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## Bio-CCS: Co-firing of established greenfield and novel, brownfield biomass resources under air, oxygen-enriched air and oxy-fuel conditions

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### Abstract

As demand for electricity and atmospheric CO<sub>2</sub> concentrations rise technologies that reduce the environmental impact of generating electricity are sought. Within the many options a combination of co-firing of biomass and carbon capture and storage (Bio-CCS) could present a negative-emission process. This work investigates co-firing of a novel brownfield and two conventional greenfield biomass reserves with coal in oxygen-enriched conditions which may enhance the efficiency of post-combustion capture units. A 20kW furnace is used to assess combustion characteristics in a range of scenarios. Results suggest oxidant staging during oxygen-enriched co-firing can exhibit lower NO emissions while achieving high combustion efficiencies.

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Biomass cofiring, brownfield biomass, oxygen enrichment, oxidant staging, Bio-CCS, negative emissions

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### Introduction

A burgeoning population demanding increasing energy will continue to see greenhouse gas (GHG) emissions rise over the next few decades. Despite a recent shift towards low emissions technologies for generating energy, in order to effectively satisfy long-term targets (such as the UK's 80% reduction by 2050) – pursuing the minimum economic, social and environmental costs – it is likely that measures that

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actively reduce atmospheric GHG concentrations will be required. One such option for geoengineering that is often cited by high-level technology roadmaps, such as [1-3], is to combine two emissions reductions techniques, biomass co-firing and carbon capture and storage known as Bio-CCS or sometimes BECCS. The combustion of biomass fuels is considered to produce no net GHG emissions since the carbon lifecycle of the biomass involves extraction of CO<sub>2</sub> from the atmosphere during the plant growth phase. If the emissions from this process are then captured and stored, preventing their escape to the atmosphere, the process overall is seen as actively removing CO<sub>2</sub> from the atmosphere. Unlike some geoengineering practices whose main purpose is to oppose the causes or effects of anthropogenic climate change, the purpose of Bio-CCS is to produce useful energy with negative emissions as a positive by-product which could be argued to promote the development of this technology over purely emission-reducing options.

In the UK an increase in biomass use is set against finite arable space for crop production, promoting unwanted competition between energy and food crops that is echoed globally. Traditionally, both food and fuel crops have been grown on greenfield sites. However, the UK has a considerable area of brownfield land which, due to previous use and potentially adverse soil contaminations, is unsuitable for food crop production. The BioRegen study investigated whether such land may be suitable for fuel crop production and produced a range of energy crops from non-food sites [4].

In this study, three biomass samples, including one grown on brownfield sites, are co-fired with coal in a 20kW furnace to establish the potential for this technology with conventional power plant technology chains and thus suitable for retrofitting. Currently, one of the issues inhibiting efficiency advances in post-combustion capture systems is the relatively dilute CO<sub>2</sub> stream produced in the combustion flue gas. An interesting option to mitigate this is to enrich the oxygen concentration of the combustion air thereby increasing the CO<sub>2</sub> concentration produced in the flue gas. This technique has been previously tested and has shown promising results with other biomass reserves [5-8]. Oxidant staging during combustion is a well-documented method of reducing emissions of NO that is practiced in industry today. Thus in order to align tests to potential future energy scenarios, in addition to standard air-firing, the biomass fuels are also co-fired in O<sub>2</sub>-enriched air under a range of levels of oxidant staging and biomass blending ratios.

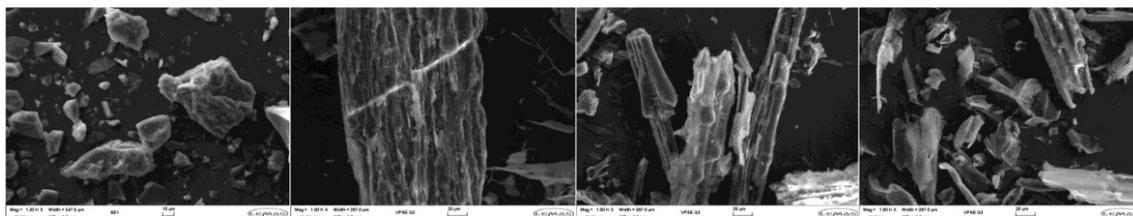


Figure 1 – SEM Images of fuels used in this experiment. From left to right: WC, SRC, RCG and MC.

## Methodology

### 1.1. Fuel Characterisation

Williamson coal supplied by a UK electricity generator was blended with three biomass reserves grown as a part of the BioRegen Project [4]. Two of the biomasses, short-rotation-coppiced willow (SRC) and miscanthus (MC) grass were grown on conventional greenfield sites while the third sample reed canary grass (RCG) was grown on a brownfield site. The ultimate and proximate analysis of the fuels

used in this study are presented in Table 1 while SEM images of the fuel samples are displayed in figure 1. The SEM images show that on average the coal particles are far smaller than their biomass counterparts but also that their morphology is markedly different. The coal particles are largely crystalline equi-dimensional particles while the biomass particles tend to include a range of particles of various sizes and shapes which several researchers have indicated could affect their reactivity during combustion, for example [9,10].

Table 1. Fuel Properties

Fuel	Williamson Coal (WC)	Short-Rotation Coppiced Willow(SRC)	Reed Canary Grass (RCG)	Miscanthus (MC)
Moisture (% <sub>ar</sub> )	3.4	6	5.8	5.5
Volatile Matter (% <sub>ar</sub> )	33.9	72.4	68.5	74
Fixed Carbon (% <sub>ar</sub> )	53.7	18.7	17.6	17.3
Ash (% <sub>ar</sub> )	9	2.9	8.1	3.3
Carbon (%)	72	47.7	42.2	46.4
Hydrogen (%)	4.5	6	5.4	5.8
Nitrogen (%)	1.7	0.5	1.5	0.3
Sulphur (%)	1.9	0	0	0
Oxygen (%) (by difference)	10.9	43	42.8	44.3

### 1.2. 20kW Combustion

Experiments were carried out with a 3.5m down-fired furnace which is schematically depicted in figure 2. The furnace has an internal diameter of 200mm and is operated at a slight negative pressure. The burner is formed of a non-swirling primary central port with a surrounding swirling secondary port. The conical quarl extends from 28-140mm over a distance of 265mm. Over-fired air (OFA) and oxygen are injected at ports in the fourth section of the furnace since this has been found to be the optimised level to reduce NO emissions in previous work on this equipment [5-6,10].

Pulverised fuel is fed to the furnace pneumatically by primary air which collects the fuel from a vibrating plate that ensures homogeneity of the feed. The fuel is fed to the plate by screw feeders: coal is fed by a Rospen twin-screw feeder while the biomass is fed by a single screw feeder. The biomass feeder was custom-built for the experimental rig. It consists of an angled lower section which forms an inverted apex. The biomass in the hopper is continually agitated by two sets of fins attached to the screw mechanism which prevents settling of the fuel and ensures homogeneity. The screw drives material from the vertical centre of the hopper horizontally to ensure a representative sample of the fuel and to reduce bridging of the sample.

Primary air is fed from a compressor and, due to carrying the fuel, is never enriched. As noted by Smart and Riley [11], this is likely to be the case in industry as it will require no changes to the fuel delivery system during retrofitting. The secondary and tertiary gas flows can consist of air and O<sub>2</sub> or a mix thereof. O<sub>2</sub> as OFA is delivered in an oxygen-rated line. Two probes collect samples from the bottom of the furnace. Fly ash is sampled from the flue box using a customised probe and cyclone arrangement connected to a vacuum pump. Gases are sampled using a custom-built, water-cooled probe. Gases are cooled and filtered prior to reaching the analysers where non-dispersive infrared equipment measured CO<sub>2</sub>, CO and SO<sub>2</sub>, NO levels were measured by chemiluminescence, and O<sub>2</sub> was measured established using paramagnetic measurements. Measurements were averaged over 15-20 minute periods with ash sampling over this period yielding approximately 1-2g of sample.

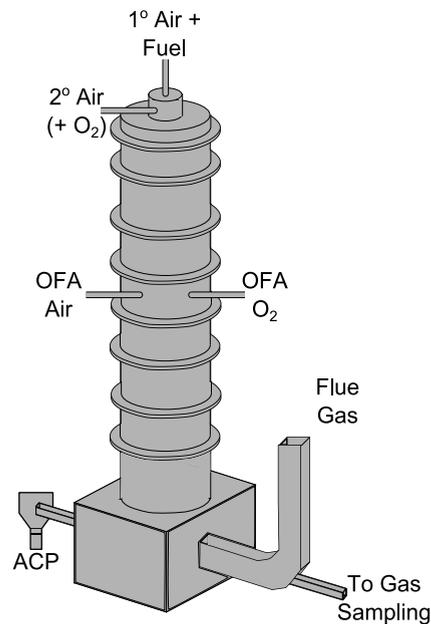


Figure 2 - Schematic diagram of 20kW furnace

### 1.3. Gas Atmospheres

Previous work has shown that enriching the O<sub>2</sub> content of the combustion atmosphere benefits carbon burnout and can help with NO<sub>x</sub> control [5-6, 11]. Thus, as well as baseline experiments conducted in an air, a combustion atmosphere enriched to 30% O<sub>2</sub> was also included in this work, the level chosen to allow comparisons with the ECO-SCRUB programme. For safety reasons only the secondary and tertiary gas lines could be enriched with oxygen; thus, in order to create an overall oxygen inlet concentration of 30%, these lines were enriched to >30% O<sub>2</sub>. In attempt to standardise the tests, the tertiary [O<sub>2</sub>] during

oxygen-enriched conditions was fixed at 45% while the secondary [O<sub>2</sub>] varies between 42-44% depending on the level of oxidant staging employed.

1.4. Ash Analysis

In order to provide more precise metals measurements, several ash samples were also analysed using X-Ray Fluorescence (XRF) analysis. For each sample a fusion bead was analysed using the Wide-Range Oxide package conducted on PANalytical Axios-Advanced XRF spectrometer at the University of Leicester, UK.

1.5. Biomass Blending Ratio

Maintaining the total thermal input at 20kW, the amount of biomass supplanting coal as the fuel was tested at 8, 15 and 20%th. The results of altering the biomass blending ratio (BBR) on emissions of oxides of SO<sub>2</sub> and NO are presented in figure 3. From these results a trend of decreasing emissions of both gases with increasing BBR is apparent when the full dataset is considered; as may be expected from the changes in fuel between the coal and the biomasses, particularly illustrated by the decreasing SO<sub>2</sub> emissions with increasing BBR. However, it should be noted that in none of the cases all of the fuel-bound nitrogen and sulphur is released in its gaseous state. Thus, although increasing BBR helps to reduce emissions of NO and SO<sub>2</sub>, other mechanisms are present which ensure that not all of the fuel-bound N and S are able to form NO and SO<sub>2</sub> respectively and this may help to explain why reductions are more prominent in some biomass reserves than others.

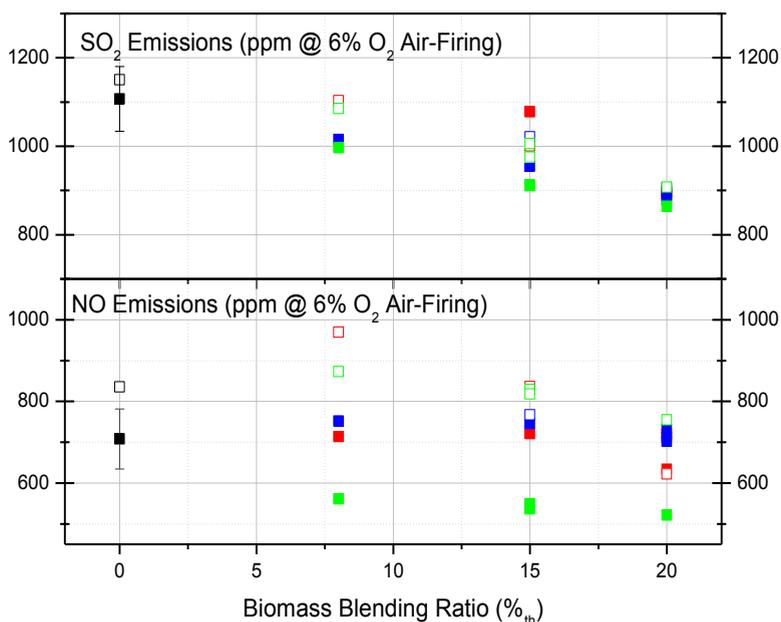


Figure 3 – Effect on emissions of NO and SO<sub>2</sub> with increasing biomass blending ratio (BBR)

### 1.6. Oxidant Staging

The extent of oxidant staging is reported as the burner stoichiometric ratio (BSR) and for this work ranges from 1.16 (unstaged) to 0.8 (31% staging). For this section of the work BBR was fixed at 15%<sub>th</sub> as this presented useful results, represented the upper limit of current co-firing practice in UK and was suitable for avoiding feeder cut outs which were common at the lower BBR.

Figure 4 presents the results for emissions of NO and SO<sub>2</sub> as well as burnout efficiency with varying BSR. Conventional reductions in NO are realized for oxidant staging and while negligible change in SO<sub>2</sub> emissions is seen with increasing BSR. However, oxidant staging while co-firing in oxygen-enriched air appears to be able to reduce NO emissions compared to the air case while maintaining high levels of carbon burnout which tend to reduce in the air case.

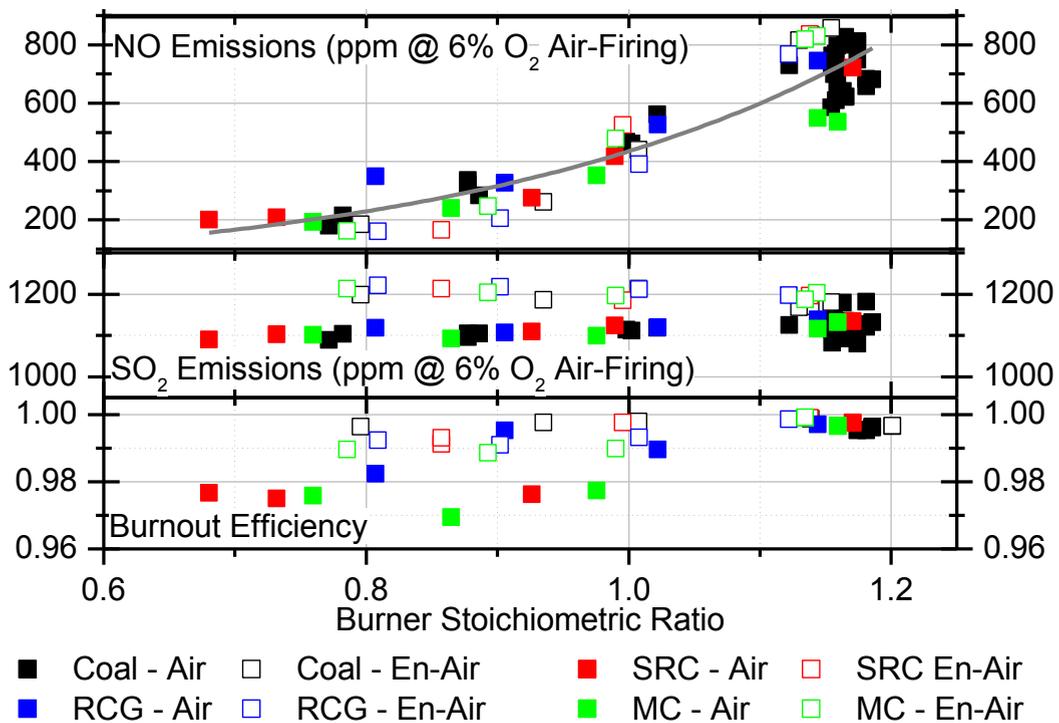


Figure 4 – Effect on carbon burnout and emissions of NO and SO<sub>2</sub> with increasing oxidant staging (reducing BSR)

### 1.7. Ash Analysis

Ash taken from unstaged biomass combustion underwent XRF analysis to quantify the amount of metal oxides retained in the fly ash. Results for each of the fuels are shown in figure 5 where it can be seen that all of the ashes collected from the co-firing tests had increased amounts of sulphur compared to air-firing, perhaps helping to explain the reductions seen in figure 3. An electron dispersive X-ray technique (EDX) coupled to a SEM device was able to semi-quantitatively identify concentrations of elements within an ash sample. Figure 6 presents an example of such imaging showing that the RCG ash

seems to contain more calcium (Ca). Comparing this map with the EDX map for sulphur suggests this higher Ca level may be responsible for a higher retention of sulphur within the ashes of the biomass samples.

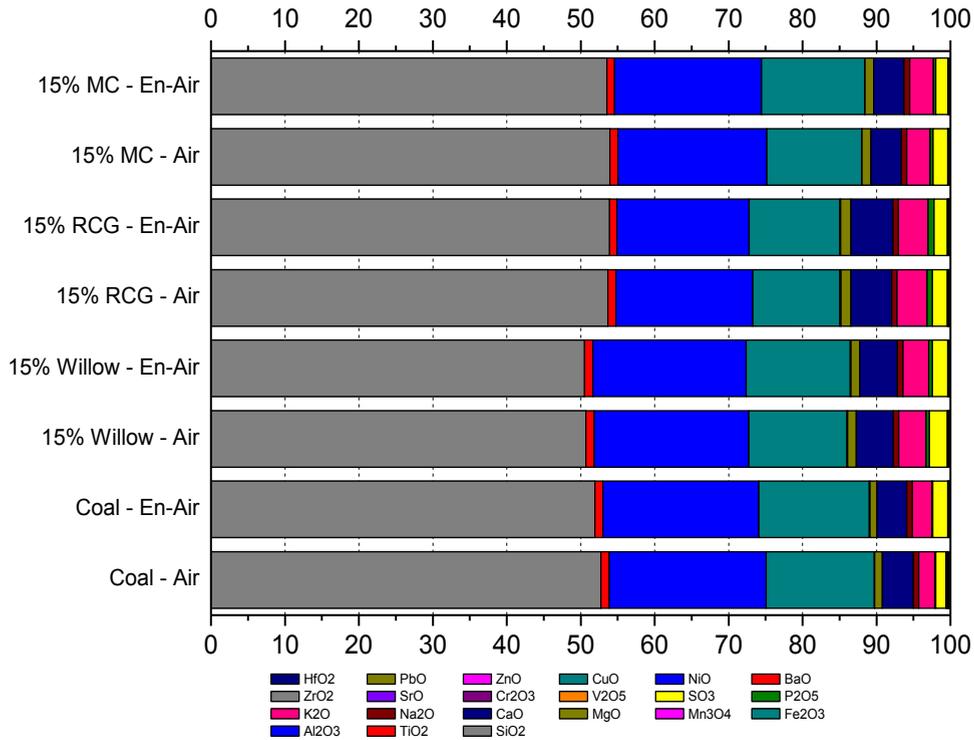


Figure 5 – Ash analysis reported as percentage oxides of different major and minor elements

## Conclusions

Three biomass resources, one grown on brownfield land, have been co-fired with coal under a variety of conventional and novel combustion conditions at 20kW scale. Results indicate that brownfield-sourced biomass could play a role in the future of UK electricity generation and also that a combustion of co-firing, oxidant staging and combustion in oxygen-enriched air could present improved combustion characteristics for retrofitted plant.

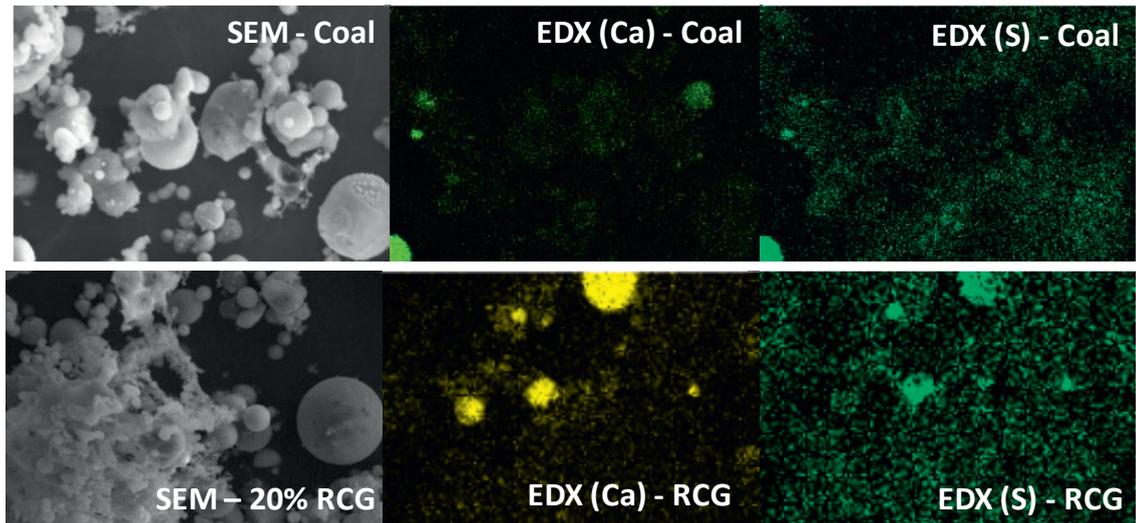


Figure 6 – Semi-quantitative identification of some elements using EDX coupled with SEM.

## Acknowledgements

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## References

- [1] IEA, Combining Bioenergy with CCS: Reporting and Accounting for Negative Emissions under UNFCCC and the Kyoto Protocol (Working Paper), International Energy Agency, 2011.
- [2] ZEP, Statigic Deployment Document II: Moving forward with CO<sub>2</sub> Capture and Storage, European Technology Platform for Zero Emission Fossil Fuel Power Plants, 2010.
- [3] APGTF, Cleaner Fossil Power Generation in the 21<sup>st</sup> Century – Maintaining a Leading Role, Advanced Power Generation and Technology Forum, 2011.
- [4] Lord, R. Biomass grown on brownfield land – a sustainable fuel source without food displacement? Technical report, (TFI Research Day), Contaminated Land and Water Centre, University of Teesside, 2011.
- [5] Nimmo W, Daood SS and Gibbs B. The effect of O<sub>2</sub> enrichment on NO<sub>x</sub> formation in biomass co-fired pulverised coal combustion, *Fuel* 2010; **89**:2945-2952.
- [6] Daood SS, Nimmo W, Edge P, Gibbs BM. Deep-staged, oxygen enriched combustion of coal, *Fuel*, 2012; **101**: 187-196.
- [7] Skeen et al., Nitric Oxide Emissions during Coal and Coal/Biomass Combustion under Air-Fired and Oxy-fuel Conditions, *Energy&Fuels*, 2010; **24**: 4144-4152.
- [8] Lu H, Ip E, Scott J, Foster P, Vickers M, and Baxter L. Effects of particle shape and size on devolatilization of biomass particle, *Fuel*, 2010; **89** (5): 1156-1168.
- [9] Bridgeman T, Darvell L, Jones JM, Williams PT, Fahmi R, Bridgewater AV et al. Influence of particle size on the analytical and chemical properties of two energy crops, *Fuel*, 2007; **86** (1-2): 60-72.
- [10] Daood SS, Javed M, Gibbs BM, and Nimmo W. NO<sub>x</sub> control in coal combustion by combining biomass co-firing, oxygen enrichment and SNCR, *Fuel*, 2012, **In press** (<http://dx.doi.org/10.1016/j.fuel.2012.06.087>).
- [11] Smart JP, and Riley GS. Use of oxygen enriched air combustion to enhance combined effectiveness of oxyfuel combustion and post-combustion flue gas cleanup. Part 1 – Combustion, *Journal of the Energy Institute*, 2012; **85** (3): 123-130.