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A comparison of circulating fluidised bed combustion and gasification power plant technologies for processing mixtures of coal, biomass and plastic waste

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Abstract

Environmental regulations concerning emission limitations from the use of fossil fuels in large combustion plants have stimulated interest in biomass for electricity generation.

The main objective of the present study was to examine the technical and economic viability of using combustion and gasification of coal mixed with biomass and plastic wastes, with the aim of developing an environmentally acceptable process to decrease their amounts in the waste stream through energy recovery. Mixtures of a high ash coal with biomass and/or plastic using fluidised bed technologies (combustion and gasification) were considered. Experiments were carried out in laboratory and pilot plant fluidised bed systems on the combustion and air/catalyst and air/steam gasification of these feedstocks and the data obtained were used in the techno-economic analyses.

The experimental results were used in simulations of medium to large-scale circulating fluidised bed (CFB) power generation plants. Techno-economic analysis of the modelled CFB combustion systems showed efficiencies of around 40.5% (and around 46.5% for the modelled CFB gasification systems) when fuelled solely by coal, which were only minimally affected by co-firing with up to 20% biomass and/or wastes. Specific investments were found to be around \$2150/kWe to \$2400/kWe (\$1350/kWe to \$1450/kWe) and break-even electricity selling prices to be around \$68/MWh to \$78/MWh (\$49/MWh to \$54/MWh). Their emissions were found to be within the emission limit values of the large combustion plant directive.

Fluidised bed technologies were found to be very suitable for co-firing coal and biomass and/or plastic waste and to offer good options for the replacement of obsolete or polluting power plants.

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1. Introduction

1.1. Co-firing and combustion

The co-combustion of coal and biomass has received widespread interest for some time as a means of conserving coal reserves and reducing net CO_2 emissions, as reported by Hein and Bemtgen [1] and Sami et al. [2]. 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 [3]. Liu et al. [4] 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 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 [5].

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The primary reactions of thermal decomposition of biomass fuels are not significantly affected by the presence of coal, which itself does not seem to be influenced by the release of volatile matter from biomass [6]. Comparisons have also been made between a small CFBC fuelled solely by biomass and a large CFBC co-fired with 8% biomass and 92% coal. The latter system performed better on all the usual indicators such as electrical efficiency, emissions reduction, specific investment and break-even electricity selling price [7].

1.2. Co-firing and gasification

Co-gasification of biomass with coal has also received attention, as it has other advantages, in addition to fossil fuel conservation and CO_2 emission reduction. For example, in Pan et al. [8,9] studies of co-gasification of pine chips with poor coal in a continuous fluidised bed reactor using an air–steam mixture, the coal alone had an organic fraction too low to support auto-thermal gasification, but the addition of biomass, with its high volatile matter content, effected synergies which make this co-gasification an attractive and economic option for the use of poor coals.

1.3. Financial incentives for co-firing biomass

More recently there have been further financial incentives for co-firing, such as the requirements for increasing the percentage of electricity generated from renewable sources, carbon taxes, the increasing cost of gate fees at landfill sites and the ban on putrescible wastes going to landfill. In addition, as industrialisation increases, so will the amount of various waste materials and the environmental problems associated with their disposal. Ekmann et al. [10] reported that energy recovery from waste may be an economically attractive source of energy as part of an integrated waste management plan.

1.4. Co-firing plastics

Although there is legislative pressure to recycle more plastic, there will still be a need for thermal treatment of waste plastic. Williams and Williams [11] showed that fluidised bed pyrolysis of waste plastic could provide oil and wax feedstock for the production of new plastics or refined fuels, or at higher temperatures, a range of gases such as hydrogen, methane, ethane and propane. The high calorific content and low moisture content of the major waste plastics make them attractive options for co-combustion or co-gasification. PVC or other chlorinated hydrocarbons should be avoided, however, in order to reduce the possibility of significant dioxin or furan emissions [12].

1.5. 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 [13] 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. {There is a dispensation of 20,000 h operation between January 2008 and December 2015 for non-compliers.} The ELV for SO_2 resulting from the gasification of coal has not yet been set. 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.

1.6. Scope of this study

In this study co-firing of a high ash coal with 20% (by thermal input) biomass, plastic or plastic/biomass mixture using fluidised bed technology was considered. Fluidised bed technologies are considered to be “fuel flexible”, so that they can handle a wide range of solid biomass and plastics. However, in this case, only relatively small percentages of the plastic and biomass were mixed with coal, as they would be appropriate in terms of availability and effect on altering the configuration of large-scale power plants.

As well as co-combustion, two forms of co-gasification (air–steam and air–catalyst) were assessed. Experiments on the co-firing of these mixtures were carried out and the results used in process simulation software to model power plants employing fluidised bed technology. Technical, environmental and economic analyses of the modelled systems were made in order to assess their efficiency, emissions and economic performance.

This study is based on the work in contract ECSC 7220-PR/089 in the ECSC Coal Research Programme (see Acknowledgements) in which a wide range of mature and current technologies, such as rotary kiln, moving or fixed bed, as well as bubbling or circulating fluidised bed, were assessed and compared for their suitability for co-firing coal with wastes. It concluded that circulating fluidised bed technologies would have the potential of coping very well with fuel mixtures of coal, biomass and/or plastic selected in the project. This viewpoint is supported in the literature by Grundy and Lilley [14], although CFBC accounts for only a small amount of the co-firing capacity in the UK, since all existing large UK coal-fired power stations use PF combustion technology.

2. Experimental work

2.1. Experimental work

Experiments were carried out at CIEMAT to investigate the combustion, at INETI on the steam/air gasification and at the University of Saragossa on the air/catalytic gasification of the fuel combinations.

2.2. Techno-economic analysis

The University of Ulster produced computer simulations of 250–300 MWe circulating fluidised bed power plants using the experimental data mentioned above, and carried out technical, environmental (emissions) and economic analyses of these proposed plants using the ECLIPSE process simulation software [15].

2.3. Fuel analysis

The ultimate, proximate analyses and calorific values of the fuels used both in combustion and gasification tests are shown in Table 1.

The Puertollano coal, which was used in these investigations, had a high ash content (32.5%, as received) and relatively high sulphur content (1.29%, dry ash free). The biomass was in the form of pine residues, with low ash and negligible sulphur content. Moisture content for both was found to be low (5.5% ar and 10.7% for coal and biomass respectively). The plastic investigated (polyethylene) has no ash or moisture content. The “as received” (ar) calorific values of the biomass and plastic were found to be higher than that for the selected coal.

2.4. Combustion

2.4.1. Circulating fluidised bed combustion pilot plant at CIEMAT

The experimental research programme on combustion was performed at the Circulating Fluidised Bed pilot plant at CIEMAT [16].

2.5. Gasification

2.5.1. Experiments at the University of Saragossa

The University of Saragossa gasifier facility is an atmospheric pressure bubbling fluidised bed reactor which uses a fluidised medium consisting of silica sand mixed with calcined dolomite, followed by two high-efficiency cyclones connected in series for particulate collection. Descriptions of the facilities and typical experimental procedures are described elsewhere [17–21].

Table 1
Fuel analysis

	Coal feedstock	Biomass	Plastic
	Puertollano coal	Pine residues	Polyethylene
Proximate analysis (% w/w)			
Volatiles	24.9	72.6	n/a
Fixed carbon	37.3	16.2	n/a
Moisture	5.5	10.7	n/a
Ash	32.3	0.5	n/a
Total	100	100	n/a
Ultimate analysis (% daf)			
C	77.33	51.57	85.70
H	5.31	4.94	14.30
N	1.93	0.90	0.00
S	1.29	0.00	0.00
O	14.15	42.58	0.00
Total	100.00	100.00	100.00
Calorific values (MJ/kg)			
HHV (ar[a])	19.06	20.20	46.12
LHV (ar[a])	18.21	19.01	43.04
HHV (daf[b])	30.64	22.75	46.12
LHV (daf[b])	29.28	21.41	43.04

[a] As received.

[b] Dry and ash free.

2.5.2. Experiments at the INETI facilities

INETI has two fluidised bed gasification installations, one at bench scale and the other at pilot scale in which air–steam gasification of biomass, plastic and co-gasification of coal with biomass and plastic wastes have been studied [22,23]. The bench-scale gasification installation is chosen for the first gasification tests of a new feedstock, to identify and solve any technical problems arising from the feeding of a new system and to analyse the effect of experimental parameters on gasification performance. Afterwards, some experimental work is done in the pilot scale installation to optimise the gasification process and to evaluate any scale-up effects. In general and apart from small variations, it was found that lab-scale and pilot installations showed similar tendencies and results, whenever equivalent experimental conditions are used. The details of the experimental work used in this study have been reported elsewhere [24].

2.5.3. Differences between the steam gasification (INETI) and the air gasification/dolomite catalyst (Saragossa) systems

Both INETI and University of Saragossa studied co-gasification of mixtures of coal, biomass and plastic wastes. Although different experimental installations were used, the operating conditions were similar. The main difference was that the University of Saragossa used only air as the gasifying agent, while INETI used mixtures of air and steam. No catalyst was used in INETI gasification experiments, but the University of Saragossa used a mixture of silica sand and dolomite (20–30 wt.%), a well-known catalyst for gasification reactions. Despite the differences in the nature of installations used by INETI and the University of Saragossa, the overall effect of varying the experimental parameters was similar in both installations, so that almost identical tendencies were attained, but the gas composition was somewhat different (see Tables 5 and 8). The gasification at INETI produced a gas with a higher concentration of H_2, due to the presence of steam, whereas the gasification at the University of Saragossa resulted in a gas with a higher fraction of CO, CO_2 and a lower hydrocarbon concentration than the gas produced at INETI, due, probably, to the use of more air and the effect of tar cracking by the dolomite.

3. Results

3.1. Combustion

3.1.1. Combustion technical data

The results of the technical data from the ECLIPSE simulations of the CFBC systems with different fuel inputs are shown in Table 2.

Table 2
Technical and emissions data for the proposed CFBC systems with different fuel mixtures

Fuel mixture (with Puertollano coal)	100% coal	20% biomass and 80% coal	20% plastic and 80% coal	10% biomass, 10% plastic, and 80% coal
Coal type		Puertollano	Puertollano	Puertollano
Excess air	20%	20%	20%	20%
Steam cycle	160 bar/538C	160 bar/538C	160 bar/538C	160 bar/538C
Reheat	Yes	Yes	Yes	Yes
Electrical usages (kW)				
FD fans (3)	7095.3	6369.8	6857.1	6613.2
ID fan	2484.8	2393.2	2439.7	2416.2
Slag outlet	108.8	92.9	92.9	92.9
Bag filter	5.7	4.9	4.9	4.9
Coal crusher	161.8	135.0	135.4	134.9
Conveyors (4)	1494.8	1564.7	1452.9	1561.9
HP and LP pump	6255.4	6241.5	6251	6246.4
Elect. utilities	3135.5	3128.44	3133.4	3131
Total usages	20,742.1	19,930.4	20,367.3	20,201.3
Electricity generated and efficiency				
HP turbine	69,171	69,015.6	69,123.3	69,070.8
LP turbines (4)	114,864.4	114,606.2	114,785.1	114,697.8
IP turbines (3)	95,607.4	95,392.3	95,541.4	95,468.8
Gross electricity	279,642.8	279,014.1	279,449.8	279,237.4
Net electricity	258,900.7	259,083.7	259,082.5	259,036.1
Thermal input LHV	640.00	640.00	640.00	640.00
Thermal input HHV	669.9	671.9	673.1	672.5
Efficiency, LHV	40.45	40.48	40.48	40.47
Efficiency, HHV	38.65	38.56	38.49	38.52
Gaseous emissions				
CO_2 (g/kWh)	874.5	854.7	828.1	841.5
CO_2 at 6% O_2 (mg/Nm^3)	239,944	244,115	231,295	237,618
SO_2 at 6% O_2 (mg/Nm^3)	243	250	246	257
NO_x at 6% O_2 (mg/Nm^3)	340	352	345	348
CO at 6% O_2 (mg/Nm^3)	59.9	62.3	60.9	61.6
O_2 (dry) (vol.%)	4.04	4.02	4.09	4.06

Table 3
Economic data for the proposed CFBC systems with different fuel mixtures (costs in $M)

Fuel mixture (with Puertollano coal)	100% coal	20% biomass and 80% coal	20% plastic and 80% coal	10% biomass, 10% plastic, and 80% coal
Coal reception & storage	22.42	18.35	18.35	18.35
Other feedstock R&S	0.00	12.86	2.96	10.23
Limestone R&S	2.03	1.69	1.69	1.68
Coal milling & storage	8.47	6.98	6.98	6.98
Coal drying	0	0	0	0
Coal feeding	4.37	3.73	3.73	3.73
Other feedstock P&F	0.00	3.60	0.83	2.86
Subtotal	37.29	47.22	34.54	43.84
Ash/slag handling	5.60	4.79	4.77	4.78
Bag filter	4.09	3.95	4.06	4.00
CFBC	147.28	143.64	146.36	145.00
CFBC HRSG	27.67	26.99	27.50	27.24
Subtotal	184.64	179.36	182.69	181.02
Steam turbine	82.52	82.40	82.49	82.44
Steam system & condenser	23.70	23.64	23.68	23.66
Cooling water	10.57	10.55	10.56	10.55
Water treatment	7.94	7.92	7.93	7.93
Chimney	3.45	3.36	3.43	3.39
Subtotal	45.65	45.47	45.60	45.54
Total	350.10	354.45	345.32	352.84
$/kWe	1352.2	1368.1	1332.9	1362.1
BESP[a] ($/MWh)	52.35	50.71	49.09	50.47

[a] Plastic cost = $21.90/tonne.

3.1.2. Combustion economic data

The economic data produced from the ECLIPSE simulations of the CFBC power plants are shown in Table 3.

3.1.3. Caveat on economic assessments

Whilst every effort is made to validate the capital cost estimation data, see Table 4, by using published information and actual quotations from equipment vendors, the absolute accuracy of this type of capital cost estimation procedure has been estimated at about ±25–30%. However, although the absolute accuracy of a single cost estimate may be only ± 25–30%, families of similar technologies, composed of similar types of equipment, are compared in these studies. Therefore, the comparative capital cost estimates should be valid, since they are based on the accurate calculation of a difference in a basic design by the mass and energy balance programme.

3.2. Gasification

3.2.1. Air–steam gasification

The data shown in Table 4 show the gas composition resulting from the air–steam gasification experiments performed at INETI.

Table 4
Gas composition (air–steam gasification experiments performed at INETI)

Gas composition (% volume/volume)				
Fuel mixture (with Puertollano coal)	100% coal	20% biomass and 80% coal	20% plastic and 80% coal	10% biomass, 10% plastic, and 80% coal
CO_2	26.5	24.9	22	24.7
CO	19.4	23.3	15.2	20
H_2	45	42	37.2	41
CH_4	7.4	7.5	13.5	9.2
C_2H_6	1.7	2.3	12.1	5.1
Char production ratio (g/g daf)	480	350	350	350
Gasifier temperature (°C)	846	846	845	846
Carbon loss in the ash (%)	8	7.7	7.7	7.2

3.2.2. Technical and economic simulation of air–steam gasification power plant

The data in Tables 5 and 6 were obtained from the ECLIPSE simulation of air–steam gasification of the coal, biomass and plastic feedstocks used in an 860 MWth IGCC power plant with a circulating fluidised bed gasifier described earlier. Table 5 shows the principal Technical Data, and Table 6 summarises the main Economic Data.

3.2.3. Air–catalyst gasification

The results shown in Table 7 show the gas composition found in the air–catalyst experiments performed at the University of Saragossa.

The optimal gasifier operating conditions depend on the purpose for the exit gas, e.g. for use in a gas turbine or in a gas engine. In general, a high hydrogen content and heating value, low char yield and tar content, and a high gas yield are desirable. A bed temperature of 850 °C and an equivalence ratio of 0.36 were found to be the best values to achieve this, regardless of feedstock mixture.

The main problem for the gasification process is the tar content of the exit gas. The injection of secondary air into the freeboard was found to reduce the tar content by 50%. Tar contents below 0.5 g/Nm^3 could be achieved, so that a quite clean gas can be obtained.

Table 5
Technical and emissions data for the proposed CFBG system (using air–steam gasification) with different fuel mixtures

INETI IGCC	100% coal	20% biomass and 80% coal	20% plastic and 80% coal	10% biomass, 10% plastic, and 80% coal
Feedstock HHV (MW)	863.40	862.82	863.01	863.22
Feedstock LHV (MW)	824.91	822.28	821.34	822.10
Coal input (kg/s daf)	28.18	23.46	23.47	23.48
Biomass input (kg/s daf)	–	6.34	–	3.17
Plastic input (kg/s daf)	–	–	3.12	1.56
AUX 1 (MW)	10.80	10.80	10.80	10.80
AUX 2 (MW)	4.25	4.38	4.47	4.29
Air compressor (MW)	205.88	193.88	196.39	194.94
Gas turbine output (MWe)	236.92	231.54	227.77	229.52
Steam turbine output (MWe)	158.00	161.62	161.20	160.05
Net electricity production (MWe)	379.9	378.0	373.7	374.5
Overall plant efficiency (%) — HHV	44.00	43.81	43.30	43.38
Overall plant efficiency (%) — LHV	46.05	45.97	45.50	45.55
CO_2 (g/kWh)	727	721	696	707
NO_x, at 6% O_2 (mg/Nm^3)	176	184	169	175
SO_x, at 6% O_2 (mg/Nm^3)	183	158	156	158

Table 6
Economic data for the proposed CFBG system (using air–steam gasification) with different fuel mixtures (INETI)

Feedstock	100% coal	20% biomass and 80% coal	20% plastic and 80% coal	10% biomass, 10% plastic, and 80% coal
Coal recp. & storage	28.3	24.4	23.9	24.1
Other feedstock R&S	0.00	5.20	3.16	4.23
Limestone R&S	1.7	1.7	1.7	1.7
Coal milling & storage	10.3	10.2	9.4	9.8
Coal drying	0.0	0	0	0
Coal feeding	12.6	11.4	11.2	11.3
Other feedstock P&F	0.00	3.45	2.10	2.81
Subtotal	52.9	56.2	51.5	53.9
Gasifier	53.9	53.5	49.5	51.5
Syngas cooler	23.3	23.9	22.9	23.7
Ash/slag handling	8.3	7.9	7.9	7.9
Convective heat transfer	0.0	0	0	0
Filter/cyclone	19.9	20.3	18.1	19.2
Cold gas cleaning	0.0	0	0	0
Fuel gas saturation	0.0	0	0	0
Gas/gas reheating	0.0	0	0	0
Subtotal	105.4	105.5	98.4	102.2
Gas turbine	107.5	106.3	105.4	105.8
GT HRSG	35.1	33.8	33.7	33.5
In bed HRSG	67.8	67.8	64.4	62.1
Steam turbine	58.7	59.4	59.3	59.1
Steam system & cond	16.1	16.3	16.3	16.2
Cooling water	5.8	5.9	5.9	5.9
Water treatment	27.4	28.3	25.4	26.2
Bag filter	0.0	0	0	0
Chimney	5.5	5.3	5.3	5.3
Subtotal	324.0	323.1	315.8	314.1
Total ($M)	482.3	484.9	465.6	470.3
Specific investment ($/kWe)	1269.6	1282.8	1246.0	1255.7
BESP[a] ($/MWh)	42.07	41.9	40.21	40.9
BESP[b] ($/MWh)			39.57	40.58
BESP[c] ($/MWh)			38.53	40.26

Note: (Costs in $M).
[a] Plastic cost = $21.90/tonne.
[b] Plastic cost = 0.
[c] Plastic cost = gate fee of $21.90.

3.2.4. Eclipse simulation results for power plants based on air–steam gasification technology

The data in Tables 8 and 9 were obtained from the ECLIPSE simulation of air–catalyst gasification of the coal,

Table 7
Gas composition (air–catalyst experiments performed at the University of Saragossa)

Gas composition (%, volume/volume)				
Feedstock mixture	100% coal	20% biomass and 80% coal	20% plastic and 80% coal	10% biomass, 10% plastic, and 80% coal
CO_2	31.9	31	33.5	36.7
CO	34.7	35.2	30.6	25.3
H_2	30.6	28.5	29.4	34.6
CH_4	1.7	4.2	5.1	2.2
C_2H_6	1.1	1.1	1.5	1.2
Char production ratio (g/g daf)	135	133	147	144
Gasifier temperature (°C)	850	850	850	850
Carbon loss in the ash (%)	7.2	6.3	7.5	6

biomass and plastic feedstocks used in an 860 MWth IGCC power plant with a circulating fluidised bed gasifier described earlier. Table 8 shows the principal Technical Data, and Table 9 summarises the main Economic Data.

Table 8
Technical and emissions data for the proposed CFBG system (using air–catalyst gasification) with different fuel mixtures

Saragossa IGCC	100% coal	20% biomass and 80% coal	20% plastic and 80% coal	10% biomass, 10% plastic, and 80% coal
Feedstock HHV (MW)	863.42	863.42	862.99	862.98
Feedstock LHV (MW)	824.93	822.85	821.32	821.87
Coal input (kg/s daf)	28.18	23.48	23.47	23.47
Biomass input (kg/s daf)	–	6.34	–	3.17
Plastic input (kg/s daf)	–	–	3.12	1.56
AUX 1 (MW)	10.80	10.80	10.80	10.80
AUX 2 (MW)	5.06	5.00	5.07	5.28
Air compressor (MW)	201.41	202.42	198.40	191.59
Gas turbine output (MWe)	184.43	190.38	183.03	172.86
Steam turbine output (MWe)	214.61	211.29	214.14	224.51
Net electricity production (MWe)	383	386	381	381
Overall plant efficiency (%) — HHV	44.38	44.69	44.18	44.18
Overall plant efficiency (%) — LHV	46.45	46.89	46.43	46.39
CO_2 (g/kWh)	769	753	739	756
NO_x, at 6% O_2 (mg/Nm^3)	177	166	161	165
SO_x, at 6% O_2 (mg/Nm^3)	178	154	151	150

Table 9
Economic data for the proposed CFBG system (using air–catalyst gasification) with different fuel mixtures (Saragossa)

Feedstock	100% coal	20% biomass and 80% coal	20% plastic and 80% coal	10% biomass, 10% plastic, and 80% coal
Coal recp. & storage	28.3	24.4	23.9	24.1
Other feedstock R&S	0.00	5.20	3.16	4.23
Limestone R&S	6.0	6.0	0.5	0.5
Coal milling & storage	11.7	11.6	9.1	9.4
Coal drying	0.0	0.0	0.0	0.0
Coal feeding	14.0	12.8	10.8	10.9
Other feedstock P&F	0.00	3.45	2.10	2.81
Subtotal	60.0	63.4	49.5	52.0
Gasifier	61.0	60.6	47.5	49.5
Syngas cooler	20.0	20.6	20.3	20.5
Ash/slag handling	8.8	8.4	8.4	8.4
Convective heat transfer	0.0	0.0	0.0	0.0
Filter/cyclone	20.6	19.3	19.6	20.5
Cold gas cleaning	0.0	0.0	0.0	0.0
Fuel gas saturation	0.0	0.0	0.0	0.0
Gas/gas reheating	0.0	0.0	0.0	0.0
Subtotal	110.4	108.9	95.8	99.0
Gas turbine	94.5	96.1	94.1	91.3
GT HRSG	37.3	37.6	36.7	36.2
In bed HRSG	97.3	89.7	97.5	114.0
Steam turbine	69.8	69.1	69.7	71.7
Steam system & cond.	21.1	20.8	20.9	21.8
Cooling water	7.2	7.1	7.2	7.4
Water treatment	5.8	5.8	5.8	6.0
Bag filter	0.0	0.0	0.0	0.0
Chimney	5.2	5.2	5.1	5.0
Subtotal	338.1	331.4	337.1	353.3
Total ($M)	508.5	503.7	482.5	504.3
Specific investment ($/kWe)	1327.0	1305.4	1265.3	1322.5
BESP[a] ($/MWh)	44.3	43.18	41.53	43.29
BESP[b] ($/MWh)			40.9	42.98
BESP[c] ($/MWh)			40.27	42.66

Note: (Costs in $M).

[a] Plastic cost = $21.90/tonne.

[b] Plastic cost = 0.

[c] Plastic cost = gate fee of $21.90.

3.3. Comparison of proposed technologies

3.3.1. Efficiency

The efficiency of current conventional coal-fired combustion plants usually ranges from 30% to about 42%, depending on technology, scale and particularly on the superheated steam conditions, with high temperatures and pressures leading to high-efficiency. Higher efficiencies could be achieved at supercritical (or ultra-supercritical) steam conditions with advanced alloy or ceramic materials. Coal-fired gasification technologies should have efficiencies from 42% up to 45–50%, with pressurised fluidised bed combined cycle systems of 45% efficiency already in commercial operation.

The efficiency of the medium–large-sized CFBC technology proposed in this project was found to be about 40.5%, which is appropriate for this scale and steam cycle, and varied only

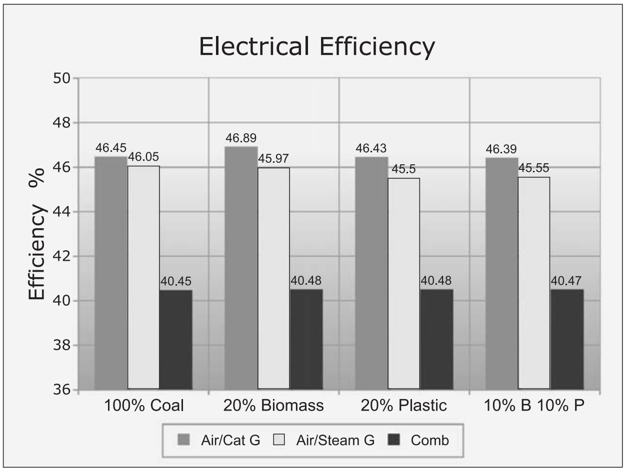

Fig. 1. A comparison of the electrical efficiencies of the air/catalyst gasification, air/steam gasification and combustion fluidised bed systems respectively for different fuel mixtures.

slightly when some of the coal was replaced by biomass and/or plastic.

The efficiency of the proposed steam/air gasification (INETI) IGCC technology was found to be about 46% (LHV), and that of the proposed air gasification with dolomite catalyst (Saragossa) IGCCs to be about 46.5% as can be seen in Fig. 1. The use of 20% biomass and/or plastic to replace coal had little effect on the electrical efficiency of either technology. These efficiencies are reasonably high, and in the expected range.

3.3.2. Emissions

CO_2 emissions from conventional coal-fired technologies would generally be around 800–1000 g/kWh for large combustion plants and between 500 and 800 g/kWh for IGCC systems.

The emission values presented in Fig. 2 show that the medium–large-sized CFBC technology was found to emit around 875 g/kWh for the plant fired by 100% coal, falling to between 830 and 860 g/kWh when biomass and/or plastic replaces some of the coal. These values are quite acceptable, and could be considered to be even lower for the biomass cases, when sustainably-grown biomass is used.

The CO_2 emissions from the proposed IGCC technologies were found in the simulations to lie between 700 and 770 g/kWh. These values lie towards the higher end of the expected range.

The SO_2 emissions were found to be around 240–250 mg/Nm^3 at 6% O_2 for the combustion plants and between 150 and 180 mg/Nm^3 at 6% O_2 for the IGCC technologies. The combustion plant values are higher than the ELV of 200 mg/Nm^3 at 6% O_2 in the new EC directive, but it would be possible to increase the desulphurisation by applying more catalyst.

The ELV for NO_x in this new EC directive is 500 mg/Nm^3 at 6% O_2, falling to 200 mg/Nm^3 at 6% O_2 in 2016. For the proposed IGCC technologies the NO_x values are expected to be within the ELV, probably around 160–185 mg/Nm^3 at 6% O_2, and the proposed combustion plants would also be compliant at present with values around 350 mg/Nm^3 at 6% O_2.

3.3.3. Economics of the proposed CFB technologies

3.3.3.1. Economics of conventional technologies. The specific investment (SI) of conventional coal-fired combustion plants ranges from around \$800 to \$1200/kWe, and for IGCCs it can be from \$500 to \$1000/kWe. The cost of electricity generation (COE) without paying back the capital costs of a plant generally ranges from \$20 to \$50/MWh. When the payback for the power plant is taken into account, the Break-even Electricity Selling Price (BESP) ranges from around \$40 to \$90/MWh.

3.3.3.2. Economics of the proposed CFBC technologies. The Specific Investments (SIs) and the Break-even Electricity Selling Price (BESP) of proposed technologies are presented in Figs. 3 and 4. The medium–large-sized CFBC technologies proposed in this project were found to have SIs between \$1330 and \$1360/kWe and BESPs from around \$49 to \$52/MWh.

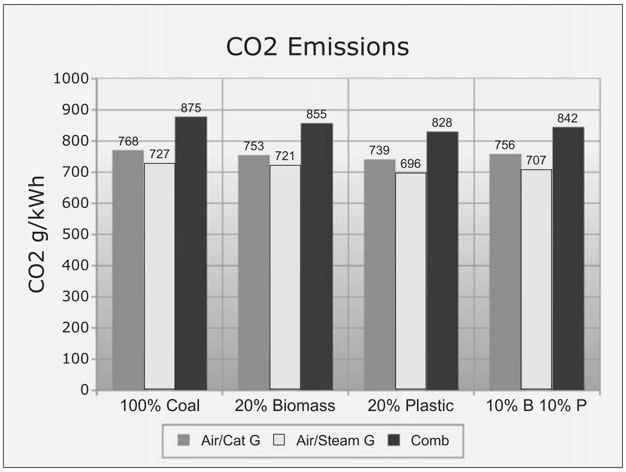

Fig. 2. A comparison of the CO_2 emissions of the air/catalyst gasification, air/steam gasification and combustion fluidised bed systems respectively for different fuel mixtures.

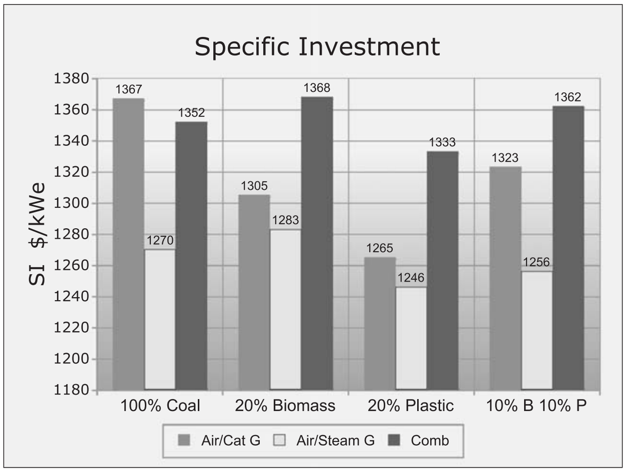

Fig. 3. A comparison of the Specific Investments of the air/catalyst gasification, air/steam gasification and combustion fluidised bed systems respectively for different fuel mixtures.

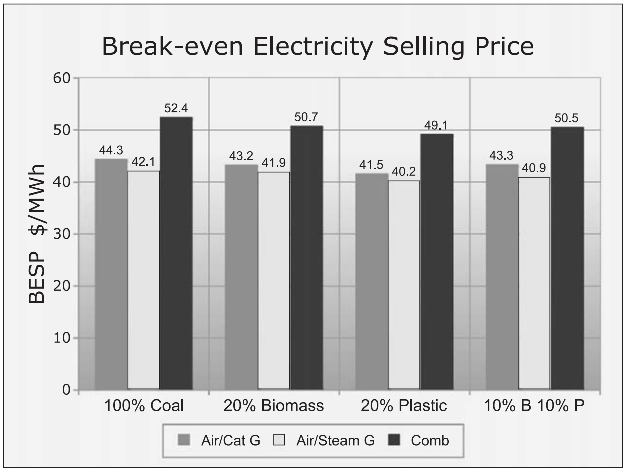

Fig. 4. A comparison of the Break-even Electricity Selling Prices of the air/catalyst gasification, air/steam gasification and combustion fluidised bed systems respectively for different fuel mixtures.

Although the SIs are high, the BESPs lie within the expected range for even larger plants.

3.3.3.3. Economics of the proposed IGCC technologies. The IGCC technologies proposed in this project were found to have SIs between $1250 and $1330/kWe and BESPs from around $40 to $44/MWh. The SIs are towards the high side, but the BESPs are quite reasonable.

4. Conclusions

The use of biomass and/or plastic to provide 20% of the thermal energy when mixed with coal in a CFB gasification or combustion power plant was investigated. Experiments were carried out to discover the optimal operating conditions and the resultant gas composition in fluidised bed combustion and gasification test rigs. These data were then used in Eclipse simulations of the CFB power plant technologies.

The technical, environmental and economic analyses of the simulated CFB combustion and gasification systems showed that their expected efficiencies, SI, BESP and emissions values would all be within the ranges of the best current technologies. Currently co-firing takes place mainly in PF power plants, but there would appear to be no obvious hindrance to favouring fluidised bed technology when replacing some of the current plants reaching the end of their useful lifetimes, or those unable to comply with the LCP directive.

Overall, co-firing was found to have an almost negligible effect on system efficiency, CO_2 emissions, capital costs and even BESP. At the level (20%) investigated here, co-firing could offer an environmentally acceptable disposal route for such biomass and wastes with the added benefit of energy recovery.

The (Puertollano) coal used in the experiments and simulations of this study has high ash and relatively high sulphur content, as well as a low calorific value. Co-firing with biomass and/or plastic waste reduced the effects of these negative properties of this coal and thereby gives a more acceptable fuel mixture.

There may also be additional benefits from co-firing e.g. the avoidance of paying landfill tax or gate fees for the plastic used in the power plant, which formerly would have gone to landfill. Co-firing with biomass may also bring financial rewards, such as those coming from the incentives for generating electricity from renewable sources, or for the avoidance/reduction of carbon taxes.

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References

[1] K.R.G. Hein, J.M. Bemtgen, EU clean coal technology — co-combustion of coal and biomass, Fuel Process. Technol. 54 (1998) 159–169.
[2] M. Sami, K. Annamalai, M. Wooldridge, Co-firing of coal and biomass fuel blends, Prog. Energy Combust. Sci. 27 (2001) 171–214.
[3] L.S. Pedersen, H.P. Nielsen, S. Kiil, L.A. Hansen, K. Dam-Johansen, F. Kildsig, J. Chrstiensen, P. Jespersen, Full scale co-firing of straw and coal, Fuel 75 (1996) 1584–1590.
[4] D.C. Liu, C.L. Zhang, B. Mi, B.K. Shen, B. Feng, Reduction of N2O and NO Emissions by co-combustion of coal and biomass, J. Inst. Energy 75 (2002) 81–84.
[5] H. Spliethoff, W. Scheuer, K.R.G. Hein, Effect of co-combustion of sewage sludge and biomass on emissions and heavy metal behaviour, Proc. Saf. Environ. Prot. 78 (2000) 33–39.
[6] E. Biagnini, F. Lippi, L. Petarca, L. Tiognotti, Devolatilization rate of biomasses and coal–biomass blends: an experimental investigation, Fuel 81 (2002) 1041–1050.
[7] D.R. McIlveen-Wright, B.C. Williams, J.T. McMullan, A comparison of power generation from biomass in a small CFBC plant with biomass co-fired with coal in a large CFBC, Proceedings of the International Conference on New and Renewable Energy Technologies for Sustainable Development — Renewables 2004, 28 June–1 July 2004, Évora, Portugal, Paper 3.5, 2004.
[8] Y.G. Pan, E. Velo, L. Puigjaner, Pyrolysis of a blend of biomass with poor coals, Fuel 75 (1996) 412–418.
[9] Y.G. Pan, E. Velo, X. Roca, J.J. Manya, L. Puigjaner, Fluidised-bed co-gasification of residual biomass/poor coal blends for fuel gas production, Fuel 79 (2000) 1317–1326.
[10] J.M. Ekmann, J.C. Winslow, S.M. Smouse, M. Ramezan, International survey of cofiring coal with biomass and other wastes, Fuel Process. Technol. 54 (1998) 171–188.
[11] P.T. Williams, E.A. Williams, Fluidised bed pyrolysis of low density polythene to produce petrochemical feedstock, J. Energy Resour. Technol. 118 (1996) 269–276.
[12] A.K. Gupta, E. Ilancgezian, E.L. Keating, Thermal destruction behavior of plastics and non-plastic wastes in a laboratory-scale facility, J. Anal. Appl. Pyrolysis 51 (1999) 107–126.
[13] Council Directive 2001/80/EU, on “The limitations of emissions of certain pollutants into the air from large combustion plants”, Official Journal of the European Communities, L309, 27th November 2001.
[14] M. Grundy, P. Lilley, Co-firing: Panacea or potential monster? Mod. Power Syst. (January 2004) 15–17.
[15] B.C. Williams, J.T. McMullan, Techno-economic analysis of fuel conversion and power generation systems — the development of a portable chemical process simulator with capital cost and economic performance analysis capabilities, Int. J. Energy Res. 20 (1996) 125–142.

[16] L. Armesto, et al., Co-combustion of coal and olive-oil industry residues in fluidised bed, Fuel 82 (2003) 993–1000.

[17] J. Gil, M.P. Aznar, M.A. Caballero, E. Francés, J. Corella, Biomass gasification in fluidised bed at pilot scale with steam–oxygen mixtures. Product distribution for very different operating conditions, Energy Fuels 11 (6) (1997) 1109–1118.

[18] I. Narváez, A. Orio, J. Corella, M.P. Aznar, Biomass gasification with air in a bubbling fluidised bed. Effect of six operational variables on the quality of the produced raw gas, Ind. Eng. Chem. Res. 35 (7) (1996) 2110–2120.

[19] J. Gil, J. Corella, M.P. Aznar, M.A. Caballero, Biomass gasification in atmospheric and bubbling fluidised bed: effect of the type of gasifying agent on the product distribution, Biomass Bioenergy 17 (1999) 389–403.

[20] P. Pérez, J. Corella, M.P. Aznar, J. Gil, M.A. Caballero, J.A. Martín, Hot gas cleaning and upgrading with a calcined dolomite located downstream a biomass fluidised bed gasifier operating with steam–oxygen mixtures, Energy Fuels 11 (6) (1997) 1194–1203.

[21] M.P. Aznar, M.A. Caballero, J. Corella, J. Gil, J.A. Martín, Commercial steam reforming catalysts to improve biomass gasification with steam–oxygen mixtures. Part II. Catalytic tar removal, Ind. Eng. Chem. Res. 37 (7) (1998) 2668–2680.

[22] F. Pinto, C. Franco, R.N. André, M. Miranda, I. Gulyurtlu, I. Cabrita, Co-gasification study of biomass mixed with plastic wastes, Fuel 81 (2002) 291–297.

[23] C. Franco, F.I. Pinto, I. Gulyurtlu, I. Cabrita, The study of reactions influencing the biomass steam gasification process, Fuel 82 (2003) 835–842.

[24] F. Pinto, RN. André, C. Franco, C. Tavares, I. Dias, I. Gulyurtlu, I. Cabrita, Effect of experimental conditions on co-gasification of coal biomass and plastic wastes with air/steam mixtures in a fluidised bed, Fuel 82 (2003) 1967–1976.