POWER GENERATION FROM BIOMASS IN A SMALL CFBC PLANT COMPARED WITH BIOMASS CO-FIRED WITH COAL IN A LARGE CFBC

D.R. McIlveen-Wright, S. Rezvani, Y. Huang and N.J.Hewitt

Centre for Sustainable Technologies (CST), Faculty of Art Design and the Built Environment, University of Ulster, Whiteabbey, BT37 0QB, Northern Ireland, United Kingdom

Contact email: dr.mcilveen-wright@ulster.ac.uk

Abstract Biomass is one of the renewable energy sources which is not intermittent, location-dependent or very difficult to store. If grown sustainably, biomass can be considered to be CO2 neutral.

The use of biomass for power generation is also considered to be important in increasing the electricity output from renewable energy sources.

However, power plants dedicated to the use of biomass fuel are not in widespread use and the acceptance of this fuel and development of the infrastructure for biomass production and transportation remain in their infancy. If small ratios of biomass can be co-fired with coal in large-scale conventional power plants, without significant technical, environmental or economic penalties, it could lead to a greater demand for biomass and stimulate the industry.

In this study a 80 MWth CFBC, fuelled by biomass only, and a large-scale 1000 MWth CFBC, cofired with coal and 8% biomass, and the same large CFBC system, fired only with coal, are modelled using the ECLIPSE process simulation package and their technical, environmental and economic properties analysed and compared.

The co-firing of biomass with coal was found to have little effect on the large-scale CFBC system, when a small ratio of biomass is used. The large scale system was found to have higher efficiency, lower CO2 emissions and lower break-even electricity selling price than the small biomass-fuelled CFBC.

Co-firing of biomass with coal could be a promising way of promoting the production, use and acceptance of biomass as a fuel in electricity generation.

.

Keywords CFBC, co-firing; electricity generation; simulations, biomass, techno-economic analysis

Nomenclature

CFBC	Circulating Fluidised Bed Combustion
daf	dry, ash-free
ar	as received
w/w	weight for weight
LHV	Lower Heating Value
HHV	Higher Heating Value
Nm^3	Normal metre cubed
HRSG	Heat Recovery Steam Generator
SI	Specific Investment (Capital Cost per kW of electricity output)
BESP	Break-even Electricity Selling Price
ID Fan	Induced Draught Fan
FD Fan	Forced Draught Fan
R&S	Reception and Storage
P&F	Preparation and Feeding
HP, IP, LP	High Pressure, Intermediate Pressure, Low Pressure

INTRODUCTION

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 [1] (Hein and Bemtgen, 1998). A life cycle assessment of several coal combustion scenarios (coal-based electricity generation, coal and biomass co-firing, post-combustion CO2 capture and coal ash valorisation) with biomass combustion asserted that co-firing was the most effective method of reducing CO2 emissions [2] (Benetto et al., 2004). 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] (Pedersen et al., 1996); lower NO_x emissions may be found during co-combustion, since there is high volatile content in biomass and biomass nitrogen preferentially forms NH_3 to HCN which is formed preferentially by nitrogen from coal [4] (Spliethoff et al., 2000); and 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 [5] (Biagnini et al., 2002).

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 and increase electricity selling price. An analysis of several power generation technologies, using 100% coal, 100% biomass and coal-biomass mixtures has been made to identify the effects of biomass fuels on power plant efficiencies [6] (McIlveen-Wright et al., 2007) and on the economic cost of reducing CO_2 emissions through the replacement of coal with different amounts and types of biomass [7] (McIlveen-Wright et al., 2003).

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 this study co-firing of a high ash coal with 8% (by thermal input) biomass in a large scale power plant is compared with a smaller plant fired only by the same quantity of biomass, both using fluidised bed technology. 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 and perform technical, environmental and economic analyses of such systems.

CIRCULATING FLUIDISED BED COMBUSTION PLANTS

In this paper a computer simulation, using the ECLIPSE process simulation software package [8] (Williams and McMullan, 1996), was made of a large scale 1000 MWth CFBC power generation system. The process flow diagram of the modelled system was based on the power plant at Gardanne, France, which has been tested for co-firing with coal and biomass. Simulations were also made of a smaller 80 MWth CFBC power plant, which was fuelled completely by biomass in this instance.

Typical 1000 MWth Coal-Fired Circulating Fluidised Combustion (CFBC) Power Station

In a typical CFBC plant coal would first be transferred from the normal coal storage facilities where it is then pulverised in mills, before being pneumatically transferred, together with limestone, using preheated primary air to a balanced draught, circulating fluidised bed boiler. Secondary air is injected through a set of nozzles higher up the chamber walls. The high fluidising velocity forms an expanded bed with material carried out of the combustor. Cyclones separate the majority of the solids from the flue gas. These solids are returned either directly to the combustor or through a set of external heat exchangers which receive preheated fluidising air. The low operating temperature (850 ^{o}C) and the staged combustion of the coal helps to reduce NO_x formation. Sulphur retention is achieved by adding limestone, so no additional flue gas desulphurisation is required.

In the combustor, the walls are lined with tubes which remove the radiant heat, and maintain the furnace temperature at 850 ^{o}C. Approximately 40% of the bed material is removed periodically from the base of the combustor and heat is extracted for low-pressure boiler feedwater heating. The rest of the solids are carried forward with the hot gases and removed by bag filters. High ash resistivity makes cold side electrostatic precipitators unsuitable and bag filters have the added advantage of promoting further sulphur retention. Before reaching the bag filter the gases are cooled by transferring heat first to steam in the superheater and reheater tubes, then to condensate in the economizer, and finally by passing through air preheaters at the back of the convective pass section. Superheating is achieved in both the external heat exchangers and the convective pass section. The reheater tubes are also located in these external heat exchangers and final economising also occurs in the convective pass section. The cooled gases are exhausted to the atmosphere via the induced draught fan and stack.

The steam from the superheater goes to the turbine stop valve and is expanded in the high-pressure turbine. The steam turbines have facilities for steam extraction and allow for transfer of steam to the regenerative feedwater heaters. Drains from the three high-pressure feedwater heaters are fed to the deaerator. The steam from the high-pressure turbine is then reheated before passing through intermediate pressure and double flow low-pressure turbines. At the crossover from the intermediate to the low-pressure turbines steam is extracted for the deaerator. Drains from the three low-pressure feedwater heaters are fed to the condenser.

The steam from the low-pressure turbine is condensed and the condensate is pumped by the extraction pump through three low-pressure surface-type heaters and a parallel ash cooler to the deaerator. Here the incoming water is heated by direct contact with the bleed steam. The boiler feed pump forces the condensate through three high-pressure feedwater heaters and the economizer before reaching the boiler and completing the steam cycle.

Recent trials have shown that, when around 5-8% of the feedstock is not coal i.e. consists of biomass and/or certain wastes, no modifications of the coal-fired plants are necessary.

In the large scale system proposed here, there probably would need to be some additional reception, size reduction, handling and storage facilities for the biomass, which has been taken into account in the design/modification of the power plant.

80 MWth CFBC System

A typical CFBC system of this size would have standard biomass feed preparation, storage and handling facilities from which the fuel would be transferred, together with limestone absorbent when coal is involved, to an atmospheric circulating fluidised bed combustor. Air is first heated in an air preheater and external heat exchangers and then fed to the base of the combustor. The high fluidising velocity of this air causes an expanded bed to form and which carries material out of the combustor into the recirculation cyclones. These cyclones separate the majority of the solids, which are then returned to the base of the combustor via external heat exchangers. Most of the ash is removed from the base of the combustor and the highly efficient cyclone filters remove the rest. The low operating temperature helps to reduce NOx formation, and sulphur retention (when coal is used) is achieved by the addition of limestone.

The hot gases from the recirculation cyclones are cooled initially in a heat recovery steam generator and finally in combustion air preheaters. The cooled gases are exhausted to the atmosphere via the induced draught fan and stack. The steam from the heat recovery steam generator goes to the turbine control valve and is expanded in the steam turbine. The steam turbine has facilities for steam extraction to allow for transfer of steam to the feedwater heaters and to the deaerator tank. The low pressure steam from the steam turbine is condensed and the condensate is pumped by the low pressure (LP) pump through the LP heater to the deaerator tank and the high pressure (HP) pump through the HP heater, before reaching the heat recovery steam generator and completing the steam cycle.

SIMULATION RESULTS

The two power plants were modelled using the ECLIPSE process simulation software and technical, environmental and economic analyses made. The larger scale 1000 MWth CFBC was assessed when fuelled by a high-ash, medium sulphur Puertollano coal, and also when co-fired with 8% (by thermal input) with biomass. The 80 MWth CFBC was analysed when fuelled by the same amount (and type) of biomass as in the 1000 MWth plant.

Fuel Analysis

The calorific values, proximate and ultimate analyses of these fuels are shown in Table 1.

Table 1. Fuel Properties.

	Coal Feedstock	Biomass
	Puertollano Coal	Pine Residues
Proximate Analysis, %, w/w		
Volatiles	24.9	72.6
Fixed Carbon	37.3	16.2
Moisture	5.5	10.7
Ash	32.3	0.5
Total	100	100
Ultimate Analysis, %, daf		
C	77.33	51.57
H	5.31	4.94
N	1.93	0.90
S	1.29	0.00
O	14.15	42.58
Total	100.00	100.00
Calorific Values		
HHV (ar) MJ/kg	19.06	20.20
LHV (ar) MJ/kg	18.21	19.01
HHV (daf) MJ/kg	30.64	22.75
LHV (daf) MJ/kg	29.28	21.41

1000 MWth System, Coal Only and Co-fired with 8% Biomass

Technical Results

The technical and emissions results for the simulations of the 1000 MWth power plant are shown in Table 2.

Table 2. Technical Results for the 1000 MWth CFBC

coal type	Peurtollano	Peurtollano
excess air	*20%*	*20%*
Steam Cycle	*160bar/538C*	*160bar/538C*
Reheat?	*Yes*	*Yes*
Fuel Mix	***100% coal***	***92% coal/ 8% wood***
Electrical Usages kW		
FD fans (3)	*11086.2*	*10854.6*
ID fan	*3882.5*	*3829.4*
Slag Outlet	*148.6*	*140.1*
Bag Filter	*7.8*	*7.4*
Coal Crusher	*221.2*	*135.5*

Conveyors (4)	*2042.9*	*2132.8*
HP & LP Pump	*9774.3*	*9765.6*
Elect. Utilities	*4899.21*	*4894.91*
Total Usages	*32062.8*	*31760.3*
HP Turbine	*108079.5*	*107985.1*
LP Turbines (4)	*179475.3*	*179318.5*
IP Turbines (3)	*149386.2*	*149255.7*
Gross Electricity	*436941*	*436559.3*
Net Electricity	*404878.2*	*404799.0*
Thermal Input LHV	*1000.00*	*1000.00*
Thermal Input HHV	*1046.7*	*1048.0*
Efficiency, LHV	*40.49*	*40.48*
Efficiency, HHV	*38.68*	*38.63*
CO2 g/kWh	*873.7*	*866.3*
CO2 mg/Nm3 at 6% O2	*239935*	*241577*
SO2 mg/Nm3 at 6% O2	*243.4*	*250.8*
NOx mg/Nm3 at 6% O2	*340.38*	*352.95*
CO mg/Nm3 at 6% O2	*59.82*	*62.01*
O2 (dry) vol %	*4.04*	*4.04*

Economic Results

The economic results for the ECLIPSE simulations of the large CFBC system are shown in Table 3.

Table 3. Economic Results for 1000 MWth CFBC

Cost ($M)	100% Coal	8% Wood
Coal Reception & Storage	33.85	31.31
Other feedstock R&S	0.00	9.26
Limestone R&S	2.90	2.68
Coal Milling&Storage	12.46	11.58
Coal Drying	0	0
Coal Feeding	5.97	5.63
Other Feedstock P&F	0.00	2.59
Sub Total	55.17	63.04
Ash/Slag Handling	7.65	7.21
Bag Filter	6.39	6.31
CFBC	201.29	199.35
CFBC HRSG	37.82	37.45
Sub Total	253.15	250.32
Steam turbine	113.37	113.29
Steam System & Conditioning	37.03	36.99
Cooling Water	15.03	15.02
Water Treatment	10.62	10.62

Chimney	4.82	4.77
Sub Total	67.50	67.40
Total	489.1904	494.0512
SI ($/kWe)	1208.2	1220.7
BESP ($/MWh)	48.79	48.51

80 MWth System, 100% Wood

Technical Results

The technical and environmental results for the CFBC using 100% biomass are shown in Table 4.

Table 4 Technical Results for the 80 MWth CFBC

Fuel Mix	8% Biomass
FD-Fan	739.5
ID-Fan	118.7
Ash Box	0.0
Gas Cleaning	0.0
Wood Convey	205.8
Absorbent Convey	0.0

Coal Convey	0.0
Ash Convey	5.5
Plastic Convey	0.0
HP Pump	474.8
LP Pump	2.9
Size Reduction	800
Total	2347.2
IP Turbine	13457.9
LP Turbine	14337.3
Electric Process	25448.0
Electric Utility	450.6
Net Electric	24997.4
Steam Cycle bar/°C	92/495
Thermal Input LHV	80
Thermal Input HHV	
Efficiency LHV %	31.25
Efficiency HHV %	29.40
CO_2 g/kWh	1019
SO_2 mg/Nm3 at 6% O_2	0.0
NO_x mg/Nm3 at 6% O_2	348.3
CO mg/Nm3 at 6% O_2	61.2
O_2 (dry) Vol %	5.5

Economic Results

The economic results for the 80 MWth CFBC using 100% biomass fuel are shown in Table 5.

Table 5. Economic Results for the 80 MWth CFBC

Cost ($M)	
Coal Reception & Storage (R&S)	*0.00*
Other feedstock R&S	*3.59*
Limestone R&S	*0.00*
Milling & Storage	*1.23*
Coal Drying	*0.00*
Coal Feeding	*0.00*
Other Feedstock Drying & Feeding (D&F)	*1.50*
Ash/Slag Handling	*0.06*
Bag Filter	*0.46*
CFBC	*18.12*
CFBC HRSG	*0.77*
Sub Total	*19.41*
Steam turbine	*15.27*
Steam System & Conditioning	*3.83*
Cooling Water	*1.85*
Water Treatment	*1.90*

Chimney	*0.67*
Total ($M)	*49.233*
Specific Investment ($/kWe)	*1970*
BESP ($/MWh)	*59.83*

COMPARISONS

Efficiency

The efficiency of the larger CFBC was found to change little from the case where it is fuelled solely by coal (40.49%, LHV) to the case where it is co-fired with 8% biomass (40.47%, LHV), as shown in Fig.1. The 80 MWth CFBC system was found to be much lower (31.29%) in efficiency, probably because the steam cycle conditions result in an intrinsically less efficient system (538°C with reheat and 160 bar for the larger system compared with 495°C and 92 bar for the smaller system).

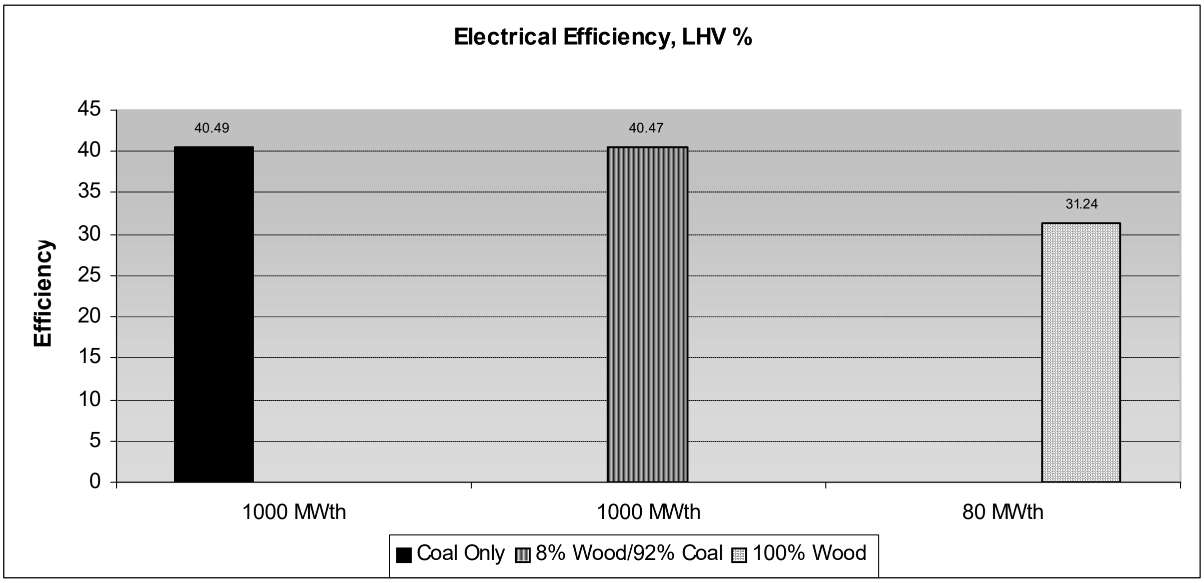

Figure 1. A Comparison of Electrical Efficiencies

Specific Investment

The capital cost per unit of electricity generated, or specific investment, SI, of the larger CFBC increases slightly from 1208 $/kWe to 1220 $/kWe if the cost of additional equipment for biomass reception, storage, size reduction and handling is taken into account. The SI for the 80 MWth CFBC fuelled by 100% biomass is much higher, around 1970 $/kWe, as shown in Fig. 2.

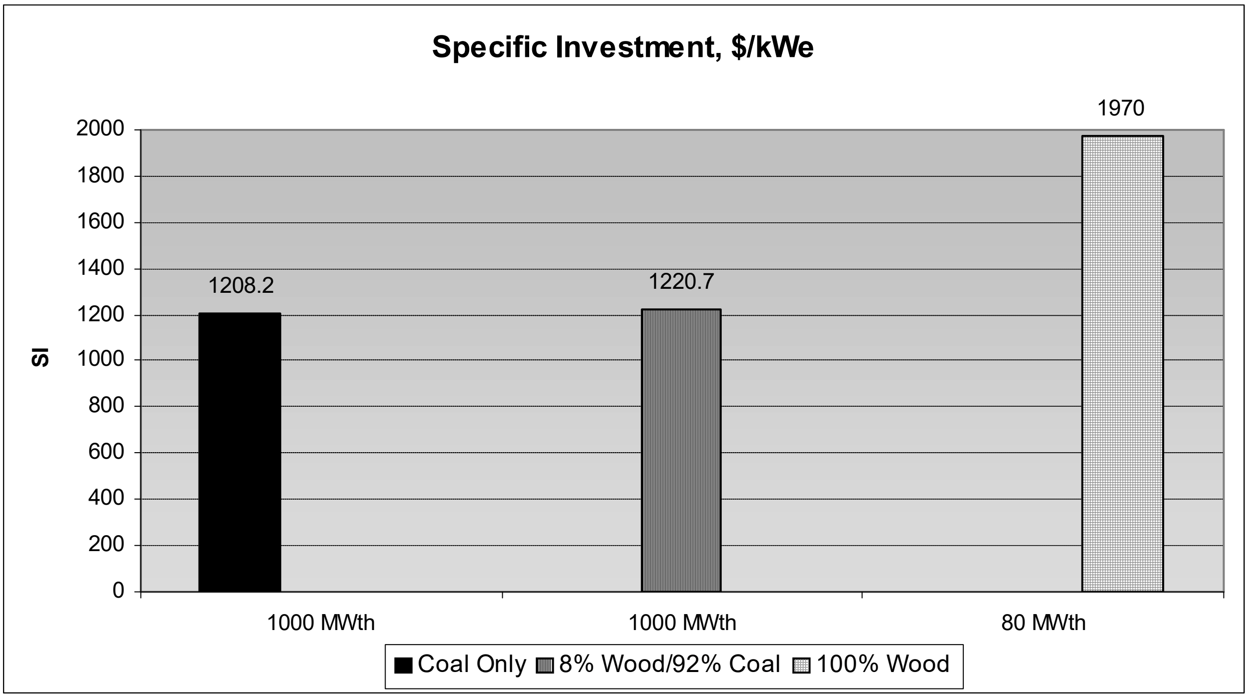

Figure 2. A Comparison of Specific Investments

Emissions

The CO2 emissions of the larger CFBC (1000 MWth) were found to be around 874 g/kWh for 100% coal, dropping to about 866 g/kWh when it is co-fired with 8% biomass. The 80 MWth CFBC was found to emit around 1029 g/kWh CO2 when fuelled with 100% biomass, as shown in Fig. 3. The smaller CFBC emits more CO2 than the larger one due to its lower efficiency.

If the biomass is grown sustainably, it can be considered to be carbon-neutral. The net CO2 emissions from the 80 MWth CFBC could be considered to be zero, when using 100% biomass fuel, and the 1000 MWth CFBC would have net CO2 emissions of around 803 g/kWh, when co-fired with 8% biomass, which is an 8% emission reduction over the 100% coal case.

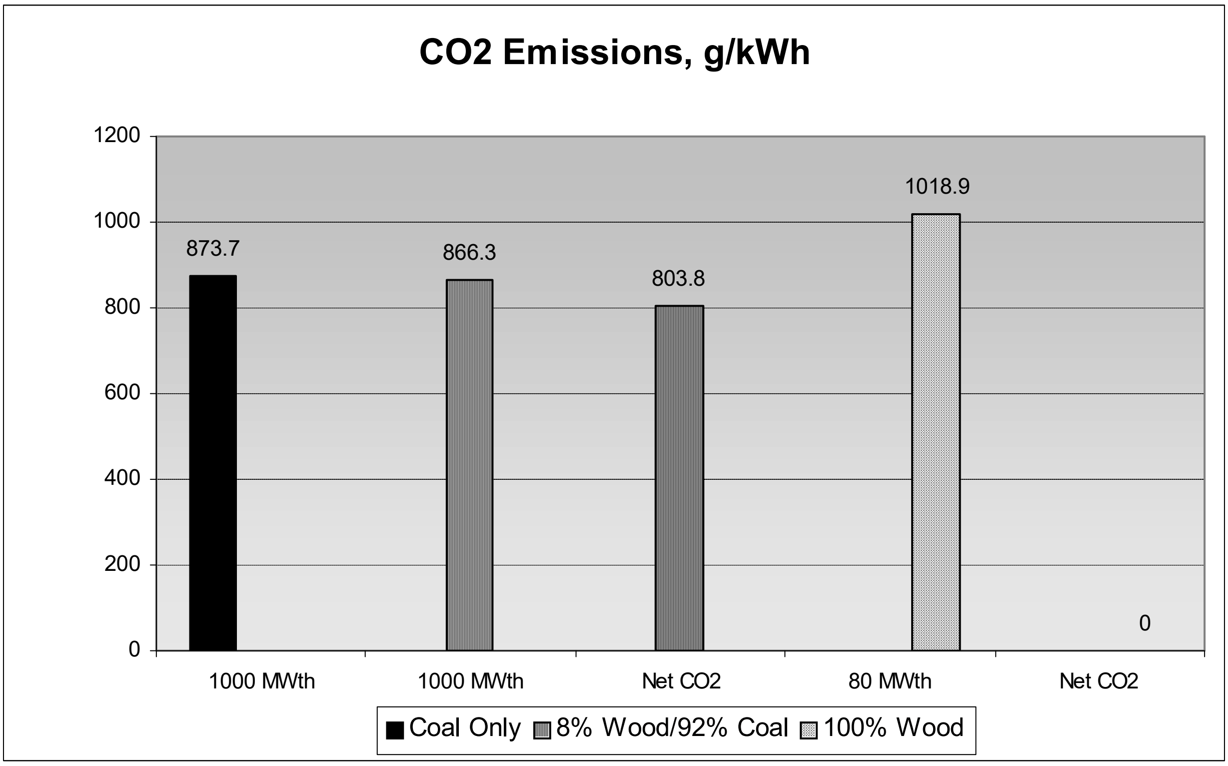

Figure 3. CO2 Emissions for both CFBC systems

Electricity Generation Costs

The break-even electricity selling price (BESP) for the larger CFBC system was found to be 48.79 $/MWh using 100% coal and 48.51 $/MWh when co-fired with 8% biomass. The coal and biomass costs were taken to be $52.25/ daf tonne and $26.06/ daf tonne respectively.

The sensitivity of the BESP to variations in the cost of coal or biomass is shown in Fig. 4. The coal and biomass costs are varied by ± 100% of their nominal values.

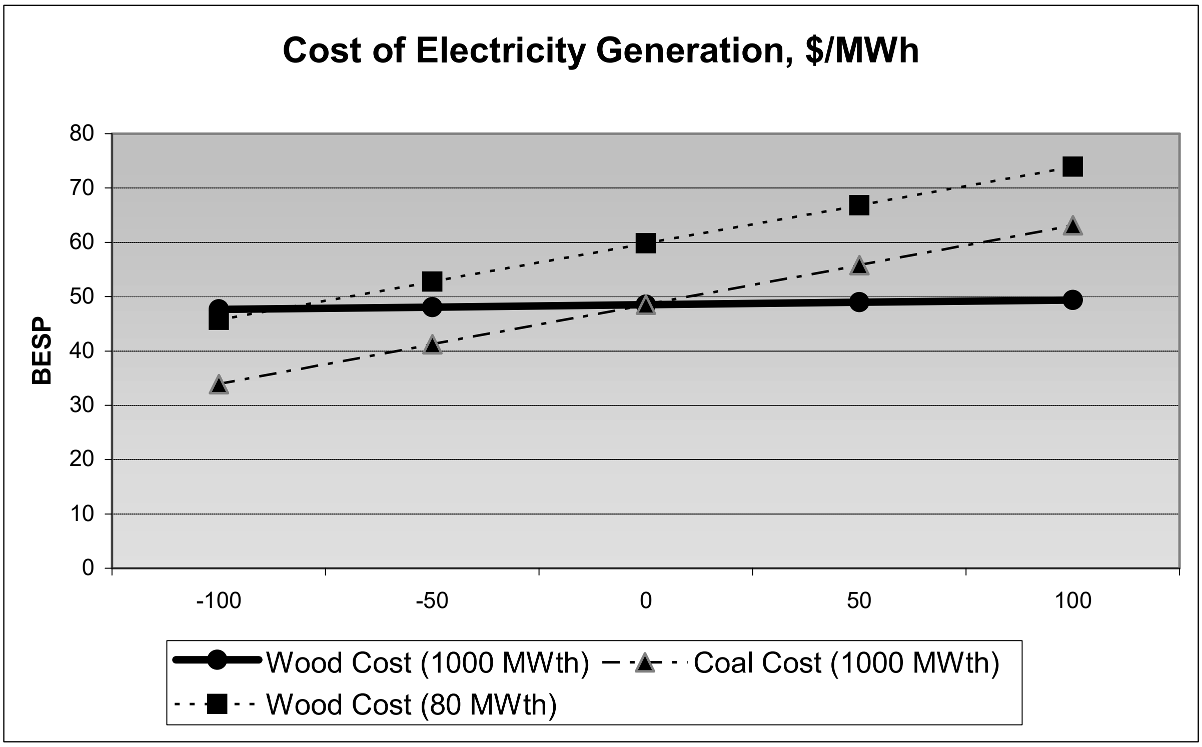

Figure 4. Variation of BESP with Fuel Price

CONCLUSIONS

Efficiency

The efficiency of the larger 1000 MWth CFBC was only negligibly affected by changing the fuel from 100% coal to co-firing with 8% biomass.

The smaller 80 MWth CFBC was much less efficient than the 1000 MWth CFBC (31.2% compared with 40.5%, LHV).

Co-firing biomass in the larger CFBC is the more efficient method for using biomass to generate electricity.

CO2 Emissions

The less efficient 80 MWth CFBC emits more CO2 than the larger 1000 MWth CFBC per unit of electricity generated, but no SOx, when fuelled by 100% biomass. However, the net CO2 emissions for the 80 MWth CFBC system may be considered to be zero, if the biomass is sustainably managed.

Co-firing with biomass lowers CO2 emissions and net CO2 emissions of the larger CFBC.

Specific Investment

The 80 MWth CFBC has an SI (about 1970 $/kWe) more than 50% higher than that of the 1000 MWth CFBC system (around 1200 $/kWe), since the larger system is more efficient.

BESP

The 1000 MWth CFBC system co-fired with 8% biomass has a lower BESP value than the 80 MWth CFBC using the same amount and type of.biomass. In addition, the BESP for the 1000 MWth system is only negligibly affected by variations in the cost of biomass, whereas the 80 MWth BESP is significantly affected , as shown in Figure 4.

Financial incentives for the use of biomass are currently available 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. These incentives have not been taken into account in this paper, as their long-term availability for co-firing applications is currently unconfirmed.

In summary, the ECLIPSE simulations of the 1000 MWth CFBC co-fired with 8% biomass showed this system had a higher efficiency, lower CO2 emissions, lower SI and BESP than the 80 MWth CFBC fuelled solely by biomass. The larger system was also insensitive to variations in the cost of biomass, which would have a significant effect on the economic viability of the small biomass-fuelled CFBC.

Co-firing small ratios of biomass with coal offers a promising way of promoting the production, trade and infrastructure of a biomass wastes or energy crops industry and the wider acceptance of biomass as a long term fuel for electricity generation.

REFERENCES

1. Hein, KRG and Bemtgen, JM, "EU clean coal technology – co-combustion of coal and biomass", Fuel Processing Technology, **54**, (1998), 159-169.

2. Benetto, E, Popovici, E-C, Rousseaux, P and Blondin, J, "Life Cycel Assessment of Fossil CO2 Emissions Reduction Scenarios in Coal-Biomass Based Electricity Production", Energy Convers. Mgmt., **45**, (2004), 3053-3074.

3. Pedersen, LS, Nielsen, HP, Kiil, S, Hansen, LA, Dam-Johansen, K, Kildsig, F, Chrstiensen, J and Jespersen, P, "Full scale co-firing of straw and coal", Fuel, **75**, (1996), 1584-1590.

4. Spliethoff, H, Scheuer, W, and Hein, KRG, "Effect of co-combustion of sewage sludge and biomass on emissions and heavy metal behaviour", Proc. Saf. Environ. Prot., **78**, (2000), 33-39.

5. Biagnini, E, Lippi, F, Petarca, L and Tiognotti, L, "Devolatilization rate of biomasses and coal-biomass blends: an experimental investigation", Fuel, **81**, (2002), 1041-1050.

6. McIlveen-Wright DR, Huang Y, Rezvani S and Wang Y, "A technical and environmental analysis of co-combustion of coal and biomass in fluidised bed technologies", Fuel, **86,** (2007), pp 2032-2042.

7. McIlveen-Wright DR, McMullan, JT and Williams BC, "The Economics of Reducing Carbon Dioxide Emissions by the Use of Biomass Co-Combustion", Proceedings of the Seventh International Conference on Energy for a Clean Environment – 'Clean Air 2003', 7-10 July 2003, Calouste Gulbenkian Foundation, Lisbon, Paper 16.1.

8. Williams BC and McMullan JT, "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 Research , **20**, (1996). pp.125-142.