A technical and economic analysis of three large scale biomass combustion plants in the UK

David R. McIlveen-Wright *, Ye Huang, Sina Rezvani, David Redpath, Mark Anderson, Ashok Dave, Neil J. Hewitt

School of the Built Environment, University of Ulster, Shore Road, Jordanstown, Newtownabbey BT37 0QB, UK

HIGHLIGHTS

▶ One large and two medium scale commercial biomass combustion plants are compared.
▶ Techno-economic and sensitivity analyses of all three plants were made.
▶ Without incentives these plants are marginally viable; with ROCs they are competitive.

ARTICLE INFO

ABSTRACT

In the past there have been several reasons for not fuelling large scale power plants with biomass instead of fossil fuels. For example, fossil fuels have higher energy density, their costs had been relatively low until recently, the required (large) amounts of biomass have not been readily available and the cost and environmental impact of road transportation of large quantities of biomass were considerable. 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. Two other examples are the medium scale biomass power plants, (a) the 44 MWe Bubbling Fluidised Bed system at Steven's Croft, Lockerbie in Scotland and (b) the 30 MWe BFBC at Wilton (Wilton 10) in England.

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 all aspects of them. System efficiencies for generating electricity and CO_2 emissions are evaluated and compared with a large coal-fired CFBC plant and a typical supercritical coal-fired 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 these 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 three biomass plants modelled were found to be competitive with the coal-fired plants at low wood costs, even without any subventions. The effect of applying the Renewable Obligations Certificate (ROC) subvention to the economics of the power plants was also assessed for a wide range of wood fuel costs.

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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

* Corresponding author.
   E-mail address: dr.mcilveen-wright@ulster.ac.uk (D.R. McIlveen-Wright).

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. The particle size of biomass feedstock was found to be a critical parameter for evaluating the thermal reaction rate and energy yield [7]. In general, a smaller particle size of has been found to accelerate the reaction rate and enhance the energy yield efficiency [8–10]. However, grinding and milling of many types of biomass, particularly softwoods, to the small particle sizes required for pulverized fuel (PF) combustion, the de facto standard for hard coal, has proven difficult. Larger biomass particles tend to increase the flame length in cofiring with coal, which was shown to be detrimental to NO formation [11]. The larger biomass particles are therefore unsuitable for oxyfuel and PF combustion, whereas fluidised bed (FB) technologies have longer residence times in order to deal with such larger particles, making FB the most appropriate technology for larger scale power generation fuelled by biomass [12]. FBC technologies are now considered to be a mature technology for CHP and industrial applications. Some older fluidised bed technologies have experienced availability as low as 70% due to failures of their refractory sections or due to erosions of parts [13] More advanced technologies are reported to have capacity factors of up to 90% [14].

Future directions for them are to increase the fuel flexibility and biomass handling of the BFBC design and to develop more supercritical variations for the CFBC [15].

In the UK the introduction of Renewables Obligation Certificates (ROCs) [16] 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 [17], which came into force in November 2011 [18] in the UK 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, only the ROC incentive has been 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 [12]. 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. An example of a medium-sized biomass power plant is the system at Steven's Croft, Lockerbie in Scotland, which is a €132 m 44 MWe Bubbling Fluidised Bed plant [19]. This plant was commissioned in 2007 and uses Siemens/Kvaerner technology. A second example, the Wilton 10, is described in more detail in Section 2.3.

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 overall capital costs for the Port Talbot, Wilton 10 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' [20] for the Port Talbot power plant it is stated that the carbon emissions, in grammes of carbon per tonne of biomass per kilometer 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. At Wilton the majority of the wood fuel is expected to be supplied from within a 50 mile radius of the plant [21].

2. Methodology

2.1. ECLIPSE

The process simulation package, ECLIPSE [22], 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 [23].

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 break-even electricity selling price (BESP) is determined based on the net present value (NPV), for a range of biomass buying prices (at 30% Moisture Content). To cover uncertainties and to identify major influences on economic viability, 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 [24,25].

2.3. Plant description

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

2.3.1. Large-scale CFBC and medium-scale BFBC2

A description of the Port Talbot CFBC power plant and the Steven's Croft BFBC have been detailed elsewhere [26]. However, a description of the Wilton 10 BFBC plant is needed and is given in Section 2.3.2.

2.3.2. Medium-scale BFBC1 –Wilton 10

2.3.2.1. Power and facilities at Wilton fuel supply. The wood for the Wilton 10 power station comes from four separate sources [21].

- Around 40% of the 300,000 t (150,000 bone dry tonnes) a year total is recycled wood from UK Wood Recycling, a company specifically founded for this project. This is received, stored and chipped on a nearby, separately owned site at Wilton.
- A further 20% comes to the site already chipped as offcuts from sawmills.
- SembCorp is working with the Forestry Commission to bring another 20% from north east forests in the form of small roundwood logs – items sometimes left on the forest floor after routine tree felling operations.
- Finally, 20% comprises specially grown energy crops in the form of short rotation coppice willow. The company Greenergy is supplying the wood, to be grown by farmers and other landowners within a 50-mile radius of the site.
- The new plant required the growth of around 7500 acres of coppice in the area, an activity that is creating local wildlife havens.

The power plant description is outlined in the artist's impression in Fig. 1 and in the schematic diagram of Fig. 2 and was transformed into the Process Flow Diagram in Fig. 3 for modelling purposes.

Fig. 1. Artist's Impression of Wilton 10 (http://www.sembutilities.co.uk/utilities/biomass-power-station.html).

2.3.2.2. Fuel Processing. All the wood needs to be chipped and mixed in careful proportions before being fed into the boiler, which uses technology already in use in Scandinavia and other areas.

2.3.2.3. Boiler at Wilton. The bubbling fluidised bed boiler was provided by Foster Wheeler and was designed to use recycled, green and short rotation coppice wood [27] and to comply with the emission limits in the Large Combustion Plant Directive and the Waste Incineration Directive. The bubbling fluidised bed boiler works with high moisture content fuels and fuels that are difficult to handle or have difficult ash characteristics. It is therefore suitable for forest waste and short rotation coppice wood [21].

2.3.2.4. Wilton 10 Turbine. The 35 MWe steam turbine and power island was supplied by Siemens PG, using the SST 400 steam turbine/generator set. This came complete with condenser, Flender gearbox, oil system, and PCS7 control system [28]. This turbine is
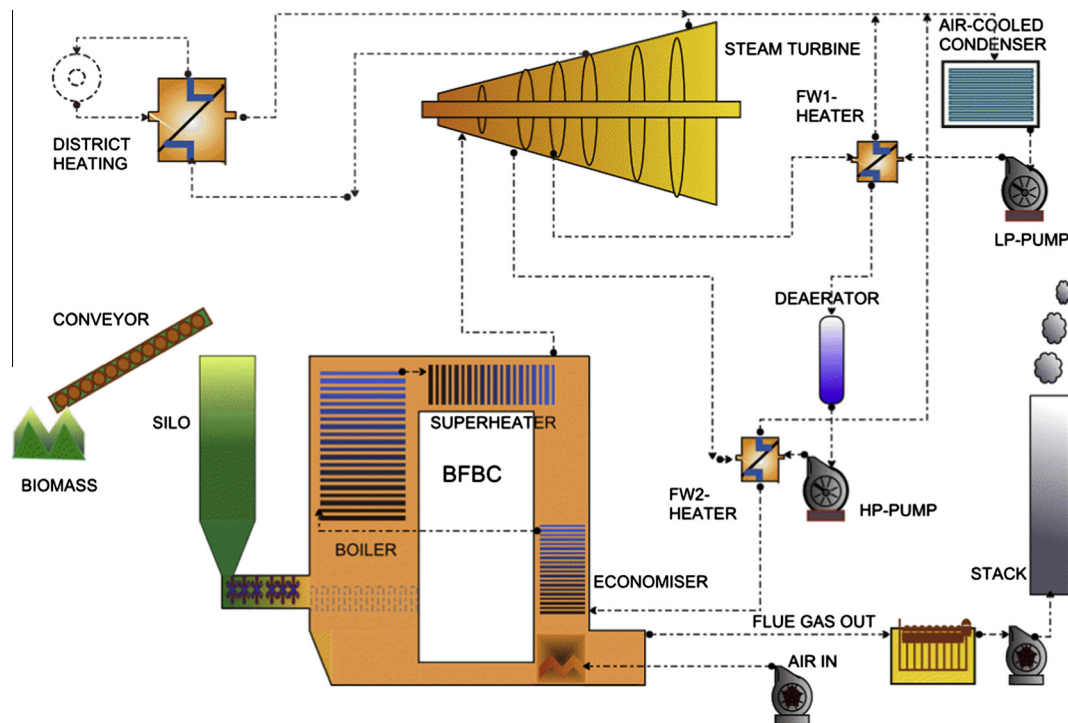

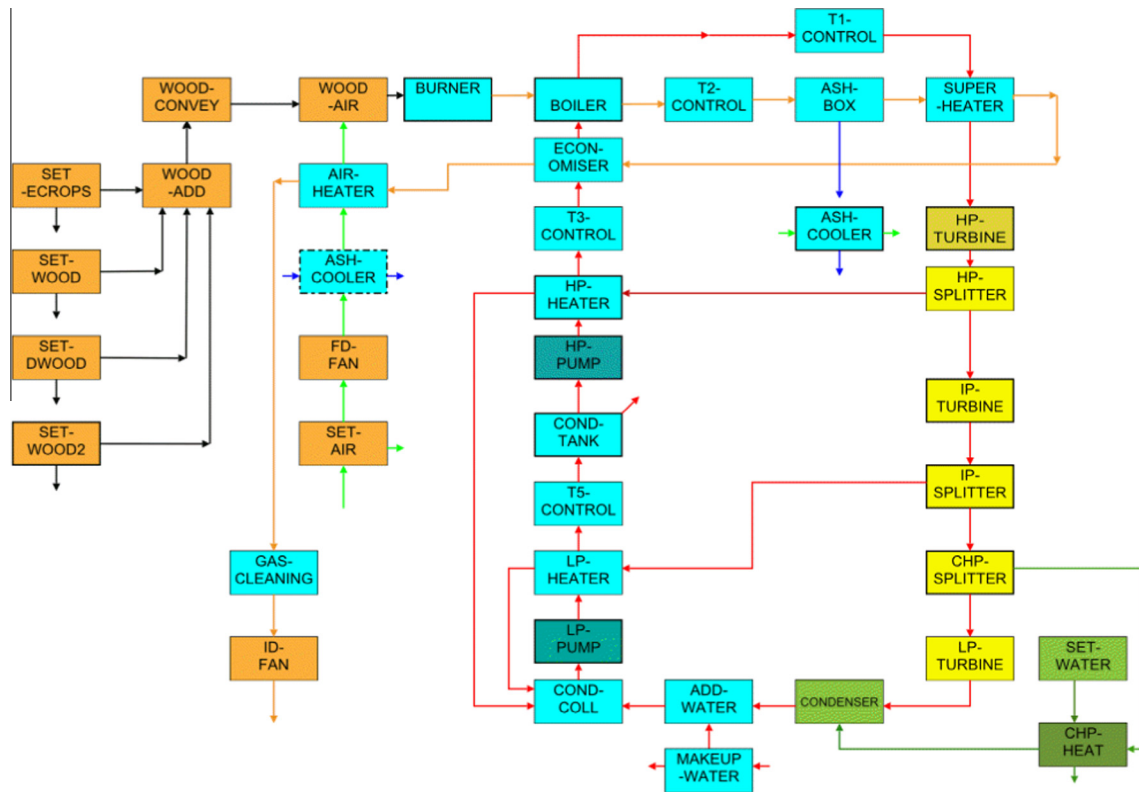**Fig. 2.** Schematic of 'Wilton 10' BFBC.

Fig. 3. PFD of 'Wilton 10' BFBC.

suitable for both back pressure and condensing operation and so could be used in both CHP and 'power only' modes.

2.3.3. 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 1.

3. Results

3.1. Technical data overview

The three systems were modelled in ECLIPSE and the technical data from the simulations are summarized in Table 2.

3.2. 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

Table 1
Willow composition.

Fuel	Willow		
	As received	Dry	daf[a]
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

[a] Daf = dry, ash free.

typical for combustion power plants with outputs greater than 125 MWe, as shown in Table 3. Similarly the publicly available capital costs for the Wilton 10 and the Steven's Croft BFBCs have been applied to the analysis.

3.3. Economic simulation results

The economics section of the ECLIPSE process simulation software were used to make an economic analysis of each power plant and the significant economic factors (Specific Investment, BESP and Payback Period) are shown in Table 4.

Table 2
ECLIPSE technical data overview.

		CFBC (PT)	BFBC1 (WI)	BFBC2 (SC)
daf Wood flow rate	Tonnes/day	5000	558.7	751.8
Steam cycle	(bar, °C)	160/538 & reheat	120/520	137/537
Thermal input, LHV	kW	997.2	112	150.7
Thermal input, HHV	kW	1081.2	120.8	162.6
Efficiency, LHV	%	35.2	30.17	28.01
Efficiency, HHV	%	32.4	27.96	26.79
Exhaust gas temp	°C	110.7	111	116.8
Exhaust gas flow	kg/s	485	57.5	74.5
Total Ash Flow	Tonnes/day	95	10.8	14.3
Specific CO_2 emissions	kg/MW h	1091	1287	1320
NOx emissions	mg/Nm³	462	465	477
O2 (dry)	Vol%	4.1	4.0	3.4
Gross electricity generated	MW	382.9	36.84	49.02
Electricity usages	MW	32.0	3.05	5.45
Net electricity output	MW	350.9	33.79	43.57

BFBC1 (WI) is based on Wilton 10 and BFBC2 (SC) on Steven's Croft. The CFBC (PT) is based on the Port Talbot plant.

Table 3
ECLIPSE cost data overview.

	BFBC1 (WI)	BFBC2 (SC)	CFBC (PT)
Total process CC (EPC) (£m, 2008)	60	90	400
Working capital (EPC, %)	2.00	2.00	2.00
Capital fees (EPC, %)	0.40	0.40	0.40
Contingency (EPC, %)	10.0	10.0	10.00
Commissioning cost (EPC, %)	1.00	1.00	1.00
Total CC (inc. commissioning costs, working capital & fees)	62.040	93.060	413.600
Total CC (inc. contingency)	68.040	102.060	453.600
Annual insurance costs (%)	1.0	1.0	1.0
Annual operating costs inc. labour & supplies (%)	2.0	2.0	2.0
Annual maintenance costs inc. labour & supplies (%)	2.5	2.5	2.5

The Break-even Electricity Selling Price (BESP) will change with the cost of fuel. In Fig. 4 this variation is shown for a range of wood costs. For example, at a wood chip cost of £50/dry tonne, 30% MC, (and no ash sales), BESP was found to be £66/MW h at DCF = 10%, and £54.2/MW h at DCF = 5% for the CFBC.

3.4. Economic sensitivity analyses

3.4.1. Sensitivity to the variation in capital costs

Capital costs and other economic data for the Port Talbot, Wilton 10 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 Fig. 5 (for DCF of 5% and 10%) for the three CFBC and BFBC models.

3.4.2. Sensitivity of BESP to the variation in load factor

The Port Talbot power plant is conceived as a base load system, operating for around 8000 h 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 or load factor, as shown in Fig. 6.

It can be seen that (with DCF = 5%) the BESP for the Port Talbot type (PT) CFBC would rise from £52.8/MW h to £73.9/MW h (40.0% rise) as the load factor decreased from 90% to 40% and from £64.5/MW h to £92.1/MW h (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/MW h to £121/MW h (46.7% rise) as the load factor decreased from 90% to 40% and from £103.1/MW h to £152.6/MW h (48.0% rise), if the DCF were 10%. The Wilton 10 type BFBC behaviour is very similar to the Steven's Croft type.

Table 4
Economic results overview ECLIPSE for the three plants.

	CFBC (PT)	BFBC1 (WI)	BFBC2 (SC)
SI (£/kW)	1182	2068	2136
BESP (£/MW h), DCF = 5%	54.2	83.3	84.6
Payback (years), DCF = 5%	21	19	19
BESP (£/MW h), DCF = 10%	66	104	106
Payback (years), DCF = 10%	14	13	13

This does not take into account any possible efficiency drops with load factor, and subsequent BESP increases.

4. Discussion and conclusions

4.1. Discussion

In Table 5, 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. 9.

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 600 MW 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.
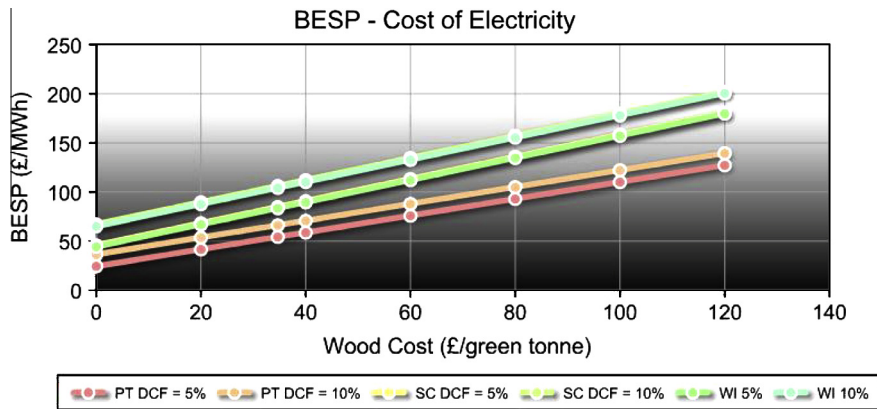
Fig. 4. BESP versus Wood Cost with no ash sales for the three plants. SC and WI practically overlap.
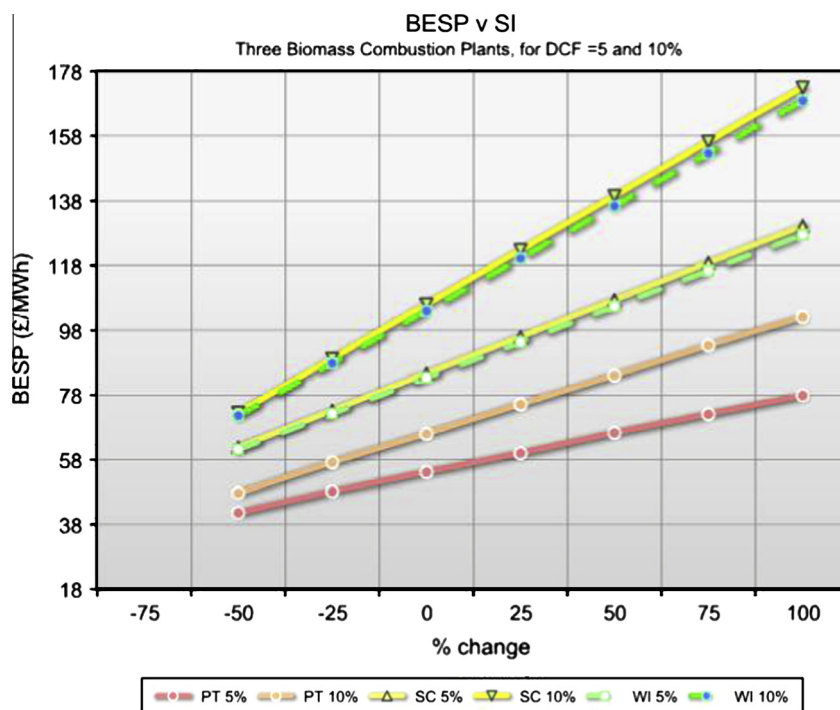

Fig. 5. BESP versus percentage change in specific capital investment (SI) for daf wood cost of £50/tonne. (Again SC and WI practically overlap).

The amount of carbon dioxide emissions follows 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. 9 and Table 5 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 wood fuel costs have shown that base load operation of the power plant is a 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 Wilton 10 efficiency and CO_2 emissions are similar, as would be expected from a plant of similar size, feedstock and steam cycle.

The specific investment values for the two BFBC power plants are high, but have been 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 smaller BFBC power plants.

Clearly the large biomass CFBC has performance characteristics approaching those of the coal-fired plants. Wood moisture content plays a significant role in reducing its performance.

The smaller BFBCs suffer from this too, and also from their lower superheated steam conditions. Their capital costs are also
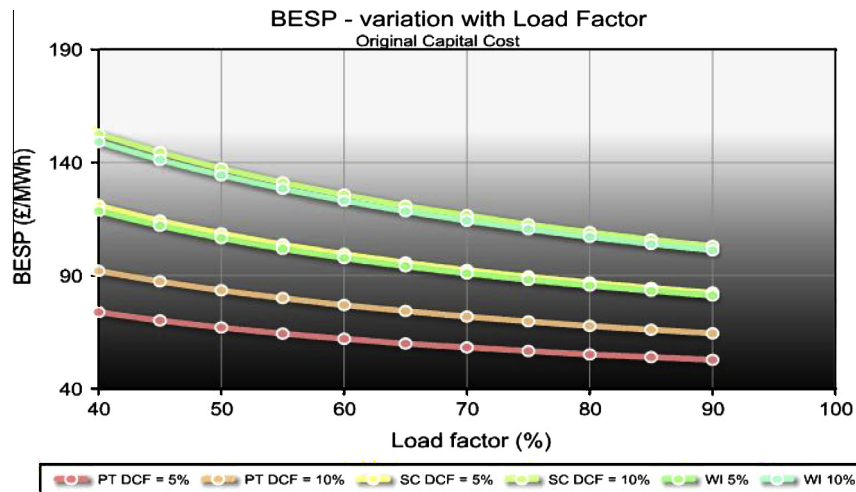
Fig. 6. Variation of cost of electricity with load factor with a wood cost of £50/daf tonne (again SC and WI practically overlap).

Table 5
Comparison of biomass and coal power plants.

	WIN	WIS	SCN	SCS	PTN	PTS	G	PF
Efficiency (LHV, %)	n/a	30.2	~31.3	28.9	~36	35.2	39.0	44.0
CO_2 emissions (g/kW h)	n/a	1287	n/a	1321	n/a	1090	841	760
Net output (MWe)	30	34	44	43.6	350	351	250	600
SI (£/kW)	2000	2068	2136	2136	1182	1182	1227[a]	969[a]
BESP (£/MW h)	n/a	83.3	n/a	84.6	n/a	54.2	45.9[b]	35.7[b]

DCF = 5% in the simulations.
WIN = Wilton 10 BFBC (Nominal), WIS = Wilton 10 (Simulation), SCN = Steven's Croft BFBC (Nominal), SCS = Steven's Croft (Simulation), PTN = Port Talbot CFBC (Nominal), PTS = Port Talbot (Simulation), G = Gardanne (simulation with Federal coal) [6], PF = Typical supercritical PF [29].
[a] 1453 $/kW converted at 1.5 $/£ is 969 £/kW, and 1840 $/kW becomes 1227 £/kW).
[b] 53.5 $/MW h converted at 1.5 $/£ is 35.7 £/MW h, and 68.9 $/MW h becomes 45.9 £/MW h.

significantly higher, as shown by their SIs being almost double those of the larger biomass CFBC and the coal-fired plants.

An extensive review of almost 500 FBC (Fluidised Bed Combustion) projects [15] showed that specific investment is expected to fall with every doubling in installed capacity (in MWe), leading to improved economics for electricity generation from FBC technologies in the future.

The specific investment (SI) reduction as a function of plant size can be calculated according to different techno-economic models. The cost model based on an Artificial Neural Network (ANN) performed on a set of data from different plants from 5 to 50 MW shows a specific cost reduction between 12% to 24% assuming a doubling in plant size [30]. The regression model by Bridgwater indicates a specific plant cost reduction of around 15% for every doubling in the CFBC plant size [31]. Fig. 7 shows a calculation of the specific cost reduction of plants between 100 and 400 MW. The calculation is based on scaling factors 0.6, 0.7, and 0.8 as reported in [15]. According to the calculation, a size increase of 100% (doubled plant size) corresponds to a specific cost reduction between 13% to 24%. A plant size increase from 100 MW to 400 MW, on the other hand, will provide an average SI reduction of 35%.

4.2. Effect of Renewables Obligation Certificates on plant viability

Renewables Obligation Certificates, ROCs, have been available since 2002 in the UK and their value is determined at auction. The average value of the auctions can be found at the online auction service [32] as shown in Fig. 8 Assuming one ROC is available for each unit of electricity generated from biomass, then a
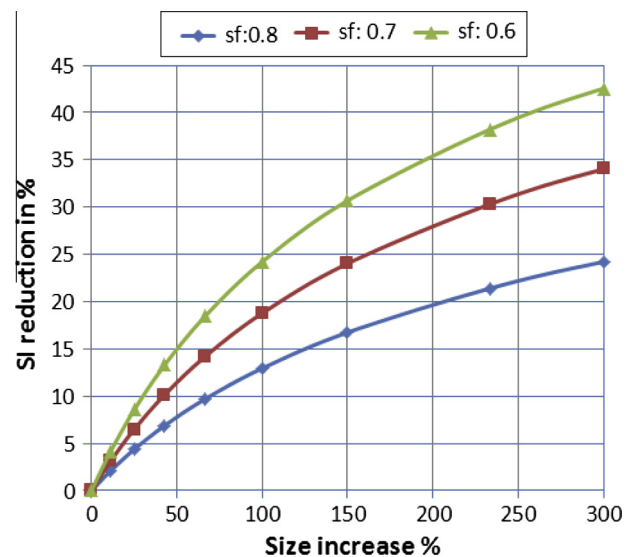

Fig. 7. SI reduction according to the plant size.

biomass-fired power plant may become competitive with fossil fuel-fired plants by receiving ROCs.

The average price for ROCs since their inception is shown in Fig. 8.

Fig. 9 shows the variation of BESP with wood cost for 3 power plants – Wilton 10, Port Talbot and Steven's Croft. Each column shows how BESP varies as the wood fuel buying price changes from
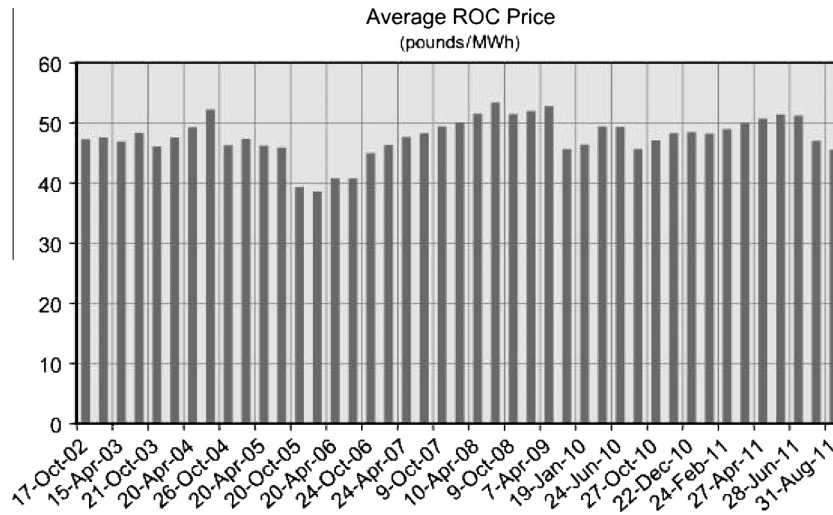
Fig. 8. The average ROC value over the period in this figure was 47.56 £/MW h.
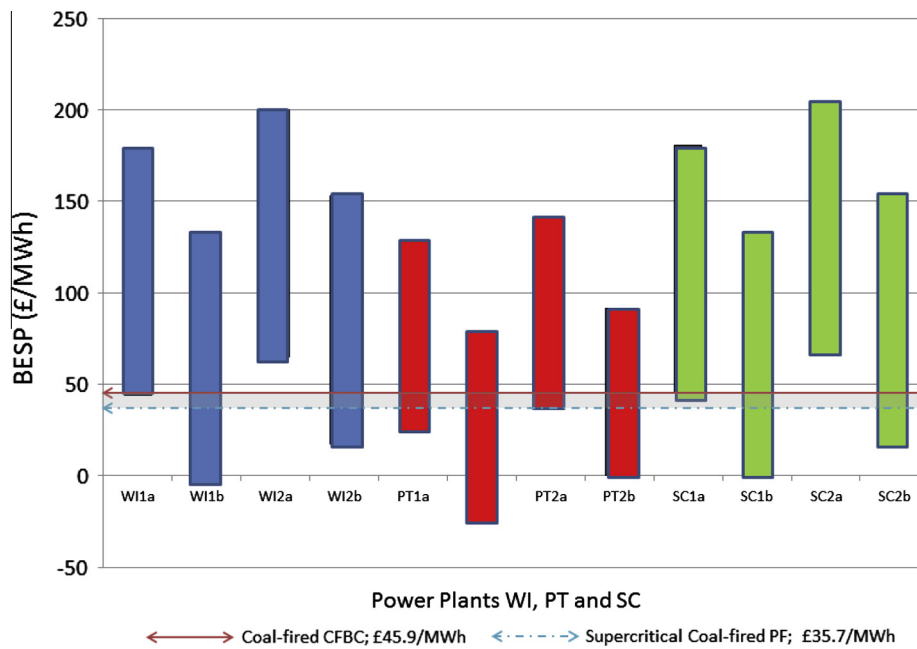

Fig. 9. Variation of BESP with wood cost for the 3 plants at DCFs of 5% and 10%, with and without the ROC subvention.

0 to 120 £/dry tonne. The first of each set of 4 columns (one set for each power plant) shows the variation of BESP with wood cost using a DCF of 5%. The second column shows the same variation as the first, except that the average ROC value has been subtracted. The third column shows the same as the first, except the DCF is taken as 10%. The fourth column shows the same as the second, except that the DCF is taken as 10%.

Two horizontal lines are shown to demonstrate the typical range of BESP for coal-fired power plants. The upper (BESP = 45.9 £/MW h) is for the Gardanne type CFBC, and the lower (BESP = 35.7 £/MW h) is for an average supercritical PF plant.

Scenarios with subscript 'b' in Fig. 9 refer to the cases with ROCs included. All of these are shown to be competitive, at some values of wood cost, with the coal-fired power plants, as shown by the horizontal lines. Scenarios with subscript 'a' refer to the cases with no ROCs included without ROCs the BFBC plants are only competitive at near-zero wood cost, and the CFBC at low wood costs.

4.3. Conclusions

The LHV efficiency for the large CFBC was found to be around 35% and about 30% for the two medium-sized BFBCs. The difference is mainly due to the higher superheated steam conditions of the CFBC. Lower CO_2 emissions are related to the more efficient conversion of fuel, so the large CFBC emits less per kW h than the small BFBCs, as shown in Table 4.

It can be seen from Fig. 9 that the 2 BFBC plants have very similar economics. Both plants are not quite economic at a DCF of 5%, but with the average ROC subvention, they can compete with the coal-fired power plants and at low wood costs, they could almost generate electricity at no cost! At low wood costs and without ROCs, the Port Talbot CFBC can compete with the coal-fired power plant, and with ROCs, it can compete even with relatively high wood costs.

The Wilton 10 plant is 'heat ready', and so could also improve its economics by selling the 10 MW of heat that could be extracted.

Acknowledgements

References

[1] McIlveen-Wright DR, Williams BC, McMullan JT. A re-appraisal of wood-fired combustion. Bioresour Technol 2001;76(3):183–90.
[2] Thornley P. Increasing biomass based power generation in the UK. Energy Policy 2006;34(15):2087–99.
[3] Thornley P, Rogers J, Huang Y. Quantification of employment from biomass power plants. Renew Energy 2008;33(8):1922–7.
[4] McIlveen-Wright DR et al. A technical and environmental analysis of co-combustion of coal and biomass in fluidised bed technologies. Fuel 2007;86(14):2032–42.
[5] De S, Assadi M. Impact of cofiring biomass with coal in power plants - A techno-economic assessment. Biomass Bioenergy 2009;33(2):283–93.
[6] McIlveen-Wright DR et al. A Techno-economic assessment of the reduction of carbon dioxide emissions through the use of biomass co-combustion. Fuel 2011;90(1):11–8.
[7] Chiang K-Y, Chien K-L, Lu C-H. Characterization and comparison of biomass produced from various sources: suggestions for selection of pretreatment technologies in biomass-to-energy. Appl Energy 2012;100:164–71.
[8] Erlich C, Fransson TH. Downdraft gasification of pellets made of wood, palm-oil residues respective bagasse: experimental study. Appl Energy 2011;88(3):899–908.
[9] Hernández JJ, Aranda-Almansa G, Bula A. Gasification of biomass wastes in an entrained flow gasifier: effect of the particle size and the residence time. Fuel Proc Technol 2010;91:681–92.
[10] Mohammed MAA et al. Air gasification of empty fruit bunch for hydrogen-rich gas production in a fluidized-bed reactor. Energy Conver Manag 2011;52: 1555–61.
[11] Holtmeyer ML, Kumfer BM, Axelbaum RL. Effects of biomass particle size during cofiring under air-fired and oxyfuel conditions. Appl Energy 2012;93:606–13.
[12] Khan AA et al. Biomass combustion in fluidized bed boilers: Potential problems and remedies. Fuel Proc Technol 2009;90(1):21–50.
[13] Basu P. Combustion and gasification in fluidized beds. Taylor and Francis; 2006.
[14] Utt J, Giglio R. Foster Wheeler's 660 MWe supercritical CFBC technology provides fuel flexibility for Asian power markets, in PowerGen Asia. Thailand: Bangkok; 2012.
[15] Koornneef J, Junginger M, Faaij A. Development of fluidized bed combustion: An overview of trends, performance and cost. Progr Energy Combus Sci 2007;33(1):19–55.
[16] Ofgem. Renewables Obligation. <http://www.ofgem.gov.uk/Sustainability/Environment/RenewablObl/Pages/RenewablObl.aspx>. 03.06.11; 2011.
[17] DECC, D.o.E.a.C.C. Renewable Heat Incentive (RHI) Scheme. <http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/renewable/policy/incentive/incentive.aspx>. 03.06.11; 2011.
[18] Renewable Heat Incentive Ltd. Renewable Heat Incentive. <www.rhincentive.co.uk/>. 2011.
[19] Anon. Stevens Croft Wood Burning Plant, Lockerbie, Scotland, United Kingdom. <http://www.power-technology.com/projects/stevenscroftbiomass/>.
[20] Anon. Non-technical Summary of the Port Talbot Biomass Power Plant. <http://www.prenergypower.com/nontechnicalsummary.pdf>. [12.10.12]; 2012
[21] Power Technology. Wood Burning Power Station at Wilton 10. <http://www.power-technology.com/projects/Wood-Burning/>. [9.06.11]; 2007.
[22] Williams BC, 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 Res 1996;20:125–42.
[23] McIlveen-Wright DR, McMullan JT, Guiney DJ. Wood-fired fuel cells in selected buildings. J Power Sources 2003;118(1–2):393–404.
[24] Rajaram S. Next generation CFBC. Chem Eng Sci 1999;54(22):5565–71.
[25] Jacquet L, et al., Scaling up of CFB boilers the 250 MWe GARDANNE CFB project. In Proceedings of the American Power Conference; 1994. p. 930–6.
[26] McIlveen-Wright D, Huang Y, Rezvani S, Ghayur A, Redpath D, Dave A, Hewitt N. A technical and economic analysis of large scale biomass combustion. In: 19th European Biomass Conference and Exhiition, ETA: Berlin; 2011. p. 1319–27.
[27] FW News. Major green power win – Wilton 10 – new biomass-fuelled boiler. 2007; <https://www.fwc.com/GlobalEC/pdf/SembCorpUK.pdf>.
[28] Anon. Wood Burning Power Station at Wilton 10, United Kingdom. <http://www.power-technology.com/projects/Wood-Burning/>.
[29] Anon., Cost and performance baseline for fossil energy plants, N.E.T.L. (NETL), editor; 2007.
[30] Rezvani S. Knowledge based approach to waste utilisation for energy generation in northern ireland, in northern ireland centre for energy research and technology, faculty of engineering. University of Ulster: Coleraine; 2005.
[31] Bridgwater AV, Toft AJ, Brammer JG. A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. Renew Sustain Energy Rev 2002;6:181–248.
[32] NFPA. Online e-ROC Auction Service. 2012. http://www.e-roc.co.uk/trackrecord.htm.