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Economic assessment of packed bed chemical looping combustion and suitable benchmarks

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ABSTRACT

CO_2 capture and storage (CCS) must be deployed on a large scale if global temperature rise is to be limited to 2 °C. To facilitate such a rapid expansion, it is crucial that costs are reduced from today's levels. Energy penalty is the biggest single contributor to the cost of CCS. This work therefore presents an economic assessment of the packed bed chemical looping combustion (PBCLC) concept for near-zero emission power production with minimal energy penalty. Results showed that the PBCLC concept integrated into an integrated gasification combined cycle (IGCC) power plant resulted in similar CO_2 avoidance costs as a supercritical pulverized coal plant with CCS: 66 €/ton (including CO_2 transport and storage). Relative to an unabated IGCC plant, the CO_2 avoidance cost was 34 €/ton, significantly lower than the costs of an IGCC power plant with pre-combustion CO_2 capture (47 €/ton). Moderate sensitivities to uncertainties regarding the PBCLC oxygen carrier material lifetime and reactor cost were observed. The promise of the PBCLC concept therefore strongly depends on future cost reductions from IGCC power plants (e.g. through hot gas clean-up and advanced gas turbine technology). Finally, a sensitivity analysis to future policy developments showed that today's CCS technology is already cost competitive with unabated power plants under policy developments consistent with the 2 °C global temperature rise goal.

1. Introduction

The global economy faces a great challenge in the first half of the 21st century: economic output must triple, while CO_2 emissions are reduced by half (450 ppm scenario in IEA (2016)). Many different technological, social and political factors can contribute to addressing this great challenge. Among these, CO_2 capture and storage (CCS) is one of the most contentious, but arguably one of the most important CO_2 reduction mechanisms.

CCS faces many challenges from factors such as the energy penalty of CO_2 capture, socio-political resistance to CO_2 storage, and the perception that CCS will prolong global dependence on dirty fossil fuels. However, it also has several unique advantages such as broad deployment possibilities across the power sector and industry, the possibility to retrofit existing infrastructure, the possibility for CO_2-negative power production when combined with bioenergy, and the provision of dispatchable energy (as opposed to non-dispatchable wind/solar resources). As an illustration of the importance of these advantages, the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014) found that many model runs simply could not achieve a strict 450 ppm climate change mitigation scenario if CCS was excluded. The model runs that found a solution resulted in a median mitigation cost that was 140% greater than the base case.

However, even though CCS may prove invaluable in a belated global push towards rapid decarbonization, significant cost reductions must still be achieved. The largest single contributor to the cost of CCS is the energy penalty associated with CO_2 capture. A recent review of the costs of CCS (Rubin et al., 2015) showed that a typical pulverized coal plant with post-combustion CO_2 capture will require about 32% more energy per unit electricity production than an equivalent plant without CO_2 capture. This is a major contributing factor to the ~62% increase in the levelized cost of electricity, not only because of greater fuel consumption, but also because most components of the power plant now need to be 32% larger to produce the same electricity output.

Chemical Looping Combustion (CLC) (Ishida et al., 1987; Lyngfelt et al., 2001) has emerged as a promising method to reduce the energy penalty associated with CO_2 capture. A conventional CLC system operates by circulating a metal-oxide oxygen carrier between two reactors to transport oxygen from air to combust fuel in an environment free of nitrogen. This results in combustion with oxyfuel CO_2 capture at almost

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Nomenclature

List of acronyms

AGR	Acid gas removal
ASU	Air separation unit
BOP	Balance of plant
CAC	CO_2 avoidance cost
CCS	CO_2 capture and storage
CLC	Chemical looping combustion
CPU	CO_2 processing unit
C&D	Compression and drying
DCS	Distributed control system
EPC	Engineering, procurement and construction
FEED	Front-end engineering design
FGD	Flue gas desulphurization
ID	Inner diameter
IEA	International energy agency
kWe	Kilowatt electric (power plant capacity)
k€	Kilo-euro (€1000)
IGCC	Integrated gasification combined cycle
LCOE	Levelized cost of electricity
LHV	Lower heating value
MEA	Monoethanolamine
MWe	Megawatt electric (power plant capacity)
M€	Mega-Euro (€1000000)
NGCC	Natural gas combined cycle
O&M	Operating and maintenance
PBCLC	Packed bed chemical looping combustion
PC	Pulverized coal
PMC	Production and material control
PV	Photovoltaics
SC-PC	Supercritical pulverized coal
SRU	Sulphur recovery unit
STC	Syngas treatment and conditioning
S&H	Storage and handling
TCR	Total capital requirement
TGT	Tail gas treatment
TPC	Total plant cost
T&S	Transport and storage
WACC	Weighted average cost of capital

no energy penalty.

Surprisingly little work has been done in terms of thorough bottom-up economic assessments of CLC power plants. Some approximate or undocumented studies show very good potential relative to benchmark cases (Lyngfelt and Leckner, 2015) estimated a cost increase of only 20 €/ton CO_2 relative to a circulating fluidized bed boiler coal plant when solid fuel CLC is used. A presentation from Chamberland et al. (2015) projects Alstom's CLC technology to add only 19.5% to the levelized cost of electricity (LCOE) of a new coal plant as opposed to a 53.5% increase for a plant with conventional oxyfuel capture. Both these studies considered CO_2 capture only (no transport and storage costs). Based on the aforementioned review (Rubin et al., 2015), these are large improvements relative to the 62% increase in LCOE and 63 $/ton CO_2 avoidance cost (CAC) of coal-fired power plants with post-combustion CO_2 capture.

An economic assessment for a natural gas-fired CLC plant showed that the oxygen carrier needs to last 4000 h to achieve parity with a benchmark NGCC plant with post-combustion CO_2 capture when an expensive NiO-based oxygen carrier was used (Porrazzo et al., 2016). An earlier work on CLC in an NGCC power plant calculated the CAC as 53.1 €/ton as opposed to 78.3 €/ton for conventional post-combustion technology (Petrakopoulou et al., 2011). The improvements from these assessments are less dramatic than the cases with coal-fired power production discussed in the previous paragraph.

This work will contribute to the field by presenting a thorough bottom-up economic assessment of a packed bed CLC (PBCLC) system integrated into an IGCC power plant. PBCLC has been presented as a promising alternative for application of pressurized CLC because it avoids the technical challenges related to gas-solid separation under high-pressure operation (Noorman et al., 2007; Spallina et al., 2013). The PBCLC-IGCC power plant configuration has also been thermodynamically assessed (Spallina et al., 2014), yielding promising performance including electric efficiency of 41% and CO_2 capture efficiency of 97%. This performance was found to be similar to an IGCC power plant configuration utilizing conventional CLC reactors (Hamers et al., 2014).

Parallel assessments of several benchmark technologies will also be presented to ensure a viable comparison. These include an IGCC plant with pre-combustion CO_2 capture, a SC-PC plant with post-combustion CO_2 capture and a SC-PC plant with oxyfuel CO_2 capture. CAC will be presented relative to both SC-PC and IGCC plants without CO_2 capture. The most important performance specifications of the different plants assessed in this study are summarized in Table 1.

Table 1
Performance specifications of the six power plants investigated in the study.

Plant	Capacity (MWe)	Plant efficiency (% LHV)	Specific emissions (g/kWh)
IGCC w/o CCS	367.4	45.2	769.8
IGCC w/pre-comb. CCS	317.3	35.3	101.4
IGCC w/CLC CCS	348.8	40.8	33.5
SC-PC w/o CCS	514.8	44.1	745.3
SC-PC w/post-comb CCS	411.2	35.2	93.0
SC-PC w/oxy-CCS	416.7	35.7	92.2

2. Methodology

The methodology for estimating the LCOE and CAC of each case will be outlined in two main sections on capital costs and operating and maintenance (O & M) costs. It is similar to the methodology outlined in previous IEAGHG reports (Mancuso and Ferrari, 2014; Mancuso et al., 2015), but will be repeated here for ease of reference. Supporting data are presented in several tables in the Appendix A.

2.1. Capital costs

The methodology for estimating the Total Plant Cost (TPC) and the Total Capital Requirement (TCR) of the different plants is outlined in this section.

2.1.1. Cost estimating bases

TCR is defined in general accordance with the White Paper "*Toward a common method of cost estimation for* CO_2 *capture and storage at fossil fuel power plants*" (Rubin et al., 2013) as the sum of:

- Total Plant Cost (TPC)
  - ○ Direct materials
  - ○ Construction
  - ○ Other costs
  - ○ Project contingency
- Interest during construction
- Spare parts cost