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Economic assessment of chemical looping oxygen production and chemical looping combustion in integrated gasification combined cycles

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ABSTRACT

Chemical looping promises significant reductions in the cost of CO_2 capture and storage (CCS) by enabling energy conversion with inherent separation of CO_2 at almost no energy penalty. This study evaluates the economic performance of a novel power plant configuration based on the principle of packed bed chemical looping. The new configuration, called COMPOSITE, integrates packed bed chemical looping combustion (PBCLC) and chemical looping oxygen production (CLOP) into an integrated gasification combined cycle (IGCC) power plant. The CLOP unit achieves air separation with minimal energy penalty and the PBCLC unit achieves fuel combustion with inherent CO_2 capture. The COMPOSITE configuration achieved a competitive CO_2 avoidance cost (CAC) of €45.8/ton relative to conventional IGCC with pre-combustion CO_2 capture with €58.4/ton. However, the improvement was minimal relative to a simpler configuration using an air separation unit (ASU) instead of the CLOP reactors, returning a CAC of €47.3/ton. The inclusion of hot gas clean-up further improved the CAC of the COMPOSITE configuration to €37.8/ton. Optimistic technology assumptions in the form of lower contingency costs and better CLOP reactor performance reduced the CAC to only €24.9/ton. Further analysis showed that these highly efficient chemical looping plants will be competitive with other low-carbon power plants (nuclear, wind and solar) in a technology-neutral climate policy framework consistent with a 2 °C global temperature rise. Economic attractiveness improves further in a high CO_2 tax scenario where large-scale deployment of CO_2 negative bio-CCS plants is required.

1. Introduction

CO_2 capture and storage (CCS) is broadly recognized as a vital climate change mitigation technology (IEA, 2016, 2017; IPCC, 2014). CCS is often the only viable solution for mitigating industrial emissions, can protect fossil fuel assets through retrofits, and can result in carbon-negative power production through bio-CCS. The latter option features prominently in 2 °C and "beyond 2 °C" scenarios from the IPCC and IEA. Most IPCC scenarios require zero emissions from the power sector by mid-century and deeply negative CO_2 emissions by the end of the century (CO_2 should be extracted from the atmosphere at a similar rate of current emissions) (IPCC, 2014). Without CCS, most model runs simply could not achieve the 450 ppm IPCC scenario.

Solid fuel CCS is therefore seen as a crucial future power sector technology: initially using coal as fuel followed by a gradual switch to biomass for achieving negative emissions. Given concerns about the limited rate of sustainable biomass production, energy conversion efficiency should be prioritized. In addition, the highly efficient CCS power plant should also have minimal local emissions to meet stringent legislation on local pollutants. The power plant configurations presented in this study aim to maximize efficiency and minimize local pollutants by relying on the integrated gasification combined cycle (IGCC) configuration.

Chemical looping combustion (CLC) technology has the potential to significantly reduce the energy penalty associated with CCS by achieving fuel conversion without direct contact between CO_2 and N_2.

Abbreviations: ASC, advanced supercritical; ASU, air separation unit; CAC, CO_2 avoidance cost; CCS, CO_2 capture and storage; CEPCI, chemical engineering plant cost index; CGCU, coldgasclean-up; CLOP, chemical looping oxygen production; FOAK, first of a kind; HGCU, hot gas clean-up; IGCC, integrated gasification combined cycle; LCOE, levelized cost of electricity; O&M, operating and maintenance; PBCLC, packed bed chemical looping combustion; PV, photovoltaic; SC-PC, supercritical pulverized coal; TPC, total plant cost; T&S, transport and storage

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When using solid fuels, two pathways exist: solid fuel CLC where the fuel is fed directly to the CLC reactors (Lyngfelt, 2014; Lyngfelt and Leckner, 2015; Spinelli et al., 2016) and the IGCC pathway where solid fuel is externally gasified and cleaned before being fed to the CLC unit (Cloete et al., 2015; Spallina et al., 2014). Economic assessments of these concepts show similar performance with a CO_2 capture cost of about €20/ton (without transport and storage) relative to their respective benchmarks (Lyngfelt and Leckner, 2015; Mancuso et al., 2017). However, the IGCC configuration has potential for further efficiency increases via hot gas clean-up (Giuffrida et al., 2013, 2010) and the integration of a chemical looping oxygen production (CLOP) unit for more efficient air separation (Larring et al., 2016).

The potential of these options to increase power plant efficiency was recently assessed (Cloete et al., 2018), showing that the inclusion of hot gas clean-up and CLOP reactor technology can increase overall power plant efficiency beyond 45%. This study will investigate whether this very high CCS power plant efficiency can translate into significant economic benefits.

Furthermore, the study will assess the economic performance of such highly efficient solid fuel CCS power plants in various macro-economic scenarios consistent with a 2 °C climate change target. These include a high CO_2 price (€100/ton), a lower discount rate (4% instead of 8%), and widespread deployment of bio-CCS. The economic performance of the best performing CCS power plant is compared to other low-carbon power generation options (nuclear, wind and solar PV) in each scenario.

1.1. Power plant configurations

This study will compare the economic performance of seven plant configurations under several different macro-economic scenarios. The plant configurations are summarized in Table 1. Two benchmark cases without CCS are considered: an integrated gasification combined cycle (IGCC) plant and an advanced supercritical (ASC) pulverized coal plant. Performance of these benchmark power plants without CCS (cases 1 & 2) are taken from Franco et al. (2011).

The CCS plants considered in this study are all based on an IGCC configuration. The first case, 3a, is a conventional pre-combustion plant where syngas from the gasifier is shifted to H_2 and CO_2, CO_2 is removed, and H_2 is fed to the combined power cycle (Franco et al., 2011). The second CCS configuration, 3b, combusts the syngas in packed bed chemical looping combustion (PBCLC) reactors where CO_2 is inherently separated out (Spallina et al., 2014). This plant configuration brings a large efficiency advantage (3.6%-points higher), even though the inlet temperature of the combined cycle is relatively low (< 1200 °C) compared to the pre-combustion case (> 1400 °C). In addition, very high CO_2 avoidance is achieved, resulting in only a third of the specific CO_2 emissions of the pre-combustion plant.

Three different configurations of the novel COMPOSITE plant (Cloete et al., 2018) are assessed. The first option (4a) directly replaces the air separation unit (ASU) in the PBCLC plant with chemical looping oxygen production (CLOP) reactors. These reactors enable air separation with no direct energy penalty, but produce an O_2 stream that is strongly diluted by sweep gases (CO_2 and H_2O), thus requiring a larger gasifier and gas clean-up unit due to the larger stream of lower heating value syngas produced. Table 1 shows that this plant configuration offers a further 2.8%-point efficiency advantage over the PBCLC ASU plant.

A further efficiency benefit can be achieved by incorporating hot gas clean-up (HGCU) technology after the gasifier. This reduces the energy penalty associated with cooling the syngas produced by the gasifier all the way to 30 °C for conventional cold gas clean-up (CGCU). As shown in Table 1, a further 2%-point efficiency benefit is possible with this configuration (case 4b). It should be noted, however, that the other IGCC plants in this assessment can also achieve a similar benefit (e.g. Giuffrida et al. (2010)), so the comparison should focus on the COMPOSITE plant with CGCU.

Finally, a COMPOSITE plant configuration is considered with less optimal performance from the CLOP reactors, resulting in a lower O_2 concentration in the stream fed to the gasifier (case 4c). This does not strongly affect the plant efficiency, but further increases the capital costs of the gasifier and gas clean-up units. Given that the CLOP reactor technology is still in the lab-scale demonstration phase, it is valuable to consider a reasonable range of possible large-scale reactor performances.

For more details about each process layout, direct references to process flow diagrams and stream tables from the aforementioned references are provided in Table 2.

Table 1
Plant configurations considered in this study (Cloete et al., 2018; Franco et al., 2011; Spallina et al., 2014).

Case	Power plant	Capacity (MWe)	Specific emissions (kg/MWh)	Efficiency (% LHV)
1	IGCC w/o CCS	391.5	734.3	47.3
2	ASC w/o CCS	754.3	763.0	45.5
3a	IGCC pre-combustion	352.7	96.0	37.0
3b	IGCC PBCLC ASU	386.9	33.9	40.6
4a	COMPOSITE CGCU 18.4% O_2	414.1	52.9	43.4
4b	COMPOSITE HGCU 18.4% O_2	433.2	35.0	45.4
4c	COMPOSITE HGCU 14.4% O_2	432.2	40.4	45.3

2. Methodology

2.1. Capital and operational cost estimates

The total capital cost estimates for the comparative power plants are based on numbers from the EU projects CESAR, CAESAR and DECARBit: "European best practice guidelines for assessment of CO_2 capture technologies" (Franco et al., 2011). There is not a significant difference between the current (2017/2018) Chemical Engineering Plant Cost Index (CEPCI) and the 2008 reference used in this report. Plant component cost data from Franco et al. (2011) will therefore be used directly in this study.

For the equipment purchase and installation cost, sizing for the benchmark IGCC plant with and without CO_2 capture is estimated based on the mass and energy balances using a bottom-up approach (BUA) for the required power plant size. This equipment cost breakdown is also used for the other IGCC configurations investigated in this study, with appropriate scaling of the gasifier and gas clean-up unit costs with the syngas stream flowrate raised to the power of 2/3. In the cases with hot gas clean-up, gas clean-up equipment costs were assumed to be only 75% of the case with cold gas clean-up based on the capital cost estimates given in Table 6.4 of Nexant (2007). Only the reference case for the ASC plant is based on a top-down approach, based

Table 2
Direct references to process flow diagrams and stream tables for the plants assessed in this study.

Case	Power plant	Reference	Process flow diagram	Stream table
1	IGCC w/o CCS	Franco et al. (2011)	Figure 4.2.1.1	Table 4.2.2
2	ASC w/o CCS	Franco et al. (2011)	Figure 3.2.1	Table 3.2.2
3a	IGCC pre-combustion	Franco et al. (2011)	Figure 4.3.1.1	Table 4.3.2
3b	IGCC PBCLC ASU	Spallina et al. (2014)	Figure 4	Table 6
4	COMPOSITE HGCU	Cloete et al. (2018)	Figure 4	Table 10