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Energetic and economic evaluation of membrane-based carbon capture routes for power plant processes

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ABSTRACT

The application of CCS technology involves considerable efficiency losses and significant additional investments. The aim is therefore to reduce these efficiency losses and to cut costs. Against this background, membrane-based carbon capture routes for the post-combustion, oxyfuel and pre-combustion technology lines will be analyzed in the following for hard-coal-fired power plants. To the best knowledge of the authors, this paper is the first one comparing membrane based capture routes on common technical and economic boundary conditions. The post-combustion process involves a cascade arrangement of polymer membranes. In the optimum case, the efficiency losses for this concept amount to 9.6 percentage points. In comparison, efficiency losses for the other two membrane-based concepts, i.e. oxyfuel (oxygen transport membrane (OTM) with vacuum pump) and pre-combustion (water-gas shift reactor—WGSMR), are considerably lower (5.3/5.5 percentage points). The main goal of this paper is to assess levelized cost of electricity (LCOE) for the process routes under consideration and their sensitivity on CO_2 allowance costs, yearly operating hours, membrane costs and membrane lifetime. The specific investment costs for the capture plants are 2410 €/kW h (oxyfuel), 2572 €/kW h (post-combustion) and 2660 €/kW h (pre-combustion). This is 66% (post-combustion), 55% (oxyfuel) and 33% (pre-combustion) above the specific investment costs for the corresponding reference case without carbon capture. Allowance prices in a range from €20 (pre-combustion) to €39 (post-combustion) per tonne of CO_2 would be necessary to compensate for the additional investments. Since it can be assumed that the membranes have a limited lifetime, the influence on electricity generation costs was calculated for different lifetimes. The results show that a technical service life of more than 3 years does not have a significant impact on generation costs. This applies to all the technological concepts investigated. In terms of LCOE and CO_2 avoidance costs (€/t_{CO_2}) it turns out that oxyfuel and pre-combustion based membrane power plants are favorable compared to the post-combustion route. However, it has to be kept in mind that the uncertainty in membrane costs are higher for the oxyfuel membranes (ceramic oxygen transport membranes) and the pre-combustion membranes (microporous ceramic membranes) compared to the polymeric post-combustion membranes which already have achieved a commercial level.

1. Introduction

Some 30% of global anthropogenic CO_2 emissions originate from coal-fired power plants (IEA, 2013). In accordance with current energy projections (EIA, 2013; IEA, 2013), electricity generation on the basis of fossil-fired power plants will continue to be of major significance for the next few decades. According to the scenarios of the Intergovernmental Panel on Climate Change (IPCC, 2014) and the International Energy Agency (IEA, 2013, 2014a), the application of CCS technologies is necessary in order to limit the increase in the average global temperature to 2 °C.

The application of CCS technologies involves considerable efficiency losses and significant additional costs. A major objective of current R&D activities is to develop concepts involving the lowest possible efficiency losses and low costs. Several studies have been made investigating efficiency and cost analysis of different CCS technologies (Black, 2013; Ciferno, 2008; European Benchmarking Task Force, 2011; Rubin et al., 2013). In the longer term, the use of membranes is also regarded as a possible option for CO_2 capture in power plants and the focus of this work. The results of existing

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Nomenclature

Abbreviation

ASU	air separation unit
BSCF	membrane material ($Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$)
CAESAR	European project (CArbon-free Electricity by SEWGS: Advanced materials, Reactor-, and process design)
CESAR	European project (CO_2 enhanced separation and recovery)
CC	carbon capture
CCS	carbon capture and storage
CM	ceramic membrane
COMP	component
D	diffusivity
DECARBIT	European project (enabling advanced pre-combustion capture techniques and plants)
DOE	department of energy (USA)
EAC	equivalent annual cost
HRSG	heat recovery steam generator
I	investment cost
IGCC	integrated gasification combined cycle
LCOE	levelized cost of electricity
MEM-BRAIN	alliance project (gas separation membranes for zero-emission fossil power plants)
METPORE	national project (nanostructured ceramic and metal-supported membranes for gas separation)
NETL	National Energy Technology Laboratory (USA)
NRW	North Rhine-Westphalia
OTM	oxygen transport membrane
PEG	polyethylene oxide
PEO	polyethylene glycol
PP	power plant
RPP	reference power plant
P	permeability
R	universal gas constant
S	solubility
T	temperature
TPD	tons per day
WGSMR	water gas shift membrane reactor

Symbols

π	mean partial pressure ratio
ξ	oxygen separation ratio

work (Brunetti et al., 2014; Kunze and Spliethoff, 2012; Luis and Van der Bruggen, 2013; Merkel et al., 2012; Ramasubramanian et al., 2012; Shao et al., 2013) indicate that membrane-based concepts may be more efficient than the currently favored CCS scrubbing. As part of the MEM-BRAIN R&D project (Czyperek et al., 2010; Czyperek et al., 2008), various membrane concepts are therefore being investigated for different technology lines (post-combustion, pre-combustion, oxyfuel). The spectrum of R&D work ranges from materials development and investigations of the optimum integration of membranes in the actual power plant process to first demonstration projects. From the membrane based carbon capture technologies, carbon capture with polymeric membranes seems closest to technical realization, since the technical complexity is comparably lower. First pilot-scale projects are on the way capturing CO_2 from real flue gas (energy.gov, 2015; Merkel et al., 2010).

Oxyfuel combustion capture for power plants with cryogenic oxygen supply has been proven in different demonstration projects (Komaki et al., 2014; Rehfeldt et al., 2011). The oxygen production via OTM is still in its development phase. Air Products has recently successfully demonstrated the performance of commercial 5 tons-per-day (TPD) membrane modules and is currently constructing a 100 TPD intermediate scale test unit (Repasky et al., 2013). An integration of an OTM into an oxyfuel power plant has so far only been studied theoretically.

Table 1
Investigated membrane-based CCS technologies.

Technology line	Type of membrane	Concept
Post-combustion	Polymer	Cascaded membrane system
Oxyfuel	Ceramic	3-end membrane integration
Pre-combustion	Microporous ceramic	Water gas shift membrane reactor Membrane and water gas shift separated

The microporous ceramic membranes are the technology farthest from being realized. To the authors knowledge, there are no demonstration projects for pre-combustion CO_2 capture via microporous ceramic membranes and the development of the membranes is still on lab-scale (Stournari et al., 2015).

As part of the present work, a comparative analysis of different membrane-based CCS power plant concepts has been made for the first time for the technology lines of post-combustion, oxyfuel and pre-combustion (Table 1). The comparative analysis focuses on a cost analysis. In the first step, a description of the basic concept is made for each technology line and the selected membrane types are characterized. The results of the energy-efficiency analyses, carried out with Aspen Plus, are then presented. The most efficient concept for the respective technology lines represents the starting point for the subsequent cost analyses. To this end, the electricity generation costs are calculated on the basis of harmonized general assumptions, which permit a well-founded and reliable comparison of the membrane concepts. Furthermore, sensitivity analyses are made in order to estimate the influence of certain parameters such as membrane area required, membrane costs, and the number of full-load hours. A comparison of the efficiency and the costs of the membrane-based concepts with that of other CCS concepts (e.g. scrubbing, cryogenic air separation) has already been published in Franz et al. (2014), Pfaff and Kather (2009) and Zhao et al. (2012) and is therefore not undertaken here.

2. Energetic evaluation

2.1. Post-combustion

Like all CCS routes, membrane-based CO_2 capture involves significant losses of energy for the power plant process, mainly caused by separation, purification and compression of the CO_2. Also process modifications such as increased flue gas treatment may have an impact on the total electric output of the power plant process. While for the post-combustion process, carbon capture (CC) is installed as a downstream unit at the end of the conventional power plant process, oxyfuel and pre-combustion capture require greater changes in the plant layout. All process evaluations were related to conventional power plant processes without CO_2 capture. The loss of efficiency was determined using simulations under uniform boundary conditions for all process routes.

2.1.1. Process description

As a reference process, use was made of the conceptual study reference power plant North Rhine-Westphalia (RPP-NRW), characterized by a thermal power of 1210 MW and a net electric