processes. In order to identify such properties, a numerical version of the attainable region approach proposed by Lindqvist et al., built as part of the of the iCCS tool developed by SINTEF Energy Research, is used to identify and assess the technical and cost performances of the optimal membrane process for a given set of membrane properties (selectivity and permeance). This numerical model is used to assess the cost performances of 1600 sets of membrane properties (selectivity and permeance) for post-combustion CO_2 capture from a coal power plant as defined by the European Benchmarking Task Force and compare it with the reference commercial solvent concept (MEA) to identify the membrane properties required in a base case that treats both membrane- and MEA-based processes as mature and developed. The results show that to reach this competiveness with simple process configurations requires a permeance of at least 3 $m^3(STP)/(m^2 \cdot h \cdot bar)$ with high selectivity, or alternatively a selectivity of at least 65 with high permeances . These limits can be reduced to permeances as low as 1 $m^3(STP)/(m^2 \cdot h \cdot bar)$ with high selectivity, or selectivities as low as 30 with high permeances, when advanced membrane process configurations are being considered. The assessments of five additional cases quantify how additional costs associated with demonstration projects and higher membrane module costs can significantly increase the selectivities and permeances required to compete with MEA based capture.

In order to link the membrane development works to the results presented in this paper, the constraint introduced by Robeson's upper bound limitation, as well as data available in the literature on membrane modules and polymeric materials, are compared with the results obtained. The inclusion of the upper bound shows that the capacity to generate thin membrane film layers is important in order to avoid reducing the range of membrane properties, in which diffusion governed membrane can be interesting in term of cost performances, especially in cases that take demonstration and/or higher module costs into consideration. The comparison with literature data shows that while several membranes and polymeric materials have the potential to be cost-competitive with further properties improvements, and once membrane-based CO_2 capture becomes mature and demonstrated, financial support will be required to demonstrate and help mature the technology.

Finally, ways to use the results presented here for membrane development by membrane development experts, for membrane selection by industrial users, and for technology development and demonstration support by decision-makers are discussed.

1. Introduction

According to data from the International Energy Agency [1], mitigation efforts across the world have led to a halt at 32.3 billion tonnes in the global emissions of carbon dioxide from the energy sector in 2014. This is the first time in 40 years that a halt or a reduction in greenhouse gas emissions, not linked to an economic turndown, has been observed. However, despite this encouraging stall, significant efforts and measures will still have to be taken in order to meet the 2 °C constraint.

Abbreviations: ASC, advanced supercritical pulverised bituminous coal; CAPEX, capital expenditures; CCR, CO_2 capture ratio; CCS, carbon capture and storage; CEPCI, chemical engineering plant cost index; EBTF, European Benchmarking Task Force; EPC, Engineering, Procurement, Construction; EPCCI, European Power Capital Costs Index; FOAK, First Of A Kind; GHG, greenhouse gas; IPCC, Intergovernmental Panel on Climate Change; LCA, life-cycle assessment; MEA, monoethanolamine; NOAK, N^{th} Of A Kind; OPEX, operating expenditures; SOAK, Second Of A Kind; TDC, total direct costs

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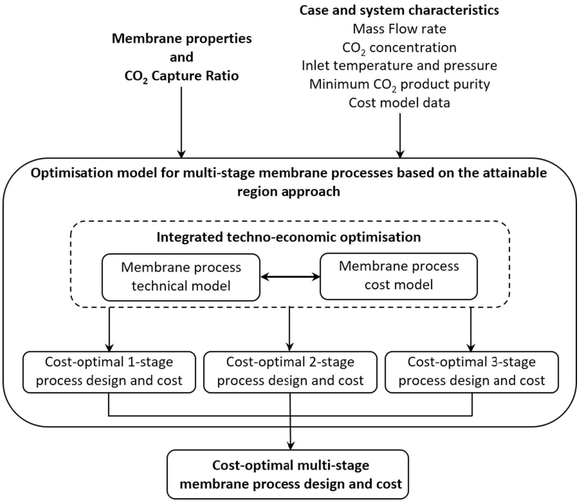

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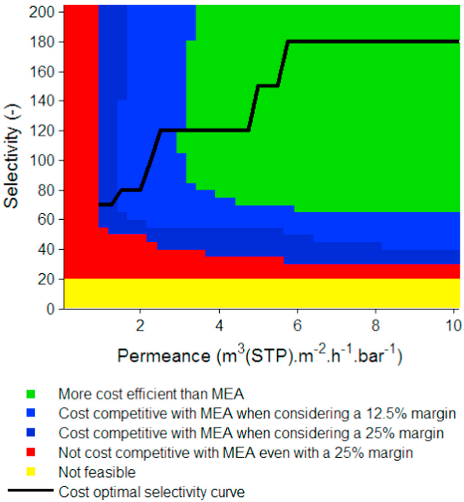

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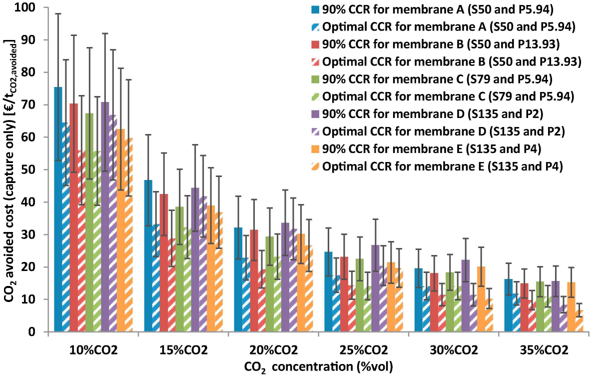

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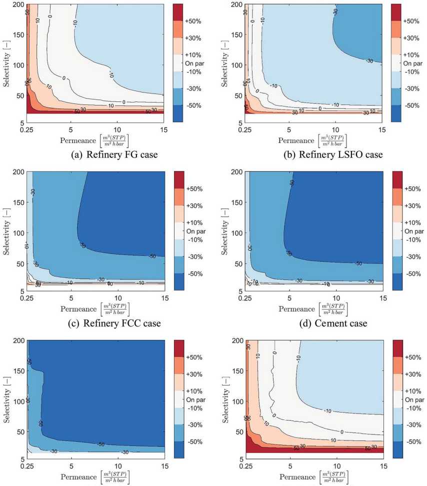

(a) Refinery FG case
(b) Refinery LSFO case
(c) Refinery FCC case
(d) Cement case
(e) Steel case
(f) Coal power plant case

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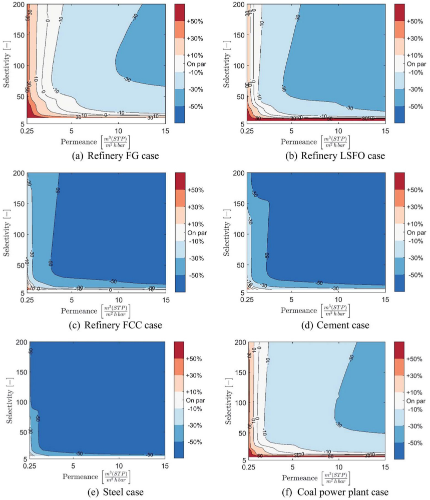
The storyline



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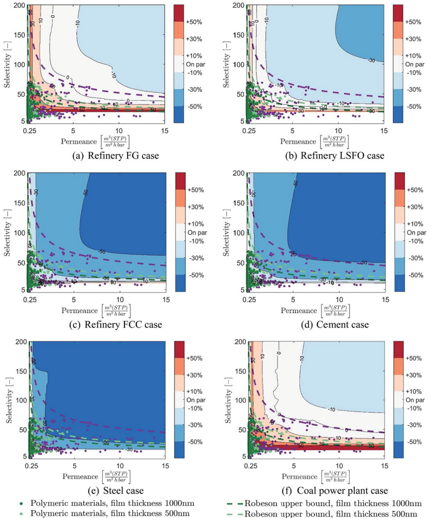

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The storyline

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Summary

- Integrated techno-economic assessments can be used to accelerate membrane materials development for cost-effective CO_2 capture

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  - Identify target characteristics and guide further development of existing materials

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  - Help reduce development costs and reach faster time to market

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  - Help industry and funding bodies to support best strategies for membrane development

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- The methodology has received positive feedback

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- Further work

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  - Extension of the methodology to other membrane applications (Hydrogen, Biogas, Natural gas...)

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- Further work
  - Extension of the methodology to other membrane applications (Hydrogen, Biogas, Natural gas...)
  - Extension of the methodology to other types of technologies

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