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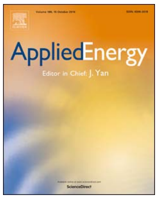

A novel methodological approach for achieving £/MWh cost reduction of CO_2 capture and storage (CCS) processes

Renato P. Cabral[a,b], Niall Mac Dowell[b,c,*]

[a] SSCP DTP, Grantham Institute for Climate Change and the Environment, Imperial College London, South Kensington, London SW7 2AZ, UK
[b] Centre for Environmental Policy, Imperial College London, South Kensington, London SW7 1NA, UK
[c] Centre for Process Systems Engineering, Imperial College London, South Kensington, London SW7 2AZ, UK

HIGHLIGHTS

- Thermodynamic analysis to improve oxy-CCS efficiency.
- 2nd law analysis quantifies potential for improvement.
- Exergy Destruction analysis identifies targets for improvement.
- Results in 3% increase in efficiency, 15% reduction in capital cost.
- This equates to a 15% reduction in the £/MWh cost of CCS electricity.

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ABSTRACT

Carbon capture and storage is widely recognised as essential for the cost effective decarbonisation of the power and industrial sectors. However its capital and operating costs remain a barrier to deployment, with significant reduction in the cost per unit of decarbonised product considered vital. In the context of power generation, this is best expressed in terms of cost per MWh of electricity generated. To achieve a meaningful reduction in the cost of low carbon electricity, capital costs must also be reduced. Thus, this work presents a novel approach for identifying system improvements via a combination of process integration and intensification based on minimisation of thermodynamic losses. Application of this methodology to an oxy-combustion CCS process led to a 3% increase of net efficiency and a 13% reduction of £/MWh of electricity.

1. Introduction

Anthropogenic carbon dioxide (CO_2) emissions from burning fossil fuels are currently recognised as the leading contributor to climate change, with 36.2 Gt being emitted in 2015 [1,2]. However, despite substantial investment in renewable energy, fossil fuels continue to play an integral role in the world's energy landscape [3]. Indeed, coal still plays a major role as a primary energy source [4] and although its global use is declining, some countries are highly reliant on this fuel, so it is expected that coal will keep being relevant in the future.

Carbon capture and storage (CCS) technologies have the potential to reduce these anthropogenic CO_2 emissions as part of a transition to a low carbon energy system [5–7]. These technologies are typically divided in three categories: pre-combustion, post-combustion, and oxy-combustion [6,8], and all are based on the idea of the capture and subsequent storage of CO_2 from the combustion of fossil fuels in either the power or industrial sectors. In all cases, high purity CO_2 has to be compressed to approximately 110 bar prior to transportation via pipeline to a storage site [9–11][1].

Oxy-combustion is a promising technology where fuel is burnt in a high-oxygen (O_2) environment, using O_2 obtained from an air separation unit (ASU), instead of with air, improving combustion efficiency [12]. Safe operation conditions are maintained by recycling a fraction of the flue gas back to the furnace, thus keeping the temperatures inside the boiler close to air-firing mode [9,13–15]. Burning coal under these conditions generates an flue gas rich in CO_2 (60–70 mol%) with appreciable quantities of H_2O (20–25 mol%), O_2 (3–4 mol%) and N_2 (0–10 mol%), which varies according to coal rank and process design [13]. This flue gas is then upgraded to transport specifications via a gas processing unit (GPU) [7,14,16].

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* Corresponding author at: Centre for Environmental Policy, Imperial College London, South Kensington, London SW7 1NA, UK.
E-mail address: niall@imperial.ac.uk (N. Mac Dowell).

[1] Actual compression pressure is a function of the design of the CO_2 transport infrastructure and the chosen CO_2 storage option.

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Nomenclature

ASU	air separation unit
CAPEX	capital expenditure
CCS	carbon capture and storage
DCC	direct contact cooler
ED	exergy destruction
F_{80}	mean particle size of coal feed to grinder
FWH	feedwater heater
G	coal grindability
GPU	gas processing unit
h	specific enthalpy
HP	high pressure
HX	heat exchanger
IP	intermediate pressure
LHV	lower heating value
LP	low pressure
MAC	main air compressor
MHX	multiple-stream heat exchanger
n	molar flow
NGCC	natural gas combined cycle
P_1	target particle size of grinding process
P_{80}	mean particle size at grinder outlet
PFD	process flow diagram
Q	heat flow
RFG	recycled flue gas
SD	spray dryer
R	perfect gas constant
RS	radiant superheater
RH	reheater
RHX	regenerative heat exchanger
s	specific enthropy
SH	superheater
T	temperature
T_{ad}	adiabatic flame temperature
W	work
W_i	bond work index
W_{min}	minimum separation work
y	molar fraction
η_{gross}	gross efficiency of the plant
η_{net}	net efficiency of the plant

Oxy-combustion can also be applied to natural gas combined cycle (NGCC), however the gas turbines need to be redesigned because the increased CO_2 concentrations in the flue gas alter its physical properties [9,12]. Unlike for pulverised coal oxy-combustion, O_2 must be compressed to the high operating pressures of the NGCC before delivered to the furnace [9].

Currently, the dominant technology for producing the quantities of oxygen required for oxy-combustion of pulverised coal (above 600 kg/MWh)[2] is cryogenic distillation [17,18]. This technology was originally commercialised by Carl von Linde in 1902 [19] and is based on separation of the constituents of air using distillation at cryogenic temperatures [20–25]. Despite its technical maturity, cryogenic distillation processes are still energy intensive consuming 200 kWh/t_{O_2} [26] which led to proposals for reducing this penalty, such as using self-heat recuperation [27]. This high energy requirement also promoted the development of alternative technologies for air separation, such as adsorption [28–30], ion transport membranes (ITM) [31–35], and chemical looping [36–38]. However, none of these technologies are suitable for the production of high purity oxygen at utility scale either because of high costs, as for adsorption processes, or the technology is still under development, as for ITM [17,39].

The requirement to add both an ASU and GPU increases the capital cost of the plant and imposes an 8–12% efficiency penalty to the process [7,40]. One way of minimising the effects of this efficiency penalty is through heat integration, which can be optimised by minimising inefficiencies within the process via an exergy destruction analysis. This analysis is based on the second law of thermodynamics, aimed at identifying inefficiencies within a system due to irreversibility [41]. Exergy refers to the amount of work that can be generated by a system on a reversible process, leaving it in equilibrium with the environment [42].

Several studies have focused on reducing this parasitic power consumption by performing thermodynamic and techno-economic analyses on double and triple column ASUs, and different GPU units [43–45]. Skorek-Osikowska et al. determined that low grade heat of compression could be used to pre-heat the feedwater reducing the number of feedwater heaters required [45]. Aneke et al. simulated an oxy-combustion process with liquid air storage and determined there was an advantage to using this strategy as well as recovering waste heat of compression [46]. Stanger et al. and Li et al. both determined that SO_x can have higher concentrations in oxy-combustion flue gas than in air-combustion due to recycling and a lack of dilution by N_2 [47,48]. This increase in SO_x has the effect of increasing acid dew point from 116 °C in air-firing to 141.6 °C in oxy-combustion [47], as well as changes in ash composition [48,49]. Oxy-combustion CCS has been demonstrated a number of times, including the Callide oxyfuel project [50–52], Lacq pilot plant [53], Compostilla OXYCFB300 circulating fluidised bed [54], and Vattenfall's pilot plant [55,56]. These projects proved the feasibility of oxy-combustion and provided further insights on operational performance of the technology.

Whilst improvements in process efficiency are important, it is vital that they do not result in increased capital cost, leading to an increased cost per MWh of low carbon electricity generated. This creates the need to develop a methodological approach that allows the evaluation of the efficacy of a process modification in this context.

In this work, we present a novel methodological approach for the identification and rational analysis of potential process performance improvements via system integration and process intensification. This approach is grounded in the application of the 1st and 2nd laws of thermodynamics coupled with a capital expenditure (CAPEX) analysis. The methodology proposed in this study is well-suited for application to other CCS technologies, or more generally to other complex industrial processes, such as liquefied natural gas processes.

2. Methods

2.1. General model

All models in this study were implemented in Aspen HYSYS v8.4 and all thermophysical properties were calculated using the Peng-Robinson equation of state fluid package. The process flow diagram (PFD) of the oxy-combustion is presented in schematic form in Fig. 1.

A medium sulphur bituminous coal with a grindability of 0.664 g/rev [57] was used in this work with the composition detailed in Table 1. The power required, W (kWh/t), to grind coal with mean particle size of 2.7 mm (F_{80}) to a target size of 90 μm (P_1) and mean particle size of 77 μm (P_{80}) is given by Eqs. (1) and (2) [57],

$$W = 10\ W_i\,(1/\sqrt{P_{80}} - 1/\sqrt{F_{80}}) \tag{1}$$

$$W_i = \frac{44.5}{P_1^{0.23}\ G^{0.82}\ (10/\sqrt{P_{80}} - 10/\sqrt{F_{80}})} \tag{2}$$

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[2] This equates to a rate of 7200 t_{O_2}/day for a 500 MW power plant.