A TECHNICAL AND ECONOMIC ANALYSIS OF LARGE SCALE BIOMASS COMBUSTION

McIlveen-Wright, D.R., Huang, Y., Rezvani S., Ghayur, A., Redpath, D., Dave, A. and Hewitt N.J.
School of the Built Environment, University of Ulster,
Shore Road, Jordanstown, Newtownabbey BT37 0QB, UK

ABSTRACT: Large scale power plants have not been considered in the past for several reasons e.g. fossil fuels have higher energy density, the previous low cost of fossil fuels, the availability of the required amounts of biomass and the cost of biomass transportation. However, the impending scarcity of fossil fuels and their increased price, as well as environmental concerns, have led to renewed interest in the use of biomass for power generation. Many power plant operators have been encouraged by subventions to test cofiring of biomass with coal, which has often proved lucrative with little reduction in generation efficiency or significant impact on capital cost, and this, in turn, has increased familiarity with the characteristics of biomass, its handling, diminution, drying, storage and use at power plants and the details of its supply chain.

One example of this increase in interest in biomass is the 350 MWe CFBC power plant at Port Talbot in Wales, and another example of a large biomass power plant is the 44 MWe Bubbling Fluidised Bed system at Steven's Croft, Lockerbie in Scotland.

The technical, environmental and economic analysis of such technologies, using the ECLIPSE suite of process simulation software, is the subject of this study. The models are based on publicly-available data from the previously mentioned plants, but are not intended to replicate them. System efficiencies for generating electricity and CO2 emissions are evaluated and compared with a large coal-fired CFBC plant and a typical supercritical PF power plant.

The specific investment (SI) and break-even electricity selling price (BESP) for each system were calculated and compared with the coal-fired plants. The sensitivity of the economics of both large power plants to such factors as fuel cost, load factor and insurance, operational and maintenance costs for two discount cash flow rates was investigated. The BESP for the two biomass plants modeled were found to be competitive with the coal-fired plants at low wood costs, even without any subventions.

Keywords: power generation, fluidised bed, modelling, economic aspects

1   INTRODUCTION

Although biomass combustion has received widespread attention [1] from time to time, large scale power plants have not been considered in the past for several reasons e.g. fossil fuels have higher energy density, previous low cost of fossil fuels, the availability of the required amounts of biomass and the cost of biomass transportation [2]. However, the impending scarcity of fossil fuels and their increased price, as well as environmental concerns, have led to renewed interest in the use of biomass for power generation, with the additional promise of employment in rural economies [3]. Many power plant operators have been encouraged by subventions to test cofiring of biomass with coal [4],[5], which has often proved lucrative with little reduction in generation efficiency or significant impact on capital cost [6], and this, in turn, has increased familiarity with the characteristics of biomass, its handling, diminution, drying, storage and use at power plants and the details of its supply chain.

In the UK the introduction of Renewables Obligation Certificates (ROCs) [7] has provided an incentive for electricity generation from renewable energy and this scheme has provided considerable stimulation to the uptake in biomass use recently, if not at first [2]. In addition, several of the nuclear and coal-fired power plants are due to be decommissioned in the next decade, and the favourable banding of ROCs for biomass, aligned with the suitability of biomass for base load operation, make biomass power plants an attractive proposition. A Renewable Heat Incentive [8], which is due to come into force in July 2011 for biomass combustion plants above 1 MWe, will provide a similar scheme to incentivise heat recovered from renewable energy. For this reason many of the new biomass combustion plants have been designed to be "heat ready", and both these initiatives should improve the competitiveness of power plants fired with biomass with those fuelled by coal. However, these incentives are not taken into account in the economic analysis presented here.

Fluidised bed technologies are generally considered to be capable of processing biomass efficiently, but they can have problems with certain types of herbaceous biomass, which can have high alkaline and ash content in small scale applications [9]. In this paper, the biomass fuel is considered to be coppiced willow, which should be little affected by these issues. One example of this increase in interest in biomass is the 350 MW power plant at Port Talbot in Wales. Here a Circulating Fluidised Bed Combustion (CFBC) system is being constructed by Prenergy Technology.

Another example of a large biomass power plant is the system at Steven's Croft, Lockerbie in Scotland. Steven's Croft is a €132m 44MWe Bubbling Fluidised Bed plant [10]. This plant was commissioned in 2007 and uses Siemens/Kvaerner technology.

In the past there have been very few large biomass power plants constructed, so it has been difficult to make accurate predictions of their capital costs. Most attempts required a "bottom up" approach, where individual equipment parts were costed and these costs summed. It also involved scaling of costs for biomass-specific equipment from the small to large scale. For this reason, it has been usual to state limitations to the accuracy of

capital costs in any economic analysis. For example in a recent analysis [6] it was stated that the absolute accuracy of this type of capital cost estimation procedure had been estimated at about ±25-30%. However, in this study the costs for the Port Talbot and the Steven's Croft power plants are known, so the economic analyses for these plants should have a much smaller error margin.

1.1 Transportation

In general the transportation of biomass has raised many questions regarding its "green" credentials, particularly if it is sustainable to transport biomass over long distances. Road transportation of biomass for a large power plant would require many truck movements and the use of considerable quantities of petroleum-based fuel, resulting in significant carbon emissions. Transportation by sea is considered to be less carbon intensive, and in the 'Non-Technical Summary' [16] for the Port Talbot power plant it is stated that the carbon emissions, in grammes of carbon per tonne of biomass per kilometre would be 1.45 for sea transport and 31.7 for road transport. For this reason the Port Talbot plant has committed to transport all biomass by sea at present, with the possibility of rail transportation in the future, since there is a rail head on site. The Steven's Croft location is also equipped with facilities for transportation by rail.

2 METHODOLOGY

2.1 ECLIPSE

The process simulation package, ECLIPSE [11], was used to perform techno-economic assessment studies of each technology using, initially, coal as the fuel. ECLIPSE has been successfully used to analyse a wide range of power generation systems using biomass, such as wood combustion plants [1], co-combustion of coal and biomass in fluidised bed technologies [4] and fuel cells integrated with biomass gasification [12].

The power plant diagram was converted to a Process Flow Diagram and then the mass and energy balance of the selected systems were modelled using ECLIPSE. With regard to the economics, the capital costs of each power plant modelled is in the public domain, which means the specific investment (SI) can be easily calculated. Following the plant cost estimation, the breakeven electricity selling price (BESP) is determined based on the net present value (NPV), for a range of biomass (at 30% Moisture Content) costs. To cover uncertainties, a number of sensitivity analyses were carried out in connection with factors such as discounted cash flow, fuel prices. Load factors, operational and maintenance costs (O&M) and capital investments.

2.2 ECLIPSE Simulations

In the large biomass power plant simulations the details for the Port Talbot power plant were used, where available. The power plant receives its feedstock by sea transport. It is assumed to have the same composition as willow with a moisture content of 30% when it arrives at the power plant.

The power plant is a circulating fluidized bed combustion system (CFBC), based on the 250 MWe Gardanne power plant[13] [14]. A description of a typical CFBC power plant is given in the next section.

3 PLANT DESCRIPTION

The models are based on publicly-available data from the previously mentioned plants, but are not intended to replicate them; rather they should provide generic versions of these types.

3.1 Large-scale CFBC

In a typical coal-fired 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°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°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 economiser 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 biomass system proposed here, the reception, size reduction, handling and storage facilities would have to be appropriate for the biomass chosen, which has been taken into account in the design/modification of the Gardanne version power plant.

The type of condenser was also changed from the standard to an air-cooled version, which is used in the Port Talbot system.

For the simulation the superheated steam conditions were taken to be 160 bar at 538°C, with reheat also to at 538°C.

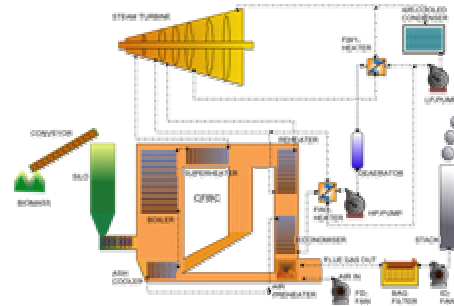

Figure 1: View of Port Talbot location [16]

Figure 2: Schematic of 'Port Talbot type' power plant

Figure 3: PFD of 'Port Talbot type' CFBC

3.2 Medium-scale BFBC

3.2.1 Power and fuel supply facilities at Steven's Croft [10]

The fuel processing facility is designed to store and blend all the various fuel sources to provide an homogeneous fuel to the power station. The fuel processing facility includes up to 14 days of round wood storage, a facility for reception of pre-chipped fuel, up to 6000 m^3 of covered chipped fuel storage, a round wood chipping facility, fuel reclamation and forwarding equipment together with systems for final preparation of the fuel to remove metals, stones and oversized materials prior to delivery to the power station. Processed fuel is then delivered at a terminal point on the supply conveyor to the power station's 10 000 m^3 A-frame storage facility.

Fuel is automatically reclaimed from the A frame using dual redundant reclaiming screw conveyors and a series of belt and chain conveyors which feed into two 1 hour buffer silos adjacent to the boiler. Final feed to the boiler is via four feed chutes which are regulated by rotary feeders. The fuel is then combusted within the bubbling fluidised bed boiler and flue gases are rigorously cleaned using bag filters with lime and activated carbon injection prior to discharge to the atmosphere.

3.2.2 Fuel Processing

A separate building for reception and processing of the fuel for the power station was completed in June 2007.

The building is designed to accept all potential wood fuel types as separate streams. Fuel brought to site is offloaded either direct to the delivery system or stocked out in the log yard (roundwood only) or inside the buildings 6000m^3 covered storage facility. Fuel is then reclaimed and blended to provide a homogeneous mix with the aim of maintaining steady moisture content. The moisture content varies significantly from fuel source to fuel source and can range from 35% up to 65%. It is therefore very important to mix the fuels to maintain moisture content at a reasonably constant level to avoid large variations in energy supplied to the boiler and air/ combustion gas flow rates. The fuel is also screened for oversized materials and metals are removed using a magnetic separator. The systems are designed with two 100% streams to give maximum reliability.

3.2.3 Boiler

The boiler chosen was a HYBEX BFBC, made by Kvaerner. The boiler conditions were designed to allow the best efficiency from the plant at 537°C, 137 bar and with a capacity to raise 126 MWth of energy. The high steam conditions have resulted in the need for specialist corrosion resistant materials in the high temperature components and a need to control fuel quality to the boiler.

3.2.4 Turbine

Steam raised within the boiler is sent to the steam turbine which generates up to 44MW of electricity at 11kV. The power is then transformed up to 33kV for transmission to the national grid at Chapel Cross substation. The turbine includes three steam bleeds for preheating duties. Low pressure steam is condensed in the air cooled condenser and recycled through to the boiler. The Siemens SST-800 turbine was chosen for the Steven's Croft project.

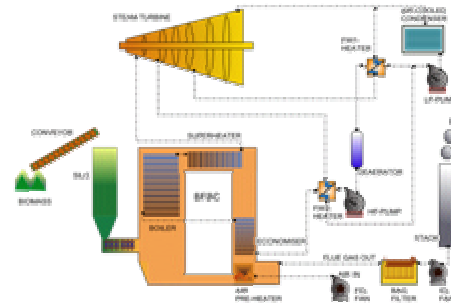**Figure 4:** Artist's Impression of Steven's Croft [10]

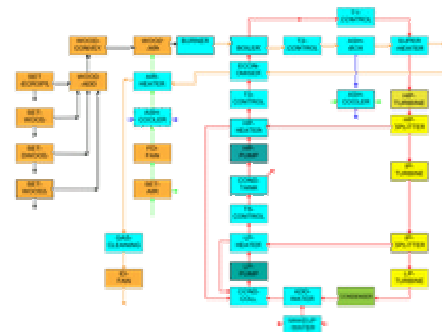**Figure 5:** Schematic of 'Steven's Croft type' BFBC

Figure 6: PFD of 'Steven's Croft type' BFBC

3.3 Moisture Content (MC) of fuel

In the ECLIPSE simulations it was assumed that the wood arrived at the power plant with a MC of 30% and was dried on site to 11.1% using the exhaust gases for wood drying. This is unlikely to be the case when the wood is transported by ship, since wood would deteriorate during the journey with such a high MC, and would need to be dried below about 15% before transportation. Recently biomass has been transported from Indonesia, Malaysia and South America for cofiring in the UK, but this material was of low MC as received. However, the premise is that wood would be locally sourced in the future and transported by train. If the wood had been dried before transportation, then the plant efficiency would be higher, and the Break-even Electricity Selling Price (BESP) slightly lower.

For the simulations, the fuel is assumed to be willow, with the composition shown in Table I.

Table I: Willow Composition

Fuel	Willow		
	As received	Dry	daf*
Proximate Analysis (wt %)			
Fixed Carbon	11.39	16.27	16.42
Volatile matter	57.99	82.84	83.58
Ash	0.62	0.89	-

Moisture	30.0	-	-
TOTAL	100.00	100.00	100.00
Ultimate Analysis (wt %)			
Carbon	35.38	50.55	51.00
Hydrogen	4.16	5.95	6.00
Oxygen	29.76	42.52	42.90
Nitrogen	0.06	0.08	0.08
Sulphur	0.01	0.02	0.02
Ash	0.62	0.89	-
Moisture	30.00	-	-
TOTAL	100.00	100.00	100.00
LHV (MJ/kg)	12.92	18.45	18.622
HHV (MJ/kg)	13.86	19.80	19.98

(* daf = dry, ash free)

4 RESULTS

4.1 Technical Data Overview

The systems, based on the PFDs shown in Figs 3 and 6, were modeled in ECLIPSE and the technical data from the simulations are summarized in Table II.

Table II: ECLIPSE Technical Data Overview

		CFBC	BFBC
daf Wood Flow rate	kg/s	5000	751.8
Steam Cycle	(bar, °C)	160/538 & reheat	137/537
Thermal Input, LHV	kW	997.2	150.7
Thermal Input, HHV	kW	1081.2	162.6
Efficiency, LHV	%	35.2	28.01
Efficiency, HHV	%	32.4	26.79
Exhaust Gas Temp	°C	110.7	116.8
Exhaust Gas Flow	kg/s	485	74.5
Total Ash Flow	Tonnes/ day	95	14.3
Specific CO_2 emissions	kg/MWh	1091	1320
NOx emissions	mg/Nm^3	462	477
O2 (dry)	Vol %	4.1	3.4
Gross Electricity generated	MW	382.9	49.02
Electricity usages	MW	32.0	5.45
Net Electricity Output	MW	350.9	43.57

4.2 Economic Data from models

The cost data for the Port Talbot power plant are used, where available, for the CFBC analysis i.e. Capital Costs for Equipment are £400 million, annual equipment maintenance costs are taken as £10 million and annual salaries as £7.5 million. The other expenses are shown as percentages of the capital costs and are typical for combustion power plants with outputs greater than 125 MWe, as shown in Table III.

Table III: ECLIPSE Cost Data Overview for CFBC

	CFBC
Total Process CC (EPC) (£k, 2008)	400,000.00
Working Capital (EPC, %)	2.00
Capital Fees (EPC, %)	0.40
Contingency (EPC, %)	10.00
Commissioning Cost (EPC, %)	1.00
Total CC (inc. commissioning costs, working capital & fees)	413,600.00
Total CC (inc. contingency)	453,600.00
Annual Insurance Costs (%)	1.0
Annual Operating Costs inc. labour & supplies (%)	2.0
Annual Maintenance Costs inc. labour & supplies (%)	2.5

A similar analysis was also carried out for the BFBC.

4.3 Economic Simulation Results

The Specific Investment for the CFBC was found to be £1,182/kW from the ECLIPSE economic simulation and the supplied capital costs and nominal output.

For a DCF of 10%, the payback period for the CFBC was found to be 14 years and with a DCF of 5%, the payback period would be 21 years.

The Specific Investment for the BFBC was found to be £2,136/kW from the ECLIPSE economic simulation and the supplied capital costs and nominal output.

For a DCF of 10%, the payback period for the BFBC was found to be 13 years and with a DCF of 5%, the payback period is 19 years.

The Break-even Electricity Selling Price (BESP) was calculated, using the cost data in section 4.2, and for a

range of wood chip selling prices, as shown in Fig. 7 for the CFBC and in Fig. 8 for the BFBC, assuming a Discounted Cash Flow Rate (DCF) of 5%. Simulations were also done for a DCF of 10%, but are not always detailed here due to lack of space.

For the CFBC: At a wood chip cost of £50/dry tonne, 30% MC, (and no ash sales), BESP was found to be £66/MWh at DCF = 10%, and BESP is £54.2/MWh at DCF = 5%, as shown in Fig. 7.
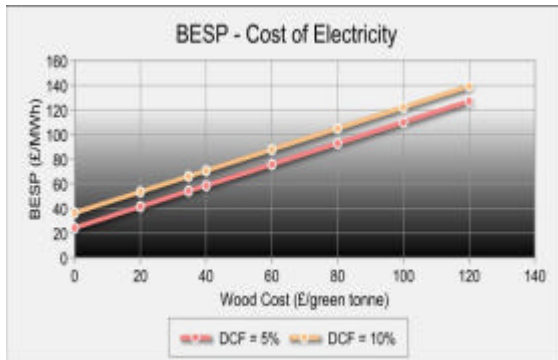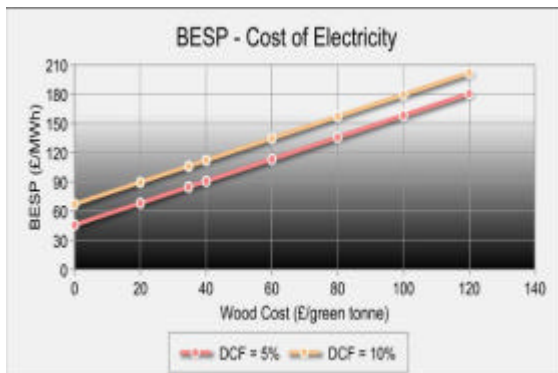

Figure 7: BESP versus Wood Cost with no ash sales for the CFBC.

For the BFBC: At a wood chip cost of £50/dry tonne, 30% MC, (and no ash sales), BESP was found to be £106/MWh at DCF = 10%, and BESP is £84.6/MWh at DCF = 5%.

Figure 8: BESP versus Wood Cost with no ash sales for the BFBC.

4.4 Sensitivity of BESP to Ash Sales

For DCF = 5%, the Payback period was found to be 21 years at a wood chip cost of £50/dry tonne, 30% MC, (Green tonne costs £34.67/tonne).

Ash flow is about 4 tonnes/hour for the CFBC when willow is assumed to be the fuel, or 34,700 tonnes/year (not 150,000 tonnes/year as published). Other types or forms of wood could have higher ash contents and this could then have a greater effect on BESP.
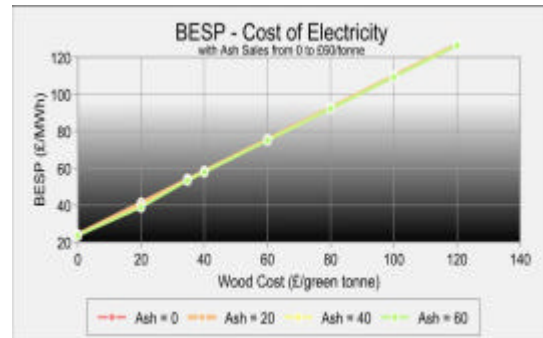

Figure 9: BESP versus Wood Cost with ash sales (in £/tonne) for the CFBC.

With a DCF = 5%, ash sales were found to have a negligible effect on BESP as can be seen in Figs. 9 and 10 where their graphs practically are overlapping. This is due to the relatively small ash content of the willow fuel.
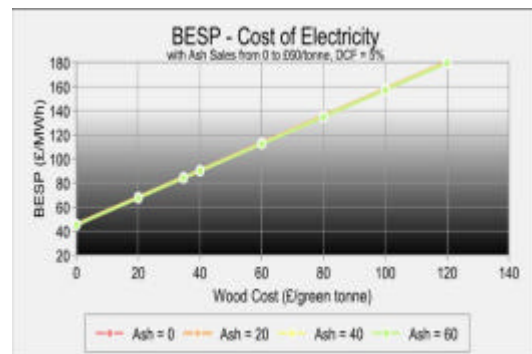

Figure 10: BESP versus Wood Cost with ash sales (in £/tonne) for the BFBC.

4.4 Economic Sensitivity Analyses

4.4.1 Sensitivity to the Variation in Capital Costs

Capital costs and other economic data from the Port Talbot and Steven's Croft plants are available and have been taken as the "base case" for the economic analysis. However, costs could increase for subsequent one-off versions of the plant, and could even eventually fall with experience or plant optimisation. For this reason the sensitivity of BESP to variations in capital costs was examined and is shown in Figs 11 and 12 (for DCF of 5%) for the CFBC and BFBC models respectively.
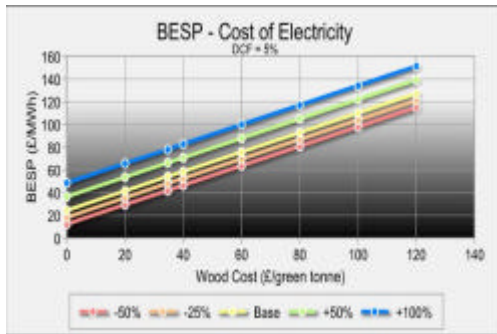
Figure 11: Variation of BESP with Green wood cost for Capital Costs from -50% to +100% of the base case at DCF of 5% for the CFBC.

In the base case, BESP was found to be £54.2/MWh at a wood cost of £50/daf tonne for the CFBC. If the Capital Costs were to drop by 50%, then BESP would fall to £41.6/MWh (a fall of 23.2%), or would rise to £66.3/MWh (an increase of 22.3%), if the Capital Costs rose by 50%, as shown in Fig. 11.
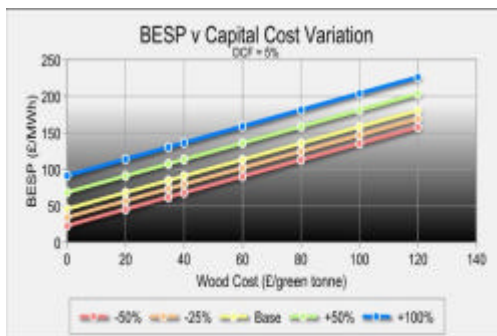

Figure 12: Variation of BESP with Green wood cost for Capital Costs from -50% to +100% of the base case at DCF of 5% for the BFBC.

In the base case, and with DCF of 5%, the BESP was found to be £84.6/MWh at a wood cost of £50/daf tonne for the BFBC. If the Capital Costs were to drop by 50%, then the BESP would fall to £61.8/MWh (a fall of 27.0%), or would rise to £107.4/MWh (an increase of 27.0%), if the Capital Costs rose by 50%, as shown in Fig. 12.

The Specific Investment also changes with variations in the Capital Costs, so the change in BESP with SI would follow the same trend as with Capital Costs and this can be seen for the CFBC and BFBC in Figs. 13 and 14 respectively.
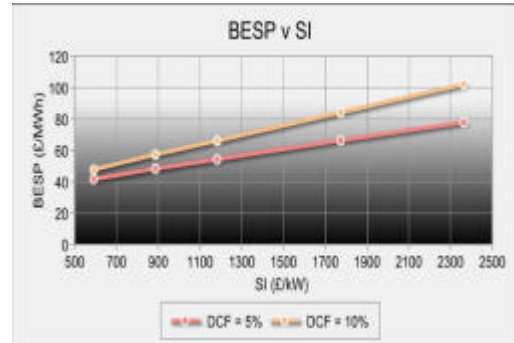

Figure 13: Variation of BESP with SI for Capital Costs from -50% to +100% of the base case for daf wood cost of £50/tonne for the CFBC.
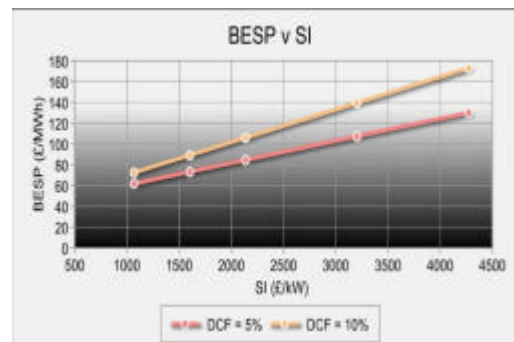

Figure 14: Variation of BESP with SI for Capital Costs from -50% to +100% of the base case for daf wood cost of £50/tonne for the BFBC.

4.4.2 Sensitivity to the Variation in insurance, operational and maintenance Costs

In addition to possible variations in capital costs, there is also the possibility that insurance, operational and maintenance costs could vary. The effect on BESP is shown in Figs. 15 and 16.
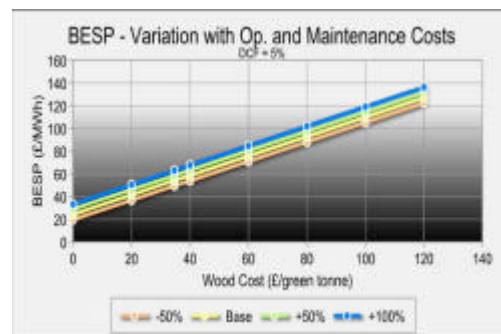

Figure 15: Variation of BESP with Green Wood Cost for Annual Insurance, Operational and Maintenance Capital Costs from -50% to +100% of the base case at DCF of 5%.for the CFBC.

For the CFBC base case, with a DCF of 5%, the BESP was found to be £54.2/MWh at a wood cost of £50/daf tonne. If the Annual Insurance, Maintenance and

Operational (O&M) Costs were to drop by 50%, then BESP would fall to £49.5/MWh (a fall of 8.7%), or would rise to £58.4/MWh (an increase of 7.7%), if the O&M Costs rose by 50%, as shown in Fig. 15.
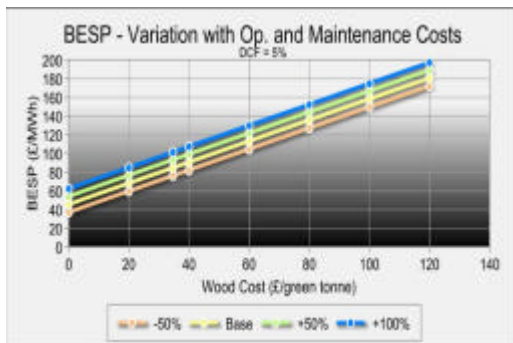

Figure 16: Variation of BESP with Green Wood Cost for Annual Insurance, Operational and Maintenance Capital Costs from -50% to +100% of the base case at DCF of 5%.for the BFBC.

For the BFBC base case, with a DCF of 5%, the BESP was found to be £84.6/MWh at a wood cost of £50/daf tonne. If the Annual Insurance, Maintenance and Operational (O&M) Costs were to drop by 50%, then BESP would fall to £76.1/MWh (a fall of 10.0%), or would rise to £93.1/MWh (an increase of 10.0%), if the O&M Costs rose by 50%, as shown in Fig. 16.

4.4.2 Sensitivity to the Variation in Load Factor

The Port Talbot power plant is conceived as a base load system, operating for around 8,000 hours a year. However it is possible that this will not always be the case and so it is useful to see how the BESP would vary with the capacity factor, as shown in Fig. 17.

It can be seen that (with DCF=5%) the BESP for the Port Talbot type (PT) CFBC would rise from £52.8/MWh to £73.9/MWh (40.0 % rise) as the Load Factor decreased from 90% to 40% and from £64.5/MWh to £92.1/MWh (42.8% rise), if the DCF were 10%. For the Steven's Croft type BFBC (with DCF=5%) the BESP would rise from £82.5/MWh to £121/MWh (46.7% rise) as the Load Factor decreased from 90% to 40% and from £103.1/MWh to £152.6/MWh (48.0% rise), if the DCF were 10%. This does not take into account any possible efficiency drops with Load Factor, and subsequent BESP increases.
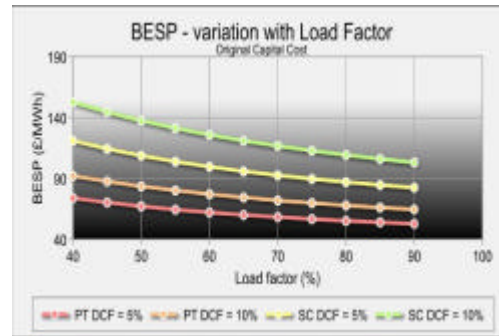

Figure 17: Variation of Cost of Electricity with Load Factor with a Wood Cost of £50/daf tonne

5 CONCLUSIONS

In Table IV, some of the nominal (from literature and websites) data are compared with the results of the simulations and with data from coal-fired power plants. The cost of electricity generation is also compared in Fig. 18.

Table IV: Comparison of biomass and coal power plants

	SCN	SCS	PTN	PTS	G	PF
Efficiency (LHV, %)	~31.3	28.9	~ 36	35.2	39.0	44.0
CO2 emissions (g/kWh)	n/a	1321	n/a	1090	841	760
Net Output MWe	44	43.6	350	351	250	600
SI (£/kW)	2136	2136	1182	1182	1227*	969*
BESP (£/MWh)	n/a	84.6	n/a	54.2	45.9**	35.7**

(DCF = 5% in the simulations)

(SCN = Steven's Croft (Nominal), SCS = Steven's Croft (Simulation), PTN = Port Talbot (Nominal), PTS = Port Talbot (Simulation), G = Gardanne (simulation with Federal coal) [6], PF = Typical supercritical PF [15])

(* 1453 $/kW converted at 1.5$/£ is 969 £/kW, and 1840 $/kW becomes 1227 £/kW)

(** 53.5 $/MWh converted at 1.5$/£ is 35.7 £/MWh, and 68.9 $/MWh becomes 45.9 £/MWh)

The efficiency of the Port Talbot type plant was found to be 35.2% in the simulation, which was close to the nominal efficiency of around 36%. This is lower than the efficiency of the coal-fired CFBC at Gardanne (39.0%) and that of a 600MW supercritical PF (44.0%), also using coal. The Port Talbot type plant has a lower efficiency than the Gardanne plant due to using the higher moisture content fuel and because it has an air-cooled condenser, rather than a conventional condenser. The higher steam conditions of the supercritical PF, as well as the use of low moisture content fuel, explains its higher efficiency.

The carbon dioxide emissions follow the plant efficiency i.e. the higher efficiency systems have correspondingly lower emissions, as can be seen in the above table.

The Specific Investment of the Port Talbot type plant is higher than the supercritical PF plant, which has the advantage of higher efficiency, economy of scale and also has benefitted from extensive exploitation. It is lower than the Gardanne plant, which suggests that the economics of CFBC development is improving.

Unsurprisingly the Break-even Electricity Selling Price (BESP) for the Port Talbot type plant is higher than that of the Gardanne or supercritical PF systems, but only to a level reflected by its deficit in plant efficiency. Power plants using biomass feedstock often attract financial incentives, which could compensate for their intrinsic higher cost of generating electricity.

In Fig. 18 it can be seen that the large biomass CFBC power plant is competitive with coal-fired power plants at generating electricity, at low wood costs, (and the smaller BFBC has a slightly higher BESP) when no subventions (such as ROCs) are considered.

The sensitivity analysis of BESP with variations to Capital Costs, Load factor and O&M Costs have made clear that base load operation of the power plant is the most important factor in its overall economic performance.

The efficiency of the simulated Steven's Croft type power plant is not significantly less than the nominal value and the CO_2 emissions are commensurate with this efficiency value.

The Specific Investment for this power plant is high, but is taken from actual, commercial figures. The BESP value is also quite high, but this is due to the high SI and low efficiency value of the Steven's Croft type power plant.

As for the Port Talbot type plant. the sensitivity analysis of BESP with variations to Capital Costs, Load factor and O&M Costs for Steven's Croft type have made clear that base load operation of the power plant is the most important factor in its overall economic performance (see Fig. 17).

In Fig. 18 it can be seen that the large biomass CFBC power plant is competitive with coal-fired power plants at generating electricity, at low wood costs, (and the smaller BFBC has a slightly higher BESP) when no subventions (such as ROCs) are considered.
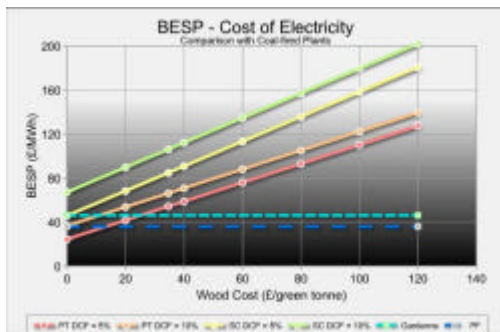

Figure 18: Comparison of Cost of Electricity for Biomass and Coal-fired power plants.

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