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Journal Name

ARTICLE

On the potential for BECCS efficiency improvement through heat recovery from both post-combustion and oxy-combustion facilities

 Received 00th January 20xx,
 Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

www.rsc.org/

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In order to mitigate climate change to no more than 2°C, it is well understood that it will be necessary to directly remove significant quantities of CO₂ with bioenergy CCS (BECCS) regarded as a promising technology. However, BECCS will likely be more costly and less efficient at power generation than conventional CCS. Thus approaches to improve BECCS performance and reduce costs are of importance to facilitate the deployment of this key technology. In this study, the impact of biomass co-firing rate and biomass moisture content on BECCS efficiency with both post- and oxy-combustion CO₂ capture technologies evaluated. It was found that post-combustion capture BECCS (PCC-BECCS) facilities will be appreciably less efficient than oxy-combustion capture BECCS (OCC-BECCS) facilities. Consequently, PCC-BECCS have the potential to be more carbon negative than OCC-BECCS per unit electricity generated. It was further observed that the biomass moisture content plays an important role in determining the BECCS facility efficiency. This will in turn effect the enthalpic content of the BECCS plant exhaust and implies that exhaust gas heat recovery may be an attractive option at higher rates of co-firing. It was found that there is the potential for the recovery of approximately 2.5 GJ_{heat}/t_{CO2} at a temperature of 100°C from both PCC-BECCS and OCC-BECCS. On- and off-site applications for this recovered heat are discussed considering boiler feedwater pre-heating, solvent regeneration and district heating cases.

Introduction

The headline result of the 2015 COP¹ was an international agreement to mitigate climate change such that warming would be limited to no more than 2°C above preindustrial levels, with stated ambitions to limit the rise to 1.5°C. To achieve these targets, it will be necessary that the world is substantially net negative in terms of CO₂ emissions by the second half of the century. Achieving this goal will require the deployment of a substantial amount of negative emissions technology such that CO₂ is being removed from the atmosphere at a rate of 2 – 10 Gt_{CO2}/yr by 2050 [1]. In this context, bioenergy with Carbon Capture and Storage (BECCS) is regarded as a key technology to achieving this goal, as early indications are that it is a relatively cost-effective and deployable technology [2]. Encouragingly, there is good reason to believe that 100 – 300 EJ/yr of primary energy equivalent of biomass could be deployed by 2050, with 500 EJ/yr considered an upper bound of what might be available [3]. This is an ambitious bioenergy deployment rate of slightly more than 4 %/yr until 2050; this is not significantly beyond current global bioenergy deployment rates [4], but sustained policy support will likely be required.

BECCS in power generation

As a concept, BECCS was first suggested in the mid-1990s [5, 6], although in this instance, the concept was being proposed from the perspective of off-setting hard-to-reach emissions from, e.g., the transport sector, as opposed to a route to removing CO₂ from the atmosphere as part of a strategy for global net negative CO₂ emissions. A BECCS process would operate via the combustion of biomass in a dedicated thermal power plant or the co-firing of biomass with a fossil fuel and the subsequent capture and sequestration of the resulting CO₂ [7]. BECCS is promising on a number of levels; in addition to generating carbon negative power, the co-firing of biomass and fossil fuels has been shown to reduce CO₂ emissions at a rate slightly greater than the rate at which co-firing is increased, in addition to producing less ash, leading to reduced waste production, relative to coal combustion [8, 9]. Moreover, substitution of biomass for coal has been shown to substantially reduce both NO_x and SO₂ formation [10]. Finally, BECCS has been referred to as a kind of “benign geoengineering” [11], which if deployed at sufficient scale has the potential to reverse the effect of unmitigated CO₂ emission since the industrial revolution. However, as has been discussed previously, BECCS will be more a more costly and less efficient form of power generation than simply low carbon power generation as might be achieved via CCS [12]. For this reason, studies aimed at reducing the cost and efficiency penalty of BECCS have value.

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DOI: 10.1039/C6FD00051G

The aim of this study is to quantify the performance of BECCS facilities operating with post- and oxy-combustion capture technologies, to qualify the role that exhaust gas heat recovery might play in improving process efficiency and finally to discuss potential end uses for this recovered energy with a view to reducing the associated cost and performance penalty.

Modelling approach

Similarly to previous studies[13, 14], this work employs the Integrated Environmental Control Model (IECM)ⁱⁱ. Here, our base-case model is a 500 MW super-critical, coal-fired power station, operating at 75% of nameplate capacity and 38.9% HHVⁱⁱⁱ efficiency. The power plant was specified to use in-furnace NO_x controls, as distinct to a post-combustion SCR process. Conventional ESP and wet FGD processes were employed for standard pollution prevention and control measures. To this plant, we added CO₂ capture and evaluated both amine-based post-combustion using a 30 wt% MEA solvent and oxy-combustion. In all cases, 90% of the CO₂ arising from the power station was captured. The base fuel was a sub-bituminous coal with a HHV of 24.6 MJ/kg and 12 wt% moisture content. To this, biomass with a HHV of 20.1 MJ/kg (dry basis) was added on a constant heating value basis, i.e., the total power generated by the power station was held constant and the fuel combustion rate increased accordingly. As the biomass moisture content is a function of the biomass pre-treatment process, this was also held as a control variable and was varied between 0 and 40% by weight.

Results and discussion

The addition of CO₂ capture to the coal-fired power station (i.e., prior to biomass co-firing) reduced the efficiency to 28.3 %_{HHV} and 31.3 %_{HHV} in the case of post- and oxy-combustion capture, respectively. Here, one must note that these are highly conservative values, both in terms of base plant efficiency and also the efficiency penalty imposed by the CO₂ capture plant with, for example, similar power plants equipped with improved systems reporting efficiencies of 33.6 %_{HHV} in the case of post-combustion CCS [15].

Figure 1: carbon intensity of power generated for BECCS with post-combustion capture as a function of %CO₂ capture and %co-firing

Figures 1 and 2 illustrate the impact of biomass co-firing and %CO₂ capture on the carbon intensity (CI) of the power plant for post- and oxy-combustion capture BECCS. Two points are evident from these images. Firstly, there is a compromise between the rate of co-firing and the degree of capture if one aims to become low carbon or carbon neutral. This speaks to the possibility of BECCS plants having substantially greater flexibility in operation, relative to conventional CCS plants. Secondly, there is a small but important difference in the carbon intensity of the post- and oxy-combustion plants at the

Figure 2: carbon intensity of power generated for BECCS with oxy-combustion capture as a function of %CO₂ capture and %co-firing

same rate of capture and co-firing. Taking the extreme point as an illustrative limiting case, it can be observed that a BECCS plant with 100% CO₂ capture and 50% co-firing has a carbon intensity of -400 kg_{CO2}/MWh with oxy-combustion capture whereas in the case of post-combustion capture, the CI is further reduced to -450 kg_{CO2}/MWh. This is a result of the post-combustion plant being less efficient than the oxy-combustion plant, and consequently requiring more fuel per MWh of power produced.

Figure 3: BECCS plant efficiency with 90% post-combustion CO₂ capture as a function of biomass co-firing and biomass moisture content.

It was observed that the exhaust gas leaving the boiler was at a temperature of 370°C had a total flowrate of slightly more than 2,000 t/hr. Both the energy density and moisture content of biomass vary as a function of biomass type and pre-treatment process employed. Thus, the net efficiency of a power plant will decrease as a function of the degree of co-firing and moisture content of the biomass, as presented in Figure 3 for the case of 90% CO₂ capture using a 30 wt% MEA solvent.

Depending on biomass co-firing rate and moisture content, 120 – 190 t/hr of the total exhaust gas was water vapour. It was observed that BECCS plant efficiency declined both as a function of co-firing and moisture content, in agreement with previous work [10]. It has been shown in previous studies that heat and water recovery from power station exhaust streams is practicable to a high efficiency[16], and that the recovered

water is high quality and suitable for immediate on-site reuse[17]. Therefore, the amount of recoverable heat from the exhaust gas was next evaluated.

In recovering heat, it was unsurprising to note that cooling the

Figure 4: Energy recovered from the BECCS power station as a function of temperature.

exhaust gas such that the water in the exhaust gas condenses significantly contributed to the overall energy recovered, as shown in Figure 4.

In this scenario, it can be observed that approximately 230 MW of heat at a temperature of ~ 95°C can be recovered, with the latent heat of condensation contributing between 36 – 39% to the overall energy recovery.

Obviously, it is preferable to recover this heat at as high a temperature as possible. Thus in the remainder of this paper, all discussion is on the basis of 90% efficient heat recovery and that the exhaust gas is cooled to 95°C. Condensing the water vapour will have the added effect of further reducing SO₂ concentration in the exhaust gas, which is beneficial for the downstream gas processing equipment, for both post- and oxy-combustion capture processes.

Figure 6: The amount of heat available at 95 – 100°C per tonne CO₂ captured as a function of biomass moisture content and degree of co-firing

We then went on to evaluate the impact of heat recovery on the power plant efficiency as a function of biomass moisture content and co-firing extent. Here, it was assumed that the heat recovery process was 90% efficient. These results are

Figure 5: 90% post-combustion BECCS plant energy efficiency after heat recovery as a function biomass co-firing and moisture content.

presented in Figure 5. Firstly, it is evident that exhaust gas heat recovery has the potential to substantially improve the overall efficiency of the BECCS process relative to that without heat recovery – these results indicate that an efficiency in the range 43 – 45 %_{HHV} is possible; a substantial increase from the base case illustrated in Figure 3. Of course, this is only true if it is possible to put all this heat to some practical use – which may well not be the case, thus limiting the practical efficiency gains that may actually be obtained. Secondly, at relatively low levels of co-firing, a dry biomass would be preferred, even with heat recovery. However, as co-firing exceeds 30%, it would appear that a biomass with a relatively high moisture content would provide a greater gain in efficiency.

Finally, it is interesting to note the amount of heat that is available at 95 – 100°C available relative to the amount of CO₂ captured. This relationship is illustrated for the case of a 90% post-combustion capture plant in Figure 6.

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DOI: 10.1039/C6FD00051G

The energy recovered by condensing the water in the exhaust gas can provide between 0.77 – 1.18 GJ/t_{CO2} and the entire exhaust gas can provide 2.3 – 2.69 GJ/t_{CO2} at a temperature of approximately 95 – 100°C. This is a material quantity of energy relative to what is required to operate a conventional post-combustion capture process. For example, a 30 wt% MEA process will require approximately 3.5 GJ/t_{CO2} captured at 120°C. Of this, approximately 30% is required to provide sensible heating with the remainder being required to reverse the CO₂-MEA reaction and generate stripping steam. This balance obviously shifts as one changes the solvent used where it is possible, for example, to increase the concentration of amine.

Conclusions and implications

It is well accepted that the mitigation of climate change will require the utilisation of a very significant quantity of biomass in general and BECCS in particular.

The current power generation paradigm rightly rewards the most efficient plants; their power is the cheapest. However, in the case of a system containing a significant quantity of negative emissions technologies, the primary aim of a BECCS facility may be to remove CO₂ from the atmosphere, whilst occasionally supplying electricity to the power market in complement to intermittent renewable power sources and providing ancillary services to the grid. Thus the design problem of “construct the most efficient process for removing CO₂ from the atmosphere, whilst occasionally selling electricity” is a markedly different to that of “construct the most efficient baseload electricity generating device”, which is the current problem statement. Further, as carbon negative power generation will likely be less efficient, and thus possessed of a higher short run marginal cost, than simply low carbon power generation, it will be vital that this distinction is recognised and supported through appropriate policy instruments to enable their deployment.

As discussed, the efficiency with which BECCS plants generate electricity efficiency will be lower than even that of a CCS plant. Recovering both heat and water from the exhaust gases of BECCS power plants is a potential option to offset the increased efficiency penalty and water footprint associated with BECCS electricity.

Whilst there is a significant amount of energy available, it is not “high grade” energy, nor, however, is it “low grade”. It is available at a range of medium temperatures that could usefully be used on- or off-site. For example, this heat could be used onsite in the initial stages of the boiler feedwater pre-heating train, consequently reducing the amount of otherwise useful steam which needs to be extracted from the low-pressure steam turbine for this purpose. This is particularly important in the context of post-combustion CO₂ capture as steam is typically bled off from between the intermediate and low pressure turbines – substantially reducing the steam flow

available to the turbine, noting that the power generated per kg of steam in the low pressure turbine may well be greater than that in the high pressure turbine [18], thus this modification may have a disproportionate benefit.

Similarly, this heat could be usefully used on-site to partially off-set the energy penalty associated with solvent regeneration. A conventional 30 wt% MEA absorption process requires approximately 3.5 GJ/t_{CO2} at approximately 120 °C. Current state-of-the-art processes require approximately 2.3 GJ/t_{CO2} [19, 20], and while this information is not currently in the public domain, one assumes that the regeneration temperature is approximately 120 °C. Similarly, approximately 30 – 40% of the energy of solvent regeneration is required for the sensible heating of the solvent mixture. Via the heat recovery approach discussed in this paper, there is approximately 2.5 GJ/t_{CO2} of heat available at 95 – 100 °C. This could provide 20 – 30% of the energy required for solvent regeneration. Given that the current state-of-the-art solvents have reduced the efficiency penalty to 6 – 7%, this could further reduce this penalty to below 5%. Moreover, noting that this heat is initially available at 370°C, it would be possible to extract a portion of this heat at a higher temperature using a thermal fluid^{iv}. This concept has not been further evaluated in this study. Finally, there are novel materials [21] currently under development with the potential for a much narrower temperature swing, i.e., the sorbent could be regenerated at temperatures under 100°C and at energy costs analogous to current state of the art solvent systems. Therefore, the availability of approximately 2.5 GJ/t_{CO2} at 95 – 100 °C would significantly reduce the parasitic energy penalty normally associated with the CO₂ capture process. In this context, it is worth noting that along with this heat recovery, we would be substantially reducing the water content of the exhaust gas. In the case of OCC-BECCS, this operation would need to be performed as a matter of course as part of the GPU^v processing and the availability of exhaust gas with a lower water content, even if not completely dry, may unlock the utility of other sorbent materials for PCC-BECCS processes which do not normally perform well with high water content gases [22].

Another use to which this grade of heat could usefully be put is domestic space heating via heat networks. In many northern European countries, the heating demand is several times greater than the electricity demand – in the UK the demand for heating is approximately a factor of 5 - 6 greater than the electricity demand. Whilst the UK has a paucity of heat networks relative to the EU, the expansion of these schemes appears likely [23, 24]. Given the quantity and quality (>200 MW, ~ 100°C) of heat available, this is approximately 1,600 GWh_{Heat}/yr. Relative to UK domestic space heating requirements of 40 – 160 kWh/day during the coldest times of the year, this is sufficient energy from one, relatively small, BECCS power station to heat approximately 65,000 homes under worst case conditions. This is clearly more exergetically efficient than burning natural gas in homes for the same duty. The integration of thermal power plants has been suggested

previously [25], but from the perspective of extracting steam from the low pressure steam turbine.

Future work in this area will include performing more detailed simulations of the BECCS power plant with both post- and oxy-combustion capture technologies with a view to understanding which heat recovery and integration strategies provide most value. Subsequently a thorough techno-economic evaluation of this process with varying degrees of heat and water recovery will be performed.

Acknowledgements

The authors thank the Engineering and Physical Sciences Research Council (EPSRC) of the UK (Grant number: EP/M001369/1) for funding required to carry out this work.

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 - ii. IECM: Integrated Environmental Control Model, Available from: <http://www.cmu.edu/epp/iecm/download.8.0.2.html>.
 - iii. HHV: Higher Heating Value
 - iv. For example, Dowtherm synthetic organic heat transfer fluids
 - v. GPU: Gas Processing Unit – part of the CO₂ purification and compression process prior to transport and sequestration
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