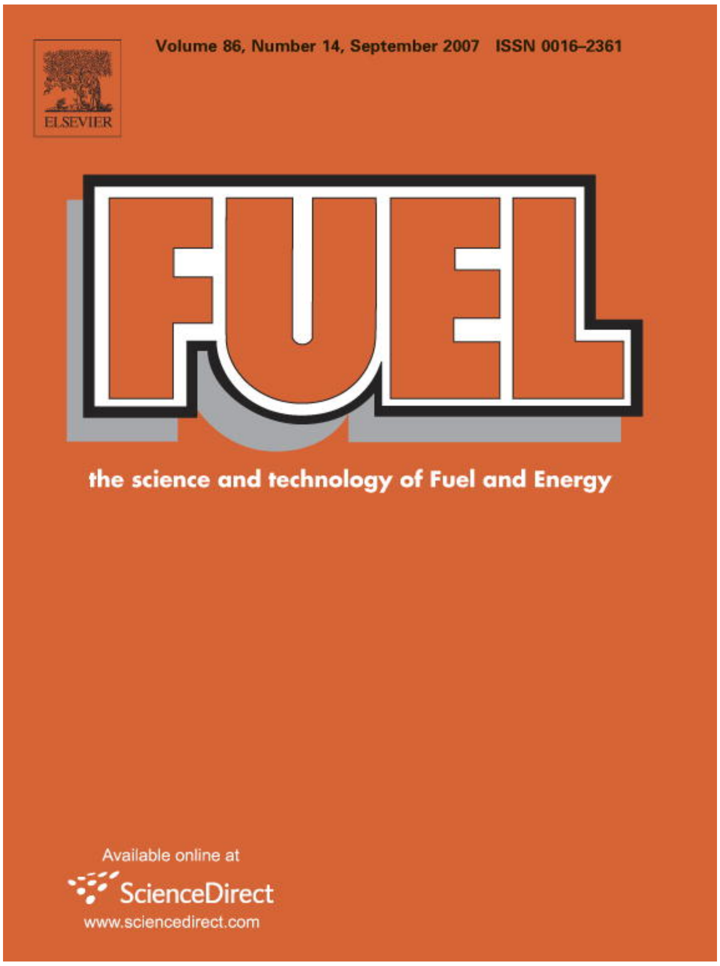
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A technical and environmental analysis of co-combustion of coal and biomass in fluidised bed technologies

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Abstract

The use of biomass, which is considered to produce no net CO_2 emissions in its life cycle, can reduce the effective CO_2 emissions of a coal-fired power generation system, when co-fired with the coal, but may also reduce system efficiency.

The technical and environmental analysis of fluidised bed technologies, using the ECLIPSE suite of process simulation software, is the subject of this study. System efficiencies for generating electricity are evaluated and compared for the different technologies and system scales.

Several technologies could be applied to the co-combustion of biomass or waste and coal. The assessment studies here examine the potential for co-combustion of (a) a 600 MWe pulverised fuel (PF) power plant (as a reference system), (i) co-firing coal with straw and sewage sludge and (ii) using straw derived fuel gas as return fuel; (b) a 350 MWe pressurised fluidised bed combustion (PFBC) system co-firing coal with sewage sludge; (c) 250 MWe and 125 MWe circulating fluidised bed combustion (CFBC) plants co-firing coal with straw and sewage sludge; (d) 25 MWe CFBC systems co-firing low and high sulphur content coal with straw, wood and woody matter pressed from olive stones (WPOS); (e) 12 MWe CFBC co-firing low and high sulphur content coal with straw or wood; and (f) 12 MWe bubbling fluidised bed combustion (BFBC), also co-firing low and high sulphur content coal with straw or wood.

In the large systems the use of both straw and sewage sludge resulted in a small reduction in efficiency (compared with systems using only coal as fuel).

In the small-scale systems the high moisture content of the wood chips chosen caused a significant efficiency reduction.

Net CO_2 emissions are reduced when biomass is used, and these are compared for the different types and scales of fluidised bed technologies. NO_x emissions were affected by a number of factors, such as bed temperature, amount of sorbent used for SO_2 capture and HCl emitted.

Keywords: Biomass; Co-combustion; Circulating fluidised bed

1. Introduction

The use of sustainably-grown biomass, which is considered to produce no net CO_2 emissions in its life cycle, can reduce the effective CO_2 emissions of a coal-fired power generation system, when co-fired with the coal, but may also reduce system efficiency.

Power generation is a major user of fossil fuels and the demand for electricity is growing steadily throughout the developed world and dramatically in the less developed countries. The replacement of all or part of these fossil fuels by renewable energy sources, such as biomass and waste, is an attractive means of reducing greenhouse gas emissions, and possibly the best (cheapest and lowest risk) renewable energy option for many power producers [1,2]. As well as the drive to use renewable resources, the co-combustion of coal and biomass has received widespread interest for some time as a means of conserving coal reserves

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and reducing net CO_2 emissions, as reported by Hein and Bemtgen [3] and Sami et al. [4]. Several other environmental advantages have been reported e.g. co-firing high-sulphur bituminous coal with 20% straw gave a net reduction in NO and SO_2 emissions [5]. Biomass and waste are also attractive because they are indigenous fuels, providing local employment and a boost to the rural economy. Conventional ways of disposing of waste, such as landfilling and dumping at sea are also becoming more difficult, more expensive and are no longer an acceptable solution.

1.1. Co-firing in practice

In practice, the technical feasibility of biomass co-firing in existing coal-fired power plants has been proved [6], even if the economics may need policy interventions to be competitive.

Co-firing up to 20% biomass with coal in utility boilers has proved successful. Results of extensive applications have shown that co-firing of biomass with coal have accomplished the following: (1) increased boiler efficiency, (2) reduced fuel costs and (3) reduced emissions of NO_x and fossil CO_2 [7].

There has been concern that the impurities in some biomasses and wastes, particularly the alkali metals and halogens, could cause operational problems with regard to slagging, fouling or corrosion. In fact it has been shown that sulphur-containing fuel, when co-fired with wood chips, could prevent the harmful formation of alkaline and chlorine compounds on boiler surfaces [8,9]. There was also concern about the disposal of the ash, particularly where limestone addition to the bed has resulted in a high calcium-content ash [10], which in normal coal combustion can be used in construction applications, and about the emission of heavy metals and toxic organic compounds.

1.2. Scope of this paper

Many of the experiments and trials have concerned co-firing in utility boilers or in existing PF power plants, designed for coal fuels. Some attention has been given to co-combustion and co-gasification of biomass and wastes in fluidised bed systems [11]. In this paper co-firing in CFBC systems of different sizes are investigated and their performance compared with each other for a range of biomass types and biomass ratios, as well as with the use of two different coals.

Co-firing in large scale CFBCs is also compared with co-combustion in other power plant technologies.

1.3. Regulations on emissions

More stringent regulations will soon come into force in Europe with regard to the emission of certain atmospheric pollutants from power plants. The EU directive 2001/80/EC [12] requires that, by January 2008, the operators of existing and new solid fuel-fired large combustion plants (>300 MWth) must comply with an emission limit value (ELV) for SO_2 of 200 mg/Nm^3 at 6% O_2. For NO_x the ELV for large combustion plants (>500 MWth) using solid fuel is set at 500 mg/Nm^3 at 6% O_2, falling to 200 mg/Nm^3 in 2016. If the solid fuel should be biomass, then the ELV is 200 mg/Nm^3. Any technology proposed for large combustion plants will need to be able to comply with this directive.

2. Methodology

General models of each technology, using coal as the fuel, were developed using the in-house ECLIPSE process simulation software package. The models were refined to incorporate the design of existing power plants and their operating conditions, usually while fuelled by coal.

Data on emissions and fuel and ash analysis were obtained from experiments conducted by EC project partners, or elsewhere, to further adapt the models for biomass and co-firing applications and to ensure that the models were realistic.

Technical and environmental (emissions) analyses of each system were carried out using ECLIPSE.

2.1. A brief introduction to ECLIPSE

To ensure that the evaluations and comparisons were performed on a consistent and reliable basis, all the processes were simulated using the ECLIPSE personal computer based process simulation package [13–15]. ECLIPSE was specifically developed for the European Commission over the period from 1986 to 1992 by the Energy Research Centre of the University of Ulster [16,17] and has been used for the techno-economic analysis for more than 20 research projects for the EC, as well as in other research.

A techno-economic study is performed in logical stages, and the first stages involve the preparation of a process flow diagram for the system to be analysed, the addition of the technical data and the completion of the converged mass and energy balance. When the mass and energy balance has been completed, the next stages involve the environmental impact analysis, capital and operating cost estimation and then the economic analysis. These analyses provide all the data required to complete the assessment study.

ECLIPSE is a powerful and convenient tool, which contains all of the program modules needed to complete rapid and reliable step-by-step technical and economic evaluations of chemical and allied processes, including mass and energy balances, capital costing and economic analyses. It is designed to be used by people with knowledge of the process to be evaluated. The programmes are written in C, but experience of C is not required. ECLIPSE uses generic chemical engineering equations and formulae and includes a high accuracy program for the steam cycle analysis. It has its own chemical industry capital costing program covering over 100 equipment types. The chemical compound properties database and the plant cost database can both be modified by the user to allow new or unusual processes to be accommodated.

3. Systems assessed

A total of 25 processes were studied in this work. Complete techno-economic analyses of these processes have been made, but only a summary of their efficiencies and emissions are given here. These are shown in Table 1, with the efficiencies and CO_2 emissions given by the computer models. All computer simulations were based on actual power plants.

The large-scale coal-fired power plants are described first of all.

3.1. PF combustion systems

The studies of a PF combustion system were based on the Amer 9 power station at Geertruidenberg in the Netherlands [18]. This is a 600 MW supercritical PF coal-fired power station with flue gas desulphurisation (FGD) [19,20].

Four processes were based around this technology, as listed in Table 1. The first (Process Number One – PN1) was the standard process as described elsewhere [21] using the standard (Federal) coal. The second process (PN2) involved replacing one level of coal burners with straw burners so that 20% of the total thermal input to the boiler could be changed from coal to chopped processed straw. No other changes were required to the process apart from balancing flows to the steam cycle and the FGD system. The third process (PN3) involved replacing one level of coal burners with sewage sludge burners so that 20% of the total thermal input to the boiler could be changed from coal to dried sewage sludge cake. Again no other changes were required to the process apart from balancing flows to the steam cycle and the FGD system.

The fourth process (PN4) was based on the use of fuel gas from a straw gasifier as a reburn fuel. Reburn technologies achieves a NO_x emission reduction of about 50% by staging the combustion within the furnace [22].

3.2. PFBC combustion systems

The first of the two PFBC processes (PN5) uses only the standard coal whereas the second process (PN6) is co-combustion of a mixture of 80% standard coal (Federal) and 20% dried sewage sludge. Both are based on a 350 MW system, the Karita Power Station New Unit 1, which started commercial operation on July 3, 2001 [23].

3.3. CFBC combustion systems

Nineteen assessment studies (PN7–PN25) were based on the CFBC systems, as tabulated in Table 1.

The superheated steam inlet conditions at the high-pressure steam turbine for the different scales of CFBC system are given in Table 2.

Table 1
Technical and environmental indicators for all systems assessed

Process number	Technology, fuel	Efficiency (%)	Total CO_2 (g/kWh)	Net CO_2 (g/kWh)
PN1	600 MWe PF, 100% Federal coal	44.0	759	759
PN2	600 MWe PF, 20% straw	43.8	773	610
PN3	600 MWe PF, 20% sewage sludge	43.8	765	765
PN4	600 MWe PF, 20% straw (reburn)	43.2	818	625
PN5	350 MWe PFBC, 100% Federal coal	41.2	783	783
PN6	350 MWe PFBC, 20% sewage sludge	41.1	792	634
PN7	250 MWe CFBC, 100% Federal coal	39.0	841	841
PN8	250 MWe CFBC, 20% straw	38.7	858	678
PN9	250 MWe CFBC, 20% sewage sludge	39.0	866	866
PN10	125 MWe CFBC, 100% Federal coal	39.0	841	841
PN11	125 MWe CFBC, 20% straw	38.7	859	678
PN12	25 MWe CFBC, Federal coal only	30.2	1107	1107
PN13	25 MWe CFBC, Federal coal + 50% straw	29.5	1163	558
PN14	25 MWe CFBC, Federal coal + 50% Wood	28.2	1266	552
PN15	25 MWe CFBC, Federal coal + 50% WPOS	29.2	1172	580
PN16	25 MWe CFBC, Bellambi coal only	30.2	1095	1095
PN17	25 MWe CFBC, Bellambi coal + 50% straw	29.6	1157	550
PN18	25 MWe CFBC, Bellambi coal + 50% Wood	28.2	1259	543
PN19	25 MWe CFBC, Bellambi coal + 50% WPOS	29.2	1166	566
PN20	25 MWe CFBC, wood only	26.5	1433	0
PN21	25 MWe CFBC, straw only	29.1	1213	0
PN22	12 MWe CFBC, Federal coal only	29.5	1132	1132
PN23	12 MWe CFBC, Federal coal + 50% Straw	28.9	1192	600
PN24	12 MWe CFBC, Bellambi coal only	29.5	1120	1120
PN25	12 MWe CFBC, Bellambi coal + 50% Straw	28.8	1182	590

Table 2
Superheated steam conditions for the CFBC systems

Plant size	Pressure (bar)	Temperature (°C)	Reheat
12 MWe	80	480	None
25 MWe	92	495	None
125 MWe	160	538	Reheat to 538 °C
250 MWe	160	538	Reheat to 538 °C

The system technologies are described more fully elsewhere, with the larger (PN7–PN11) based on the 250 MWe CFBC at Gardanne, France [24,25].

The 12 MWe (PN22–PN25) and 25 MWe (PN12–PN21) CFBCs were based on Midtkraft's 78 MWth CFBC Grenaa CHP plant in Denmark.

3.4. Fuel properties

Fuel properties play important roles in the technical performance of the power plants, so their relevant details have been given in Table 3. In this study the use of two coals, Federal and Bellambi, which have different properties is examined. Federal is high sulphur, low ash and Bellambi is a low sulphur, higher ash coal. In addition we have examined co-firing the following biomass types, wheat straw, sewage sludge, wood chip and WPOS (woody matter from olive stones).

Moisture Content has a very significant effect on system efficiency. The use of high moisture content fuels will have an adverse effect on efficiency.

4. Results of the technical and environmental analysis

The 25 processes were successfully modelled using ECLIPSE. All processes were based on models of "real" power plants, as described in Section 3, and experimental data from laboratory, pilot plant or industrial trials were incorporated into the processes.

4.1. Large scale power plants

The efficiency results of the ECLIPSE simulations for the large scale power plants are shown in Fig. 1. The CFBCs were found to have lower efficiencies (around 39%) than the other two combustion technologies (supercritical PF around 44%, PFBC around 41%), as shown in Table 1.

Also, it was found that co-firing with 20% of straw or dewatered sewage sludge caused only a small efficiency penalty, irrespective of which technology was used.

The drop in efficiency is due to the fact that straw has a higher moisture content than coal.

The gross CO_2 emissions for the supercritical PF plant were found to be about 760 g/kWh when fired with Federal coal only (Process PN1). These emissions rose only slightly when the plant was co-fired with 20% straw (PN2) or with 20% dried sewage sludge (PN3). Using reburn from 20% gasified straw (PN4), the gross CO_2 emissions rose to around 820 g/kWh. This is a knock-on effect of the higher moisture content of straw with respect to coal. The higher moisture content of straw causes a drop in efficiency and consequently an increase in CO_2 emissions.

4.2. All CFBC plants

Simulations of CFBCs at different scales were made and their LHV efficiencies for electricity generation plotted in Fig. 2.

The 250 MWe and the 125 MWe (PN7–PN11) were found to have similar efficiencies of around 39%, whereas the smaller 80 MWth (~25 MWe) and 43 MWth (~12.5 MWe) systems were only around 29% efficient (PN12–PN21 and PN22–PN25 respectively).

The simulations of the large CFBCs gave gross CO_2 emission values of 840–870 g/kWh, as shown in Fig. 3. These are typical of other current coal-fired power plants.

Gross CO_2 emissions for the smaller CFBCs were found to be quite a lot higher than those of the larger plants, typically 1100–1260 g/kWh. The plant using only wood had the highest gross CO_2 emissions (PN20, 1430 g/kWh).

If it can be assumed that the biomass used here was sustainably grown i.e. the amount used in combustion will be regrown within a short period (and take up a similar amount of carbon in regrowth), then the CO_2 output from

Table 3
Analysis of feedstocks used

Feedstock	Federal coal	Bellambi coal	Wheat straw	Wood	WPOS	Sewage sludge
Water (% ar)	6.30	6.00	14.2	33.3	13.5	4.0
Ash (% db)	6.62	13.83	4.55	0.9	10.0	21.88
HHV (MJ/kg daf)	35.64	36.18	19.90	18.73	20.89	22.94
LHV (MJ/kg daf)	34.25	35.00	18.20	17.37	19.77	21.13
Ultimate analysis (% daf)						
Carbon	84.0	87.6	48.84	51.0	52.06	53.92
Hydrogen	5.70	4.70	7.08	6.0	6.04	7.85
Nitrogen	1.50	1.90	1.28	0.1	3.59	5.06
Sulphur	2.60	0.80	0.16	<0.1	0.64	0.89
Chlorine	0.14	0.01	0.28	0	0	0.38
Oxygen	6.06	4.99	42.36	42.9	37.67	31.90

ar = as received, db = dry basis, daf = dry, ash free.

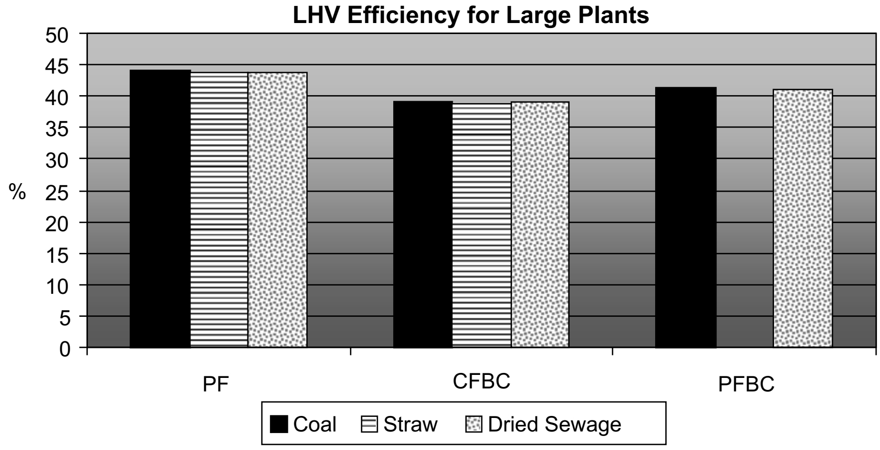

Fig. 1. A comparison of the efficiencies of some large-scale power plants (using Federal coal).

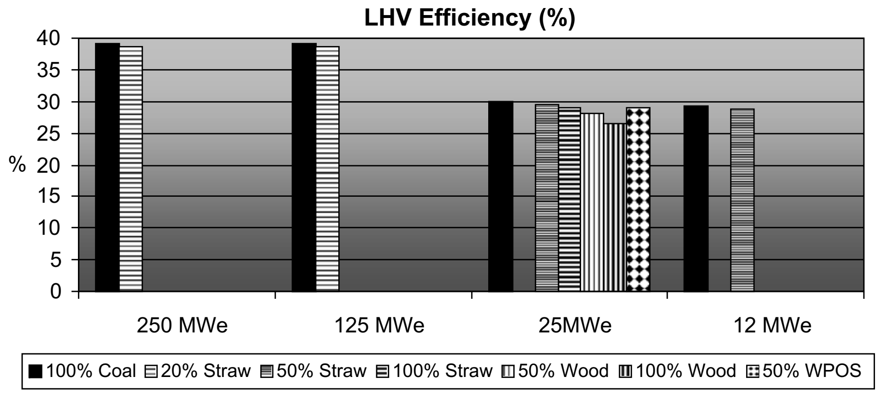

Fig. 2. A comparison of the LHV efficiencies of CFBC power plants of different scales and with different fuels (coal type: Federal coal).

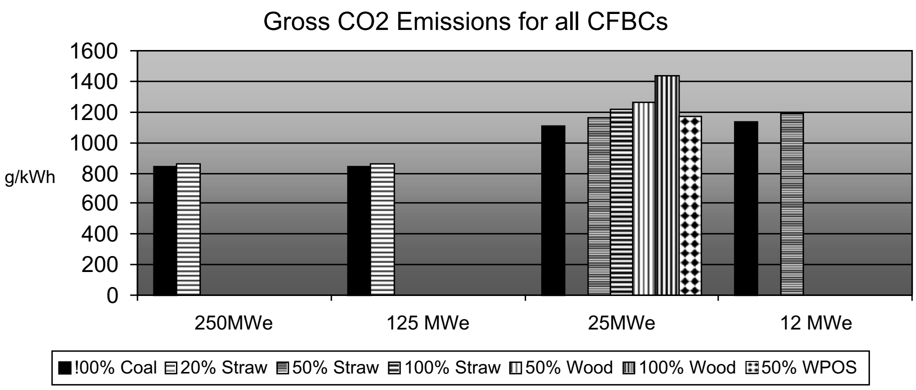

Fig. 3. Gross CO_2 emissions (g/kWh) for all CFBC power plants (using Federal coal).

biomass can be neglected. CO_2 emissions from biomass can be neglected, if the same amount of biomass is replanted as the amount combusted. The replanted biomass takes up CO_2 by photosynthesis, thus absorbing the CO_2 emitted during combustion.

This has been taken into account in Fig. 4 for the CFBC processes i.e. their net CO_2 emissions are shown.

The benefit of using such biomass, compared with "coal only" firing, on the net CO_2 emissions can be clearly seen. The net CO_2 emissions can be seen to fall considerably in all the co-firing or "biomass only" cases.

4.3. *Superheated steam conditions for all CFBCs*

The superheated steam conditions for the range of selected CFBCs were given in Section 3.3.

The 250 MWe and the 125 MWe CFBCs have the same values for their steam conditions, which are much higher

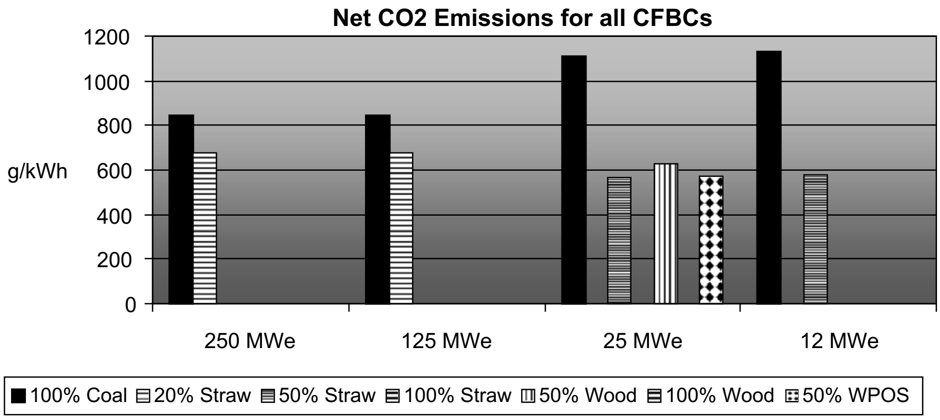

Fig. 4. Net CO_2 emissions for all CFBC power plants (using Federal coal).

than those for the smaller plants. The efficiencies of the larger plants were found to be much higher than those of the smaller plants (see Fig. 2), and the same as each other, in line with the steam conditions. The steam conditions, i.e. the temperature and pressure at the superheater, are the main determinants of the efficiency of a steam cycle. The two larger plants (250 MWe and 125 MWe) are of the same design and although one has twice the output of the other, they have the same superheated steam conditions, and so their efficiencies will be very similar.

The 80 MWth plants are only slightly more efficient than the 43 MWth plants, but their steam pressures and temperatures are only slightly higher too (see Table 2).

Higher efficiency implies lower fuel use and hence lower CO_2 emissions. The more efficient, usually larger, systems emit less CO_2, as seen in Figs. 1–4.

4.4. HCL emissions for all CFBC processes

The HCl emissions from the simulations of all the CFBC processes are shown in Fig. 5. More HCl is emitted from the large CFBCs when they are co-fired with 20% straw than when using just coal as the fuel.

The 80 and 43 MWth systems follow the same trend, with the 50% straw and 100% straw systems emitting much more HCl than the "coal only" systems.

The systems co-fired with 50% wood or 50% WPOS were found to emit less HCl than those using only coal.

If we recall the chlorine content of the fuels, as shown in Table 3, then there is a clear correlation between it and the HCl emissions. Straw has a larger chlorine content than coal, and the HCl emissions were found to be higher when co-firing with straw.

Wood and WPOS have less Cl content than Federal coal, and the HCl emissions are lower when co-firing with wood and WPOS.

4.5. SO_x emissions for all CFBC processes

The SO_x emissions resulting from the simulation of the CFBC processes are shown in Fig. 6. In general it has been assumed that the quantity of limestone added to the CFBC

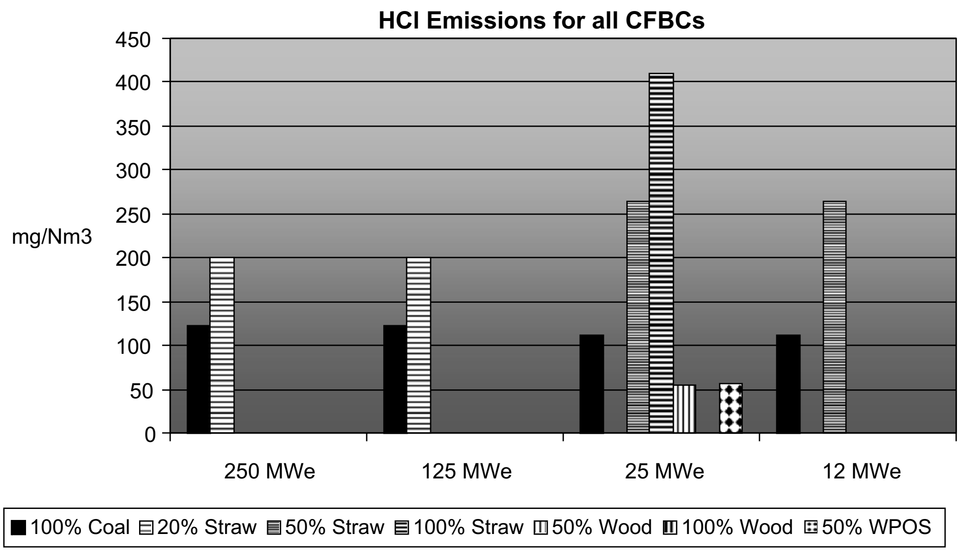

Fig. 5. HCl emissions (mg/Nm^3 at 6% O_2) for all CFBCs, using Federal coal.

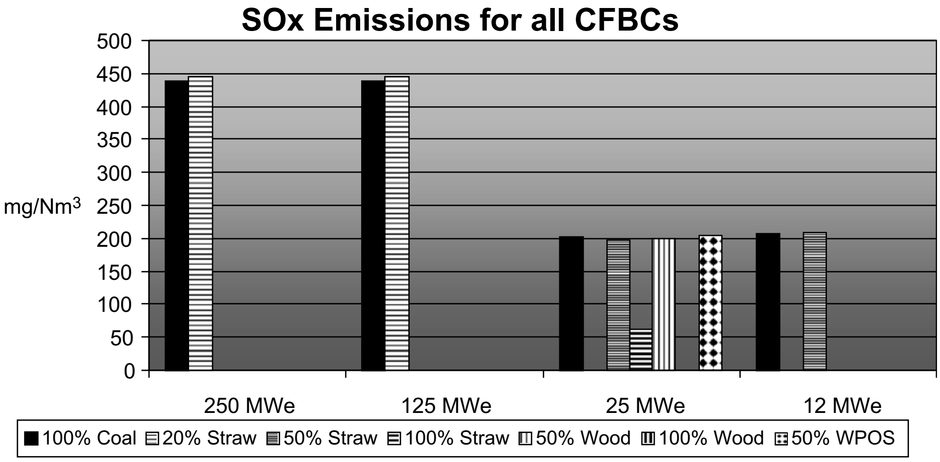

Fig. 6. SO_x emissions (mg/Nm^3 at 6% O_2) for all CFBCs, using Federal coal.

would be set in order to take up 95% of the sulphur for the "coal only" case.

For the co-firing cases, the limestone flow would be adjusted to keep the emissions similar to the "coal only" case. In fact, for the smaller CFBC systems, the limestone flow was adjusted so that the SO_x emissions complied with the EU directive 2001/80/EC ELV of 200 mg/Nm^3 at 6% O_2 (see Section 1.3).

In fact there may be a valid case for using limestone as the principle bed material as it has been successfully proven that, in a bubbling fluidised bed combustor, the limestone bed material eliminates the bed agglomeration. Also, the calcium particles, which escape from the limestone bed material and are adhered on heat exchangers, reduce the sintering of ash deposits on the tubes [26].

4.6. NO_x emissions for all CFBCs

The NO_x emissions from the simulation of the CFBC processes are shown in Fig. 7. In the large plants, the use of 20% straw results in a decrease in the NO_x emissions.

Also, for the process of co-firing with 50% straw in the smaller plants, NO_x emissions decrease compared with the "coal only" case.

NO_x emissions for the smaller plants were found to be similar for the 50% straw, 50% WPOS and 50% wood chip cases.

However, when we look at the nitrogen content of wood, straw and WPOS in Table 3, they can be seen to be very different. And, the nitrogen content of the Federal coal and the straw are similar. Therefore, it is difficult to see any correlation between the nitrogen content of the fuels and the NO_x emissions.

Liu et al. [27] stated that lower NO_x emissions may be found during co-combustion, because most of the biomass is released as volatiles, about 75% at temperatures above 800 °C, and fuel-N that exists in biomass is predominantly liberated as NH_3 which could on one hand form NO_x and but also act as reducing agent in further reactions with NO_x to form N_2. Since most of fuel-N in coal is retained in the char and is then oxidised to NO_x the NH_3 originating from biomass could lead to the reduction of NO_x. The

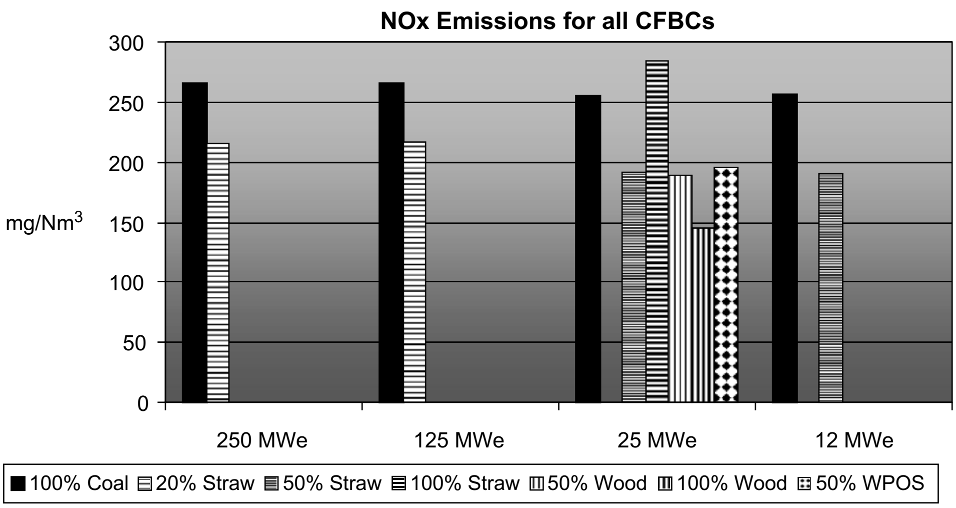

Fig. 7. NO_x emissions (mg/Nm^3 at 6% O_2) for all CFBCs, using Federal coal.

form of fuel-N released with coal volatiles is HCN which is then oxidised to form N_2O and NO_x depending on the operating conditions [28].

The presence of HCl, SO_2, limestone and fly ash and their effects on NO_x emissions are discussed in Section 4.9.

4.7. Efficiency of 80 MWth CFBC plants using either Federal or Bellambi coals

A comparison of the effect on electrical efficiency of using two different coals in the 80 MWth CFBC processes is shown in Fig. 8. The Federal coal is a high sulphur low ash coal, whereas the Bellambi coal is low sulphur, high ash.

No significant difference in the electrical efficiency of the power plant was found when using either coal, which is not surprising, given that their calorific values are similar and so are their moisture contents.

4.8. Gross CO_2 emissions of 80 MWth CFBC plants using either Federal or Bellambi coals

Since there is no difference in efficiency when either coal is used, it follows that no (significant) difference in their gross CO_2 emissions can be expected, as can be seen in Fig. 9.

4.9. NO_x emissions of 80 MWth CFBC plants using either Federal or Bellambi coals

The effect of using two different coals on NO_x emissions for the 80 MWth CFBC processes is shown in Fig. 10. NO_x emissions were found to be generally higher when the Bellambi coal is used.

The NO_x emissions have been shown to bear little direct correlation to the nitrogen content of the fuels, and could either be "thermal NO_x" i.e. depend on the temperature within the CFBC chamber, or affected by the other reactive compounds in the ash and fuels. Since biomass fuels usually contain more moisture than coal, their use reduces peak temperatures in PF systems, thus reducing NO_x emissions [1]. This could be affecting temperatures in the CFBC too. However, biomass contains a higher percentage of volatiles than coal, and so biomass particles can burn at higher temperatures in the gas phase than the bed temperature.

The NO_x emission values can also depend on whether limestone is added to the fluidised bed or not. It has been

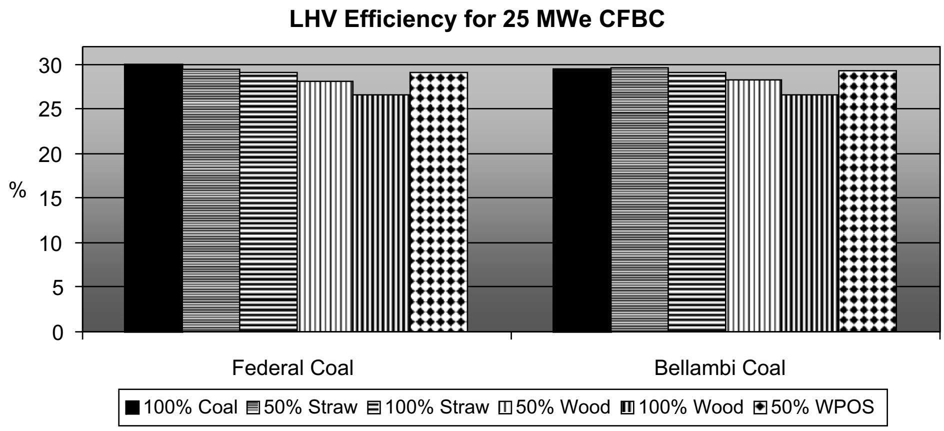

Fig. 8. The effect of different coals on the LHV efficiency.

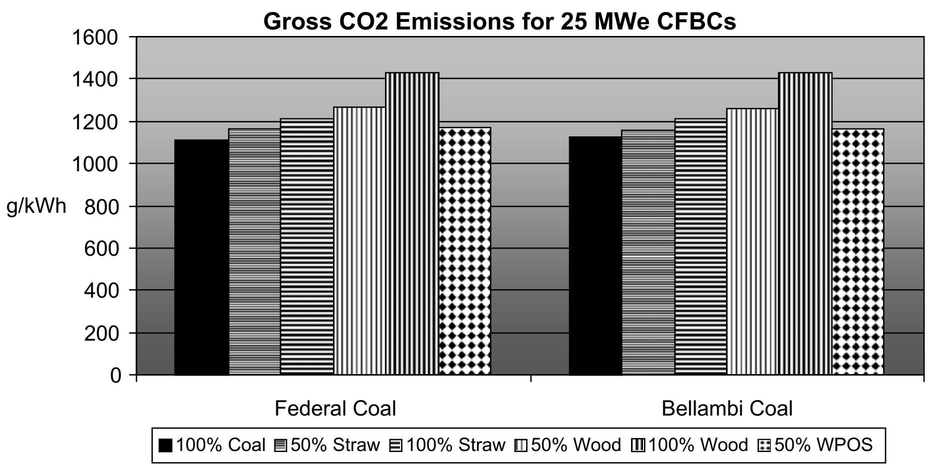

Fig. 9. The effect of different coals on gross CO_2 emissions.

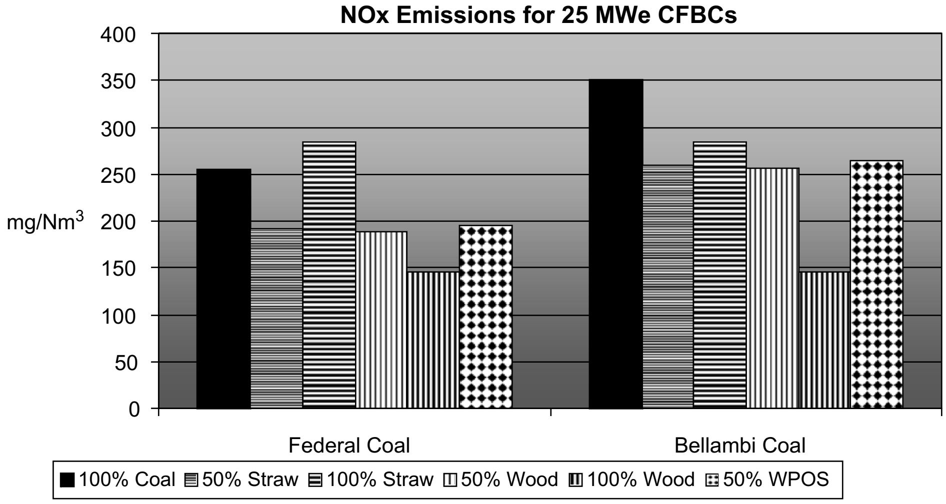

Fig. 10. The effect of different coals on NO_x emissions (mg/Nm^3 at 6% O_2).

shown that limestone use can lead to the reduction of N_2O emissions, but a rise in NO/NO_x [29]. Sulphur capture by the sorbent takes place optimally between 800 and 900 °C, so thermal NO_x is unlikely to be released from the bed.

When Federal coal is used instead of Bellambi coal, there are higher SO_2 emissions (and increased sorbent use) and higher HCl emissions, see Sections 4.10 and 4.11. It has been reported [30] that an increase in gas phase HCl emissions leads to a decrease in NO_x formation. It is suggested that the HCl interacts with the sorbent material converting the surface CaO to $CaCl_2$. Since the CaO is required as a catalyst both in the oxidation of volatile nitrogen to NO at the base of the reactor, and also in the reduction of NO by CO throughout the reactor, net NO_x formation will be inhibited (and for the same reason, SO_2 emissions increased), if CaO is converted to $CaCl_2$.

The Bellambi coal has a much higher ash content than the Federal coal and this ash could help maintain a higher temperature within the combustion chamber, so promoting thermal NO_x. The ash can also provide a catalytic surface that promotes nitrogen oxidation. It has also been suggested [31] that the sorbent decreases HCl formation in the gas phase and promotes chlorine combination with the fly ash, particularly the coarser particles, thus reducing corrosion possibilities in the combustion chamber, which are mainly caused by smaller particles.

4.10. *SO_x emissions of 80 MWth CFBC plants using either Federal or Bellambi coals*

In Fig. 11 the effect on SO_x emissions of using different coals is shown.

When the limestone feed is set to remove 95% of the entrained sulphur, then there will still be more sulphur in the system when the Federal coal is used. The Federal coal has more sulphur in it than the Bellambi coal, and the SO_x emissions are higher. The limestone flows are adjusted (i.e. reduced) for the co-firing cases to have the same SO_x emission levels as with the respective coal used.

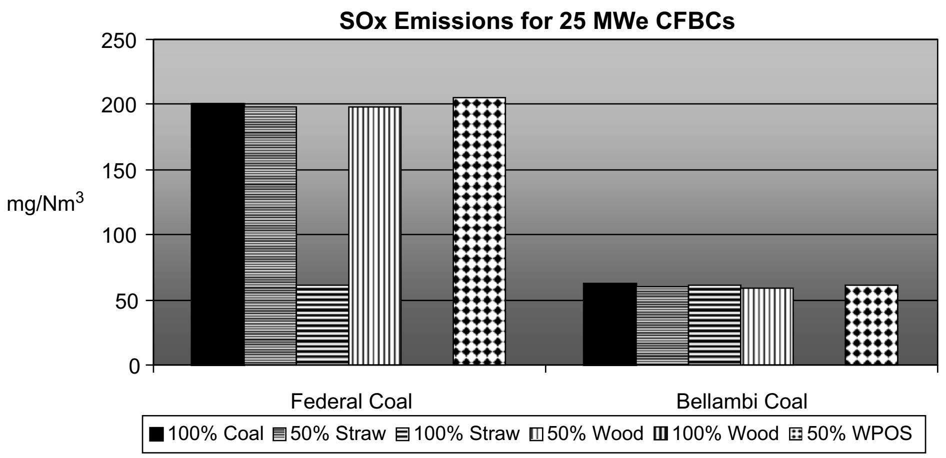

Fig. 11. The effect of different coals on SO_x emissions (mg/Nm^3 at 6% O_2).

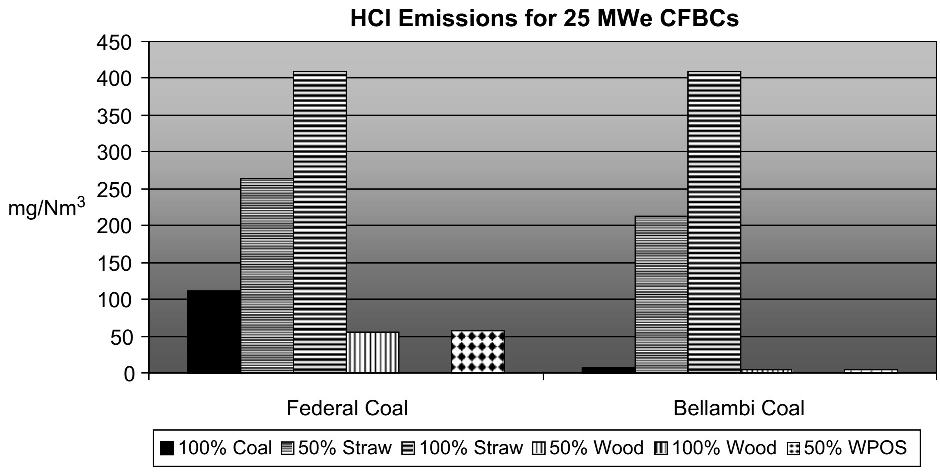

Fig. 12. The effect of different coals on HCl emissions (mg/Nm^3 at 6% O_2).

4.11. HCl emissions of 80 MWth CFBC plants using either Federal or Bellambi coals

A comparison of the effect on HCl emissions of using two different coals in the 80 MWth CFBC processes is shown in Fig. 12. The chlorine content of Federal coal is significantly higher than Bellambi coal, and this is reflected in the higher emissions of HCl whenever Federal coal is used instead of Bellambi coal.

5. Conclusions

Twenty-five processes concerned with the use of biomass in CFBC systems based on actual power plants were analysed and the results summarised here.

It has been shown that CFBC power plants of different sizes could operate effectively and efficiently with a range of biomass types and loads in co-firing applications, with lower net CO_2 emissions (compared with coal as the sole fuel), and comply more readily with EU legislation on NO_x and SO_x emissions. More specific details of these conclusions are given in the following sections.

5.1. Efficiency of CFBC processes

- Co-combustion of biomass with coal causes a slight fall in efficiency for electricity generation, compared with the "coal only" case, for all scales of power plant.
- For the large scale power plants, the CFBC systems are less efficient than the supercritical PF or PFBC plants.
- The efficiency of the CFBCs, and their CO_2 emissions, depend on the superheated steam conditions of the plant and the moisture content of the fuel. (Varying the moisture content of wood and co-firing it with coal in a bubbling fluidised bed combustor proved to have no effect on SO_2 emissions, and increased wood moisture content only slightly decreased the emissions of oxides of nitrogen [32].)

5.2. Emissions from CFBC processes

- Net CO_2 emissions decrease as the biomass ratio increases.
- HCl and SO_x emission levels are related to the chlorine and sulphur component in the fuel (although the actual SO_x emissions are controlled by absorbent use in the CFBCs). Chlorine concentration in some fuels, such as straw, could be reduced by appropriate fuel pre-treatment with water. This can also have a beneficial effect on ash fusion temperatures [33].
- No clear relationship between fuel nitrogen content and NO_x emissions was established. All processes could meet the EU directive NO_x ELV of 500 mg/Nm^3 (until 2016), but the post-2016 ELV of 200 mg/Nm^3 (see Section 1.3) was only met when biomass was co-fired with the coal (see Fig. 7).
- CFBCs can handle a range of biomass fuels. Since the emissions are generally related to the fuel properties, the type and amount of biomass can be selected to comply with emissions regulations.

5.3. Comparing the use of Federal and Bellambi coal

- There is no significant efficiency gain in choosing either coal (or variation in CO_2 emissions).
- SO_x emissions were higher when Federal coal is used, in line with its higher sulphur content.
- Similarly, the higher chlorine content of Federal coal resulted in higher HCl emissions than when Bellambi coal is used.
- NO_x emissions were found to be higher when the Bellambi coal is used (perhaps due to the much higher ash content of the Bellambi coal, and the higher HCl, SO_2

and subsequent higher sorbent use for Federal coal, which reduce NO_x).

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