Applied Energy 195 (2017) 289–302

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Bio-Energy with CCS (BECCS) performance evaluation: Efficiency enhancement and emissions reduction

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HIGHLIGHTS

- A study of biomass co-firing with CCS is presented.
- The impact on process efficiency of a range of solvents is considered.
- We show that with heat recovery, carbon negative power plants can be 38% efficient.
- BECCS plant efficiency and carbon negativity are strongly related.

ARTICLE INFO

Article history:
Received 23 November 2016
Received in revised form 26 January 2017
Accepted 10 March 2017

Keywords:
Bio-energy
Carbon Capture and Storage (CCS)
BECCS
Greenhouse gas removal (GGR)
Negative emissions technologies (NETs)

ABSTRACT

In this study we evaluate the feasibility of the recovery of waste heat from the power plant boiler system of a pulverised fuel power plant with amine-based CO_2 capture. This recovered heat can, as a function of fuel type and solvent selection, provide up to 100% of the heat required for solvent regeneration, thus obviating the need for withdrawing steam from the power plant steam cycle and significantly reducing the efficiency penalty imposed upon the power plant by the CO_2 capture process. In studying the thermochemistry of the combustion process, it was observed that co-firing with low moisture biomass achieved higher adiabatic flame temperatures (AFT) than coal alone. The formation and emission of SO_X reduced as biomass co-firing proportion increased, whereas NO_X emissions were observed to be a function of AFT. The power generation efficiency of a 500 MW 50% co-firing BECCS system increased from $31\%_{HHV}$ with a conventional MEA solvent, to $34\%_{HHV}$ with a high performance capture solvent. The heat recovery approach described in this paper enabled a further efficiency increase up to $38\%_{HHV}$ with the high performant solvent. Such a system was found to remove 0.83 Mt_{CO_2} from the atmosphere per year at 90% capacity factor.

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1. Introduction

Carbon capture and sequestration (CCS) technologies are well accepted as being vital for the mitigation of climate change [1]. There is growing interest in developing long-term CO_2 mitigation strategies that have the potential for deep reductions in atmospheric CO_2 concentrations. CCS with so-called negative emissions technologies (NETs) or greenhouse gas removal (GGR) technologies are expected to play an essential role in limiting global warming below 2 °C, as advised by IPCC [2] and in meeting the 1.5 °C target proposed by COP21 [3]. "Negative emissions" technology that combines biomass-derived energy and CO_2 sequestration was first introduced by Williams (1996) [4] for hydrogen fuel production and Herzog (1996) [5] for electricity generation. Biomass grown and harvested sustainably is considered an appropriate substitute for fossil fuels [6,7]; during growth, there is a net transfer of atmospheric CO_2 into biomass, and the conversion of the biomass to produce electrical energy and the capture and geological storage of the arising CO_2 enables the permanent removal of that CO_2 from the atmosphere [8,9]. This is referred to as bio-energy with carbon capture and sequestration, or BECCS [10–13],[1] and can achieve an overall negative CO_2 balance when carefully deployed [14–17,18–20,10]. The IPCC highlighted BECCS as an important mitigation option in the fifth assessment report [2], and it was the most widely selected negative emissions technology by integrated assessment models to meet temperature targets [9].

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[1] Originally termed BECS by Kraxner et al. (2003) [8].

http://dx.doi.org/10.1016/j.apenergy.2017.03.063
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In addition to reducing CO_2 emissions, biomass co-combustion has been shown to reduce NO_X, SO_X and particulate emissions [21]. Full-scale studies demonstrate that high proportions of biomass co-firing is possible without any effect on boiler or combustion efficiency, provided modern burner technology is used [22]. Dedicated biomass combustion at the utility scale is possible with, for instance, the Drax Power Station operating two of its 660 MW generating units with a 100% biomass fuel [23]. The conversion of these units from coal to biomass is reported to have cost £700 M, which covered all capital required for the storage, handling and conversion of the biomass [24]. On the other hand, biomass-dedicated power plants are typically one-tenth the size (1–100 MW) of conventional coal-fired plants, due to limited biomass availability and high cost of transportation [25,26]. Fuel availability is region specific, as there will be variation in feedstock properties, land/water availability, crop yields, transportation costs and other parameters. However, biomass supply chains in the UK have yet to fully develop. Consequently, large-scale plants such as Drax must import wood pellets to meet fuel requirements, 58% from the US, 21% from Canada, and 7.5% from Latvia [27].

Biomass tends to have a lower heating value and often higher moisture content compared to high quality coal (shown by Table A1). Therefore, biomass co-combustion tends to reduce power plant output relative to dedicated coal combustion [28], for a constant fuel combustion rate. The addition of CO_2 capture technology will impose a further energy penalty, appreciably reducing electricity output per unit of primary fuel utilised [29]. The size of a biomass power plant needs to be large enough to exploit economy of scale, however, size is limited by biomass availability and cost [26]. When the capacity of an electricity generation plant is doubled, capital cost increases approximately 62%. Larger power plants are more thermally efficient than small-scale plants. For instance, a 200 MW power plant converts 30–39% of the thermal energy into electricity, whereas a 25 MW plant converts 20–25% into electricity [30]. Subsequently, the cost of generating electricity is higher for small-scale power plants [31]. Ultimately, the higher thermal efficiency and lower cost of electricity generation make larger facilities more profitable than small-scale plants, thus outweighing the higher construction costs [30].

2. Enhancement of BECCS performance

In comparison to other energy systems, BECCS is a promising candidate for negative emissions (as shown by Fig. 1). In the near to medium term, most, if not all, BECCS power plants will continue to compete in liberalised electricity markets. Thus, efficiency improvements will serve to reduce the marginal cost of electricity generation, allowing the facility to operate at a higher load factor [32,33]. Therefore, further improvements to its performance will encourage large scale deployment of the technology.

In conventional post-combustion capture technology, heat is supplied to the solvent regeneration process in the form of saturated steam. This reboiler heat duty (*HD* in MJ/t_{CO_2}) is the sum of three contributions: (i) the sensible heat to raise the solvent from absorber to desorber temperature; (ii) the heat of evaporation to produce the steam supplied to the reboiler; and (iii) the heat of absorption, *i.e.* the heat necessary to desorb the CO_2 from the solution [35]:

$$HD = \frac{Cp \times (T_R - T_{feed})}{\Delta\alpha} \frac{M_{sol}}{M_{CO_2}} \frac{1}{x_{solv}} + \Delta h_{vap,H_2O} \frac{p_{H_2O}}{p_{CO_2}} \frac{1}{M_{CO_2}} + \frac{\Delta h_{abs,CO_2}}{MW_{CO_2}} \tag{1}$$

where $_{Cp}$ is the specific heat of the solution, T_R and T_{feed} are the temperatures at the reboiler and desorber inlet, respectively, $\Delta\alpha$ is the difference in CO_2 loading between the absorber outlet (rich) and inlet (lean), x_{solv} is the solvent mole fraction in the solution, $\Delta h_{vap,H_2O}$ is water latent heat of evaporation, p_{H_2O} and p_{CO_2} are the vapour and CO_2 partial pressures in the gas phase at the desorber top, $\Delta h_{abs,CO_2}$ is the heat of absorption of solvent, lastly, MW_{CO_2} and MW_{sol} are the molecular weights of CO_2 and the solution.

This solvent regeneration process requires low grade thermal energy, on the order of 150 °C, typically provided by the condensation of steam at ~3 bar [36,29]. The main steam supply for CO_2 capture is extracted from the steam cycle of the power plant, which incurs an efficiency penalty on the system [37,38]. To minimise the efficiency penalty associated with CO_2 capture, several options for extracting steam from the power plant steam cycle have been proposed: steam extraction from the cross-over pipe between the intermediate pressure (IP) and the low pressure (LP) steam turbines [39–43], steam cycle retrofits designed for optimised integration with CO_2 capture [36,44], and steam extraction from an appropriate point within the LP turbine [45]. Further improvements to power plant energy efficiency can be achieved through waste heat recovery. Pfaff et al. (2010) used waste heat from the CO_2 capture plant to improve the efficiency of the power station. Heat recovered from the stripper overhead condenser and the CO_2 compressor intercoolers were utilised for pre-heating of the steam cycle condensate and combustion air [46]. Another energy source is flue gas heat recovery, which can be used to improve power plant efficiency through fuel drying [47] or applied in a low pressure economiser to heat the condensate in the steam cycle [48–51]. Alternatively, the heat recovered from flue gas can provide energy for solvent regeneration in CO_2 capture [52,53], where the measured flue gas temperature at the economiser outlet is ~345 °C [54].

All of these studies on efficiency improvements have focussed on applications in fossil fuel-fired power plants. However, there is relatively little work on efficiency improvement in biomass-fired plants. In a 500 MW supercritical power station co-firing biomass and coal, the temperature of the exhaust gas leaving the boiler can reach 370 °C [55]. Therefore, the additional recovery of relatively low-grade heat from the boiler system has the potential to improve the power generation efficiency of a BECCS power plant, albeit at the cost of the additional capital associated with the heat recovery system. Importantly, the moisture content of biomass can vary significantly; as Table A1 demonstrates it varies between 5 and 60 wt%. As moisture content increases, lower heating value (LHV) decreases due to reduced content of combustible matter per kilogram of biomass [56], which in turn decreases net efficiency of the power plant [55]. However, increased moisture content in the fuel enhances heat transfer properties of the flue gas, thereby improving heat recovery [57].

The quality of biomass has an impact on the system efficiency and heat recovery potential of the flue gas. Specifically, suppose we have the option of a high quality (low moisture, high heating value and likely higher cost) or a low quality (high moisture, low heating value and likely lower cost) fuel. In order to produce a constant amount of power, less of the high quality fuel will be required, leading to less recoverable heat in the boiler system. In the case of a low quality fuel, the contrary is true. This is simply another way of saying that high quality fuels tend to result in improved thermal efficiency, and reduced stack losses than low quality fuels. Hence, the amount of recoverable heat within the boiler will depend on fuel quality. This study comprehensively evaluates the potential use of this recovered heat for solvent regeneration in BECCS systems. The remainder of the paper is structured as follows: we first present engineering and thermodynamic models of the BECCS system. The effect of biomass quality and co-firing

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