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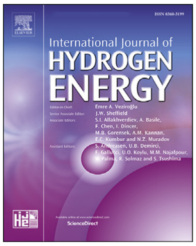

Pure hydrogen co-production by membrane technology in an IGCC power plant with carbon capture

Aristide Giuliano, Massimo Poletto, Diego Barletta[*]

Dipartimento di Ingegneria Industriale, Università degli Studi di Salerno, Via Giovanni Paolo II, 132, 84084 Fisciano, SA, Italy

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ABSTRACT

The CO_2 capture in Integrated Gasification Combined Cycle (IGCC) plants causes a significant increase of the cost of electricity (COE) and thus determines high CO_2 mitigation cost (cost per ton of avoided CO_2 emissions). In this work the economic sustainability of the co-production of pure hydrogen in addition to the electricity production was assessed by detailed process simulations and a techno-economic analysis. To produce pure hydrogen a Water Gas Shift reactor and a Selexol® process was combined with H_2 selective palladium membranes. This innovative process section was compared with the more conventional Pressure Swing Adsorption in order to produce amount of pure hydrogen up to 20% of the total hydrogen available in the syngas.

Assuming for a base case a hydrogen selling price of 3 €/kg and a palladium membrane cost of 9200 €/m^2, a cost of electricity (COE) of 64 €/MWh and a mitigation cost of 20 €/ton_{CO2} were obtained for 90% captured CO_2 and 10% hydrogen recovery. An increase of the hydrogen recovery up to 20% determines a reduction of the COE and of the mitigation cost to 50 €/MWh and 5 €/ton_{CO2}, respectively. A sensitivity analysis showed that even a 50% increase of cost of the membrane per unit surface could determine a COE increase of only about 10% and a maximum increase of the mitigation cost of further 5 €/ton_{CO2}.

Introduction

According to the IPCC report of 2014 [1], global warming of more than 2 °C could have serious consequences, such as the substantial increase in the number of extreme climatic events. The major cause of global warming is the increase of carbon dioxide in the atmosphere. Carbon pricing mechanisms, either cap and trade systems or carbon tax, already adopted by about 40 countries, can be effective political tools in order to aim at the greenhouse gas emissions reduction according to the 2015 Paris agreement [2].

In recent years, coal is still a significant source of energy for economic and geopolitical reasons. In this scenario, the so-called Clean Coal Technologies (CCT) have been developed to aim at extracting, treating and using coal in an efficient manner and with a reduced environmental impact.

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[*] *Corresponding author.*
E-mail address: dbarletta@unisa.it (D. Barletta).

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The Integrated Gasification Combined Cycle (IGCC) is a well established technology to produce electricity through a Combined Cycle Unit (CCU) from low calorific fuel gas obtained by gasification of coal, refinery petcoke, and other residues [3]. In addition to electricity generation, IGCC allows the co-production of hydrogen and steam. The IGCC has promising potentialities to apply pre-combustion CO_2 capture technologies [4]. In fact, the CO_2 in the clean syngas is available at high pressure, which makes the capture easier and significantly reduces the compression costs for final storage [5]. However, the addition of a carbon capture and storage (CCS) section causes a significant loss of net produced energy corresponding to a reduction of efficiency, the so called energy penalty, up to ten points [6]. Optimized process schemes were also proposed to reduce these efficiency losses [7]. In particular, this depends on a net loss of the mass flow rate of the gas through the gas turbines, and on a further reduction of efficiency due to the presence of a water-gas shift stage [8]. Moreover, according to the estimates by Cormos [6], there is a 22.5% increase in investment costs to carry out a 90% CCS capture. The resulting Cost Of Electricity (COE) with CCS increases up to more than 90 €/MWhe [9].

In order to mitigate the economic disadvantages of the carbon capture, it is possible to implement the co-production of pure hydrogen that has a high added value and can be used for both energy and industrial uses [10], for example as a reactant into the LTPEM fuel cells [11].

Pressure Swing Adsorption (PSA) is a common hydrogen separation technology for large-scale separations due to its technical simplicity and low operating costs [12]. The conventional process solution is, thus, given by a water gas shift stage to enrich the syngas in H_2 and CO_2, followed by a PSA section to separate the hydrogen [13]. Process simulation results by Riboldi & Bolland [12] showed that it is possible to significantly change the relative amounts of electricity and hydrogen with acceptable global plant efficiency, including the pure hydrogen stream.

More recently, extensive research work has been performed to develop highly selective metal membranes to obtain hydrogen with purity larger than 99% [14]. Process integration and reaction enhancement were pursued by several studies proposing the WGS catalytic reactor and the hydrogen selective membranes occurring in a single unit named water gas shift membrane reactor (WGSMR) [15,16]. An alternative promising technology for both electricity and hydrogen production from gasification with CO_2 capture is provided by Syngas Chemical Looping (SCL) [17]. More recent developments aim at an integration of gasification and chemical looping by the so-called Coal Direct Chemical Looping (CDCL) [18,19], with the chemical storage by methylcyclohexane (MCH) and/or coupling with Solid Oxide Fuel Cells (SOFC) [20].

A comparative preliminary techno-economic analysis by Li et al. [21] revealed that both WGS coupled with membrane technology and SCL technology are competitive for electricity and hydrogen production with 90% CO_2 capture. However, the economic figures of this study might be approximate since detailed sizing of main process units was not addressed. Some techno-economic studies addressed the integration of Pd-based H_2-selective membranes in a IGCC plant, but for power generation only [22–24]. Techno-economic analysis with investment cost estimate based on accurate sizing of the additional process equipment to co-produce hydrogen by membrane technology is lacking in the literature.

The aim of this work is to provide a technical and economic analysis of an IGCC process with up to date carbon capture technologies and with co-production of electricity and high purity molecular hydrogen in order to mitigate the capture costs of CO_2. In order to achieve this purpose:

- The most promising alternative processes at the industrial scale are selected and included in the flowsheet to separate H_2 and CO_2. Innovative palladium-based membranes are considered for the co-production of pure H_2, while absorption with the Selexol® solvent is assessed for carbon capture. The latter process sections are optimized from a technical and economic standpoint of view and compared with the traditional sequence of Selexol® process and Pressure Swing Adsorption (PSA).
- Detailed unit sizing of the new process section is performed by rigourous design methods available in process simulation software.
- Investment and operating costs for the capture and storage of CO_2 and pure H_2 production, and consequently of the entire IGCC power plant are calculated. Two macroscopic indexes, the production cost of energy and the mitigation cost of the carbon capture, are estimated to assess the alternative process technologies for different values of the CO_2 capture percentage.
- A sensitivity analysis on the Pd membrane cost is performed to take into account the cost uncertainty of developing technologies.

Process simulation

Case study description

In this work the section of CO_2 capture and H_2 production of an IGCC power plant was simulated. The inlet stream to this section was the syngas stream, mainly formed by CO and H_2, coming out of the gas cleaning section of an IGCC plant. In particular, in this case study we referred to the clean syngas stream generated from a solid 50:50 mixture of coal and petroleum coke in the 335MWe Puertollano IGCC power plant according to the data simulated and reported by Sofia et al.

Table 1 – Composition and conditions of clean gas flowrate [25,26].

Temperature [°C]	130
Pressure [bar]	22
Molar flowrate [kmol/h]	8612
Mass flowrate [ton/h]	216.2
CO fraction (%)	59.0
CO_2 fraction (%)	2.5
H_2 fraction (%)	20.8
H_2O fraction (%)	2.3
N_2 fraction (%)	15.1

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