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Thermodynamic evaluation of carbon negative power generation: Bio-energy CCS (BECCS)

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Abstract

Bio-energy with carbon capture and storage (BECCS) is an important greenhouse gas removal (GGR) technology with the potential to provide significant reductions in atmospheric CO_2 concentration. The power generation efficiency of BECCS can be improved by using heat recovered from flue gas to supply energy requirements of the solvent regeneration process. This paper assesses the influence of solvent selection and biomass co-firing proportion on recoverable heat, energy efficiency and carbon intensity of a 500 MW pulverized fuel BECCS system. The effects of (i) coal type (high and medium sulphur content), (ii) biomass type (wheat straw and clean wood chips, (iii) variable moisture content, and (iv) biomass co-firing % on AFT and emissions of SO_X and NO_X was evaluated. Compared to firing of coal alone, co-firing low moisture biomass generated higher adiabatic flame temperature. As biomass co-firing proportion increased, SO_X emissions decreased, whereas NO_X emissions increased with greater AFT. Factors that enhanced BECCS efficiency included the use of high performance solvents and higher heat recovery (higher AFT and flue gas flow rate). These results lead to the development of a performance matrix which summarizes the effect of key process parameters.

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Keywords: Bio-energy; carbon capture and storage; BECCS; heat recovery; energy efficiency; negative emissions; biomass co-firing.

Nomenclature

AFT	adiabatic flame temperature
SO_X	sulphur oxides
NO_X	nitric oxides

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HHV	higher heating value ($MJ.kg^{-1}$)
HD	solvent regeneration heat duty ($MJ.t_{CO2}^{-1}$)

1. Introduction

There is growing interest in the use of CCS and "negative emissions" technologies to achieve significant reductions in atmospheric CO_2 concentration. Bio-energy and carbon capture and storage (BECCS) was first introduced as a negative emission technology for applications in hydrogen production [1] and electricity generation [2]. Biomass is a CO_2 neutral substitute for fossil fuels, as there is a net transfer of CO_2 from the atmosphere into the growing biomass. The CO_2 from combustion is then captured and stored in geological formations, thus permanently removing CO_2 from the atmosphere and achieving an overall negative CO_2 balance [3-8]. BECCS was the most widely selected negative emissions technology selected by integrated assessment models to meet global warming temperature targets of below 2 °C set by IPCC [9], and 1.5 °C as proposed by COP21 [10]. Additional to the CO_2 emission reductions, another advantage of biomass co-combustion is the decreased emissions of SO_X and NO_X [11, 12].

In comparison with coal, biomass typically has lower heating value and high moisture content, which reduces the energy efficiency of the power plant [13]. An additional energy penalty is imposed by solvent regeneration of the CO_2 capture process [14]. Improvements to BECCS energy efficiency are necessary to reduce marginal costs of electricity generation, enabling the plant to operate at higher load factor [15, 16]. Therefore, further enhancement of BECCS performance can improve commercial viability and encourage full scale deployment of the technology.

The solvent regeneration process requires low grade heat, typically supplied in the form of saturated steam at ~3 bar [14, 17]. Steam is supplied through extraction from the power plant steam cycle, thus imposing an efficiency penalty on the system [18, 19]. To improve the energy efficiency of power generation with CO_2 capture, the following strategies have been proposed: (i) optimal location for steam extraction [20, 21], (ii) design of steam cycle retrofits [17, 22], or (iii) waste heat recovery [23].

Previous research has demonstrated that heat recovery from flue gas can be used to supply energy for solvent regeneration in the CO_2 capture process [24, 25]. The amount of recoverable heat from flue gas will depend on the point along the pollution control pathway (e.g. exit of boiler, ESP or FGD), as well as fuel type and quality [18]. The moisture content of biomass can change significantly, affecting the flue gas heat transfer rate [26], which in turn influences power plant efficiency [27]. Therefore, an extensive performance assessment of biomass-specific power systems is necessary.

To improve the energy efficiency of BECCS in this study, heat recovery from boiler exhaust flue gas has been used to supply heat for the CO_2 capture process. This paper evaluates the performance of a 500 MW BECCS system under different operating conditions (e.g. variable fuel, different capture solvents, and effect of heat recovery). The effects on combustion performance from different: (i) coal type (high and medium sulphur content), (ii) biomass type (wheat straw and clean wood chips with variable moisture content) and (iii) biomass co-firing proportion percentage was demonstrated in terms of adiabatic flame temperature (AFT) and emissions of SO_X and NO_X. The effect of solvent technology (e.g. different heat duty) and biomass co-firing proportion on the system energy efficiency and carbon intensity was evaluated. Lastly, a performance matrix was developed, summarizing the influence of key process parameters on the BECCS system performance.

2. Methodology

2.1 Power plant model and solvent selection

High and low sulphur coal, as well as high (wheat straw) and low (clean wood chips) ash biomass, with different moisture content (5% to 50%) were selected for this analysis. Table 1 summarizes the composition of these fuels.

Table 1: Fuel composition of the types of coal and biomass selected for this study.

	High sulphur coal	Medium sulphur coal	Clean wood chips	Wheat straw
Reference	[28]	[29]	[29]	[11, 30]
HHV ($MJ.kg^{-1}$ dry)	27.14	27.06	19.16	19.22
Fuel Composition	wt %	wt %	dry wt %	dry wt %
C	63.75	64.6	50	19.22
H	4.5	4.38	5.4	48.7
O	6.88	7.02	42.2	5.7
Cl	0.29	0.023	0.02	39.1
S	2.51	0.86	0.05	0.32
N	1.25	1.41	0.3	0.1
Moisture	11.12	9.5	-	-0.6
Ash	9.7	12.2	2.0	5.5
Ash compositions	% ash	% ash	% ash	% ash
SiO_2	46.8	50	43.1	56.2
Al_2O_3	18.0	30.0	8.9	1.2
Fe_2O_3	20.0	9.8	3.9	1.2
CaO	7.0	4.0	28.0	6.5
MgO	1.0	0.5	4.2	3.0
Na_2O	0.6	0.1	2.0	1.3
K_2O	1.9	0.1	5.5	23.7
TiO_2	1.0	2.0	0.4	0.06
P_2O_5	0.2	1.8	2.2	4.4
SO_3	3.5	1.7	1.8	1.1
MnO	0	0	0	1.34

Different solvent scenarios were considered:

1) High heat duty scenario (base case) using MEA with a reboiler heat duty of 3600 MJ/t_{CO2} [28], and temperature of 120°C;
2) Medium heat duty scenario using the industrial solvent Cansolv (2300 MJ/t_{CO2} at 120°C) [29,30];
3) Low heat duty scenario using a "new solvent" that operates at 2000 MJ/t_{CO2} and 80°C.

The "new solvent" heat duty is based on data for biphasic solvent, with which an overall heat duty reduction of 30% could be reached compared to MEA [31]. The heat duty of 2900 MJ/t_{CO2} is the reported achievable limits for MEA in literature [32]; thus a 30% reduction to 2000 MJ/t_{CO2} is more consistent with state-of-the-art CO_2 capture systems [33-35].

This data was incorporated in a model of an ultra-supercritical 500 MW coal-fired power plant with a 90% post-combustion CO_2 capture in the Integrated Environment Controlled Model (IECM) software [28]. IECM calculated the fuel flow rate and the power plant net power output for each solvent/fuel type/co-firing scenario, which then enabled for calculation of the power plant efficiency (% HHV) and carbon intensity (kg_{CO2} emitted per MWh generated).

2.2 Combustion reaction analysis in FactSage

A thermo-chemical analysis of coal co-combustion with biomass was performed using the software FactSage 7.0, which uses minimization of total Gibb's free energy of the system [36]. The species formed at chemical equilibrium are calculated based on the specified temperatures, pressure and composition of fuel and air [36, 37]. Table 2

summarizes the fuel blending scenarios of coal and biomass that were modelled in FactSage. For each scenario, biomass co-firing proportion was increased from 0% to 50% at increments of 5%. IECM provided data for fuel firing flow rates based on the blended fuel composition in a 500 MW ultra-supercritical power plant. The fuel flow rates in tonnes per hour was used as the mass basis in the equilibrium calculations. Complete combustion requires an excess air coefficient (λ) of 1.1–1.8 in large scale applications, and 1.5–2.0 for small scale systems, depending on the combustion technology [38]. For all combustion simulations in this study, λ = 1.3 was used to ensure complete combustion and maintain an O_2 concentration of ~5–6% in the flue gas.

Table 2: The co-firing scenarios modelled in FactSage.

Scenario	Coal type	Biomass type
A	Medium sulphur coal	Wheat straw 5% moisture
B	Medium sulphur coal	Wheat straw 16% moisture
C	Medium sulphur coal	Wood chip 5% moisture
D	Medium sulphur coal	Wood chip 50% moisture
E	High sulphur coal	Wheat straw 5% moisture
F	High sulphur coal	Wheat straw 16% moisture
G	High sulphur coal	Wood chip 5% moisture
H	High sulphur coal	Wood chip 50% moisture

Each fuel blend was simulated from 200°C to the AFT (calculated by FactSage). This subsequent flue gas mixture was cooled from the AFT to 370 °C (temperature of the flue gas at the boiler exit as predicted by IECM). The objective of the equilibrium analysis was to study the influence of biomass co-firing proportion and fuel composition on: (i) AFT, (ii) SO_X and NO_X emissions, and (iii) exhaust gas properties at 370 °C. The calculated AFT and exhaust gas properties (flow rate and specific heat capacity) were then used in the subsequent heat recovery calculations.

2.3 Heat recovery model in MATLAB

To calculate the fraction of heat duty recoverable from the boiler exhaust gases, a heat exchanger model was implemented in MATLAB, which was modelled as the association of a heater, an evaporator and a super-heater [39]. Based on the boiler exhaust gases flow rates and temperatures from the FactSage analysis, calculations were conducted for each co-firing proportion and solvent scenario.

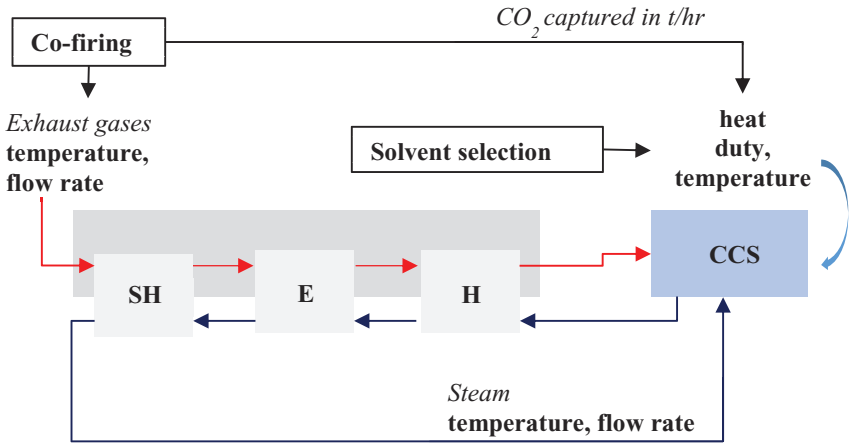


Figure 1: Overview of the heat exchanger model (SH: super-heater, H: heater, E: Evaporator).

3. Results and discussion

3.1 Adiabatic flame temperature (AFT)

The AFT can change with different fuel composition and initial temperature [40]. As demonstrated by Sami et al. (2001), increased ash content or moisture content significantly reduces AFT [41]. Figure 2 illustrates the effect of coal co-firing with different proportions of biomass on AFT. There was a general increase of AFT with higher biomass co-firing percentage. Although higher heating value (HHV) of the blended fuel reduced as biomass co-firing % increased, the fuel firing rate increased to meet the specified capacity of the power plant (500 MW).

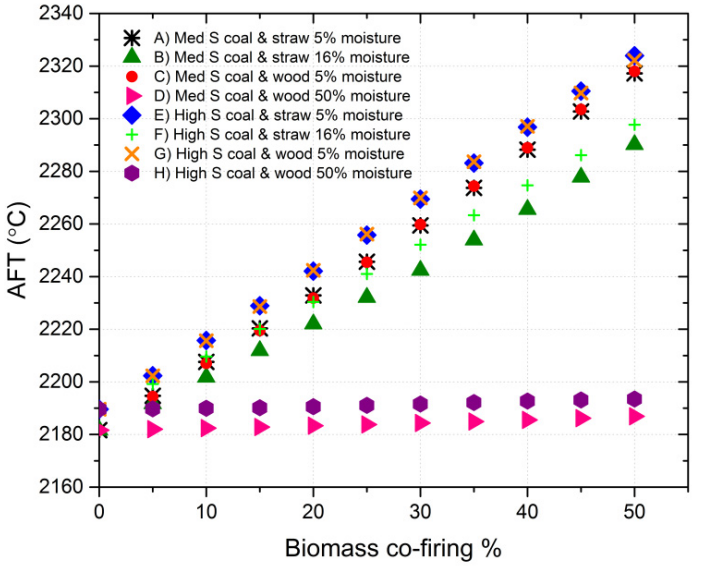


Figure 2: Adiabatic flame temperature during co-combustion of coal with biomass at different proportions.

The moisture content of biomass influenced the degree at which AFT increased. The greatest increase in AFT was achieved with the co-combustion of low moisture biomass (5% moisture by weight) with coal, where 50% co-firing increased the AFT by 136 °C (scenarios A and C of medium S coal and 5% moisture wood/straw). The 5% moisture biomass enhanced combustion performance due to having much lower moisture content compared to the two coals (9.5 wt % and 11.1 wt %). Co-firing coal with moderate 16% moisture straw also provided substantial increases to AFT (108 °C). In contrast, co-firing coal with 50% moisture biomass only increased AFT by 4–5 °C. Co-firing the same biomass with high sulphur coal generated higher AFT compared to medium sulphur coal. This is likely the result of medium sulphur coal having higher ash content compared to high sulphur coal (shown in Table 1). The observed influence of ash content and moisture content on AFT seem to concur with previous research [41].

3.2 SO_X and NO_X emissions reduction

The emissions of SO_X and NO_X are represented as mole fraction of the exhaust flue gas at 370 °C (as calculated by FactSage). Figure 3 (left) demonstrates that increasing the biomass co-firing proportion significantly reduced SO_X emissions. The SO_X emissions reductions can be attributed to the following: (i) reduction in fuel sulphur content, (ii) presence of chemical compounds in ash that can absorb SO_2 [11]. Previous research indicate SO_X emissions decrease linearly with higher biomass co-firing % [11, 12]. This linear trend is apparent for biomass co-combustion

with high sulphur coal in Figure 4 (left). The decrease in SO_X emissions is due to wood chip and wheat straw having significantly lower sulphur content compared to coal.

Figure 4 (right) demonstrates a non-linear decrease of SO_X emissions during biomass co-firing with medium sulphur coal. In the case of scenario D, SO_X emissions remain constant. At such low sulphur content, this non-linear (almost step-change) behavior may occur as the result of equilibrium reaction shifts that are concentration driven. The SO_X reaction equilibrium is also affected by the levels of alkali metal oxides in the ash, where CaO, MgO [11, 42], N_2O and K_2O [43, 44] have demonstrated an essential role in SO_X reduction.

Even with reduced nitrogen content in the fuel, NO_X emissions increased with higher biomass co-firing proportion in Figure 3 (right). The effect of biomass co-firing on NO_X emissions can vary significantly. For instance, some studies demonstrate reductions in NO_X emissions with increases to biomass co-firing % [45, 46]. In contrast, other studies co-firing biomass at significant proportions demonstrated that NO_X emissions increased [47, 48] or remain unchanged [49] compared to coal only combustion. Thus, NO_X emissions mainly depend on combustion conditions [11, 12, 47]. Due to greater AFT with higher biomass co-firing %, NO_X emissions increased proportionally. In practice, combustion conditions are controlled to minimize NO_X emissions (e.g. air staging, fuel staging) [48].

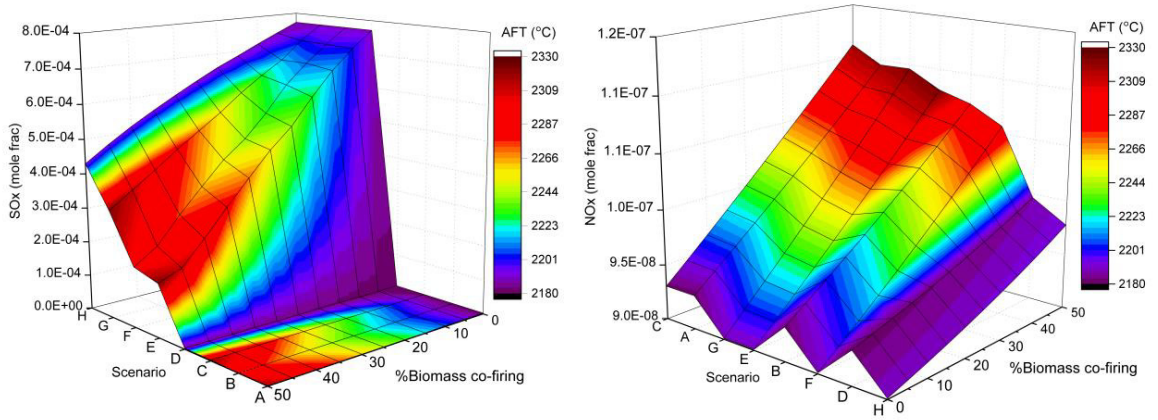


Figure 3: Emission of SO_X (left) and NO_X (right) during co-firing of coal with biomass at different proportions. Refer to table 2 for scenario information.

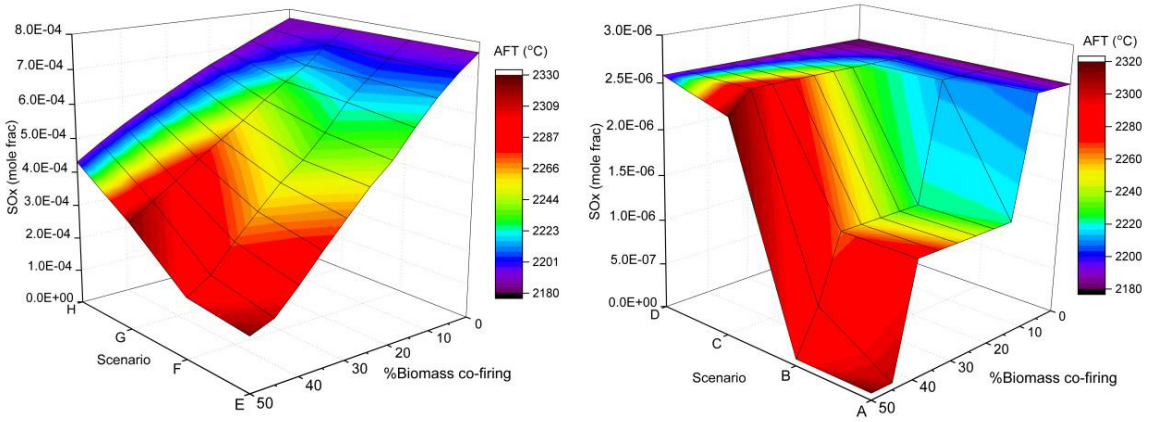


Figure 4: The SO_X emissions during combustion of high sulphur coal (left) and medium sulphur coal (right) with biomass at different co-firing proportions. Refer to table 2 for scenario information.

3.3 Recoverable heat

The heat recovery analysis was conducted for the co-combustion of high sulphur coal and wheat straw (16% moisture), with the biomass co-firing proportion varying from 0 to 50%. The fraction of heat duty compensated by heat recovery correlated against solvent heat duty and co-firing proportion is presented in figure 5.

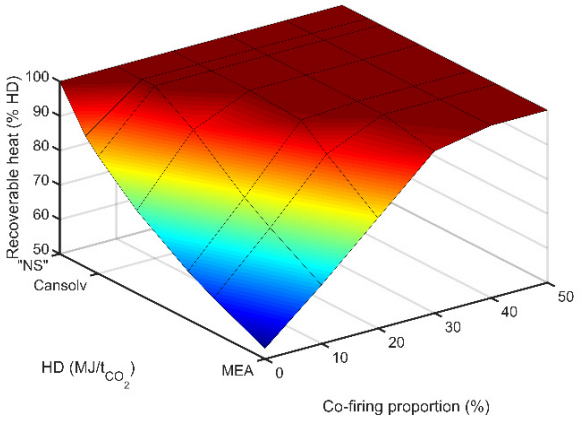


Figure 5: Fraction of solvent heat requirement compensated through recovery as a function of solvent heat duty and co-firing proportion

At 0% co-firing (*i.e.* coal only), heat recovery is only capable of supplying 100% heat duty requirements in the "new solvent" scenario. For the given power plant capacity, increasing the proportion of biomass required higher fuel firing rates (due to the lower HHV). Subsequently, an increase in biomass co-firing proportion resulted in higher exhaust gases flow rate and temperature, which in turn, increased the amount of recoverable heat. At 40% biomass co-firing or more, all of the heating requirement could be supplied through heat recovery in all three solvent scenarios.

3.4 Efficiency

By using a new solvent and heat recovery at 50% biomass co-firing, an efficiency of 38% was achieved (figure 6), which is 8% above the world average coal fired power plants [50]. This efficiency enhancement solution could potentially lift current limitations on biomass co-firing proportion.

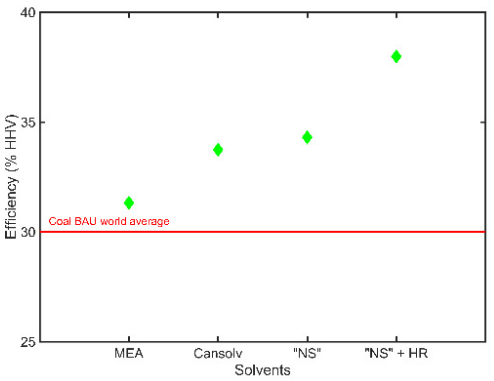


Figure 6: Efficiency in different solvent and heat recovery scenarios at 50% co-firing.

3.5 Carbon intensity

As efficiency increases however, less fuel per MWh is burned, hence less CO_2 is captured. This effect is illustrated in figure 6, which shows that power plants which are less efficient at converting fuel into electricity remove more CO_2 from the atmosphere. Hence, the low efficiency MEA system captured -295 kg CO_2/MWh at 50% co-firing, whereas the 'new solvent' combined with 100% heat recovery captured -245 kg CO_2/MWh. These counter-intuitive results underpins the importance of choosing the appropriate performance indicator – power generation efficiency or amount of CO_2 removed from the atmosphere – when evaluating BECCS performance.

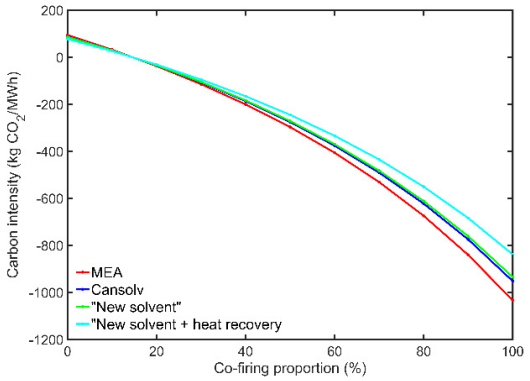


Figure 7: Carbon intensity as a function of co-firing proportion in different solvent and heat recovery scenarios

3.6 Performance matrix

The performance matrix in Table 3 demonstrates the effect of key properties on the process performance, based on the previous sections. The measure of performance in a BECCS system depends on whether the objective is to optimize: (i) efficiency, (ii) CO_2 negativity, (iii) pollutant reduction, or (iv) combination of these. To optimize the electricity generation efficiency of BECCS, the system should co-fire low ash coal with minimal proportions of low moisture biomass while using flue gas heat recovery with a high performance CO_2 capture solvent (low heat duty). Conversely, BECCS is most CO_2 negative when co-firing low quality biomass (high moisture and ash) with the least efficient CO_2 capture system (e.g. high heat duty MEA solvent). Importantly, it is assumed that the biomass is completely combusted, *i.e.*, efficient use is being made of the biomass resource. To reduce emissions of SO_X and NO_X, biomass co-firing proportion can be increased while controlling combustion conditions and using coal that is low in sulphur.

Table 3: The relationship between key properties with performance parameters in a BECCS system. * For a given power plant capacity, the combustion of a fuel with lower HHV will require higher fuel firing rates, subsequently increasing flue gas flow rate and heat recovery.

Performance parameter	Ash content	Sulphur content	Moisture content	HHV	Biomass co-firing %	Solvent heat duty
NO_X ↓			*dependent on combustion conditions*			
SO_X ↓	↑	↓	↓		↑	
AFT ↑	↓		↓		↑	
Heat recovery ↑	↓		↓	↓*	↑	↓
Efficiency ↑	↓		↓	↑↓	↓	↓
CO_2 negativity ↑	↑		↑	↑	↑	↑
Exhaust gas flow rate ↑				↓	↑	

4. Conclusion

There are different measures of power plant performance depending on whether the objective is to optimize: (i) efficiency, (ii) CO_2 negativity, (iii) pollutant reduction. In a BECCS system, factors that enhance efficiency included the use of high performance solvents (low heat duty) and higher heat recovery (higher AFT and flue gas flow rate). To achieve greater carbon negativity with BECCS, low electrical efficiency systems are more desirable; as more biomass fuel is burned, thus more CO_2 is captured and permanently stored. Lastly, to minimize pollutant emissions, increasing biomass co-firing proportion can significantly reduce SO_X emissions, whereas control of combustion conditions is required to regulate NO_X emissions. It is important to distinguish between the efficiency of power generation and the efficiency of biomass utilization. Whilst a BECCS plant which is "inefficient" at converting biomass to electricity will remove more CO_2 from the atmosphere, it is therefore a "better" GGR asset. However, a BECCS plant which is inefficient at combusting biomass (e.g. large particle size, producing a lot of char) will remove less CO_2 from the atmosphere, and is therefore "worse", both as a GGR asset and as a power plant. It will always be important to maximize the efficiency with which the biomass resource is utilized. It is therefore important to have clarity on the purpose of a BECCS facility – atmospheric CO_2 removal or power generation. As things stand, these objectives would appear to be in competition.

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