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A TECHNICAL AND ECONOMIC ANALYSIS OF THREE LARGE SCALE BIOMASS COMBUSTION PLANTS IN THE UK

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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 of medium scale biomass power plants are the 44 MWe Bubbling Fluidised Bed system at Steven's Croft, Lockerbie in Scotland and 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 CO2 emissions are evaluated and compared with a large coal-fired CFBC plant and a typical supercritical coal-fired PF power plant.

The specific capital 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 capital investment for two discount cash flow rates was investigated. The BESP for the three biomass plants modeled were found to be competitive with the coal-fired plants at low wood costs, even without any subventions. The effect of applying the Renewables Obligation Certificate (ROC) subvention to the economics of the power plants was also assessed for a wide range of wood fuel costs.

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

NOMENCLATURE

Abbreviation

BESP	Break-even Electricity Selling Price
BFBC	Bubbling Fluidised Bed Combustion
CFBC	Circulating Fluidised Bed Combustion
Daf	dry, ash free
IEA	International Energy Agency
MC	Moisture Content
NPV	Net Present Value
O&M	Operational and Maintenance
ROC	Renewables Obligation Certificate
SI	Specific Investment

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 was 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, 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 [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, 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' [11] 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. At Wilton the majority of the wood fuel is expected to be supplied from within a 50 mile radius of the plant [12].

2. METHODOLOGY

2.1 ECLIPSE Process Simulator

The process simulation package, ECLIPSE [13], 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 [6] and fuel cells integrated with biomass gasification [14].

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.

This power plant model is a circulating fluidised bed combustion system (CFBC), based on the 250 MWe Gardanne power plant [15],[16].

3. PLANT DESCRIPTION

3.1 Large Scale CFBC and Medium Scale BFBCs

Descriptions of the Port Talbot CFBC power plant and the Steven's Croft BFBC have been detailed elsewhere [17]. However, a description of the Wilton 10 BFBC plant is needed and is given in the next section.

3.2 Medium Scale BFBC, Wilton 10

3.2.1 Fuel Supply for Wilton 10

The wood for the Wilton 10 power station comes from four separate sources [12].

- Around 40% of the 300,000t (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 7,500 acres of coppice in the area, an activity that is creating local wildlife havens.

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.

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 [18] 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 [12].

3.2.4 Wilton Turbine

The 35MWe 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 [19]. This turbine is suitable for both back pressure and condensing operation and so could be used in both CHP and 'power only' modes.

Figure 4 Impression of Wilton 10 (http://www.sembutilities.co.uk/utilities/biomass-power-station.html)

The power plant description is outlined in the artist's impression in Fig 4 and in the schematic diagram of Fig 5 and was transformed into the Process Flow Diagram in Fig 6 for modeling purposes.

Figure 5 Schematic of Wilton 10 BFBC

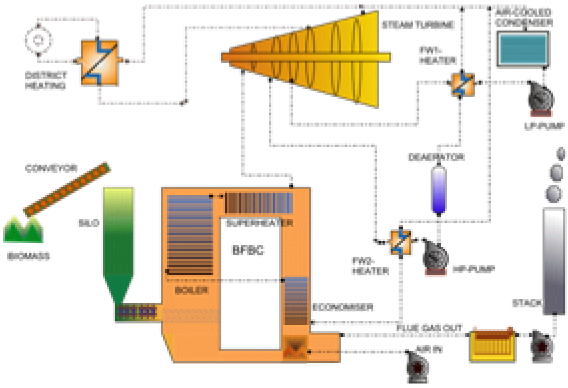
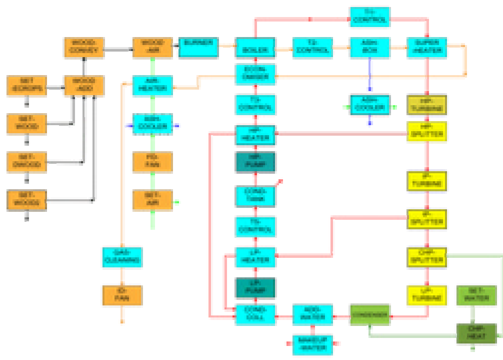


Figure 6 PFD of Wilton 10 BFBC



3.3 Moisture Content 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 ECLIPSE Technical Data Overview

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

Table II: ECLIPSE Technical Data Overview

		CFBC	BFBC1	BFBC2
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 CO2 emissions	kg/MWh	1091	1287	1320
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 is based on Wilton 10 and BFBC2 on Steven's Croft. The CFBC is based on the Port Talbot plant.

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 25 MWe, as shown in Table III.

Table III: ECLIPSE Cost Data Overview

	BFBC1 WI	BFBC2 SC	CFBC
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

4.3 Economic Simulations Overview

Table IV ECLIPSE Economic Results Overview for the three plants

	CFBC	BFBC1 WI	BFBC2 SC
SI (£/kW)	1,182	2,068	2,136
BESP (£/MWh), DCF=5%	54.2	83.3	84.6
Payback (years), DCF=5%	21	19	19
BESP (£/MWh), DCF=10%	66	104	106
Payback (years), DCF=10%	14	13	13

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 outputas shown in Table IV.

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.

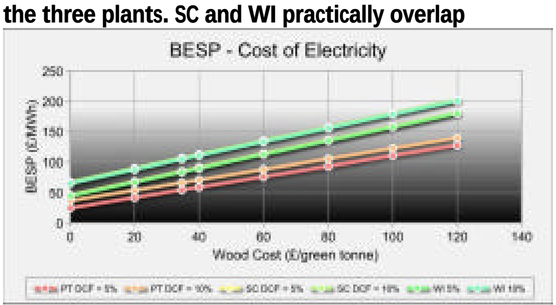
The Specific Investment for BFBC2 was found to be £2,136/kW from the ECLIPSE economic simulation and the supplied capital costs and nominal output.

For a DCF of 10%, the payback period for BFBC2 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 the BFBCs, assuming a Discounted Cash Flow Rate (DCF) of 5% and also for a DCF of 10%.

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 three plants. SC and WI practically overlap

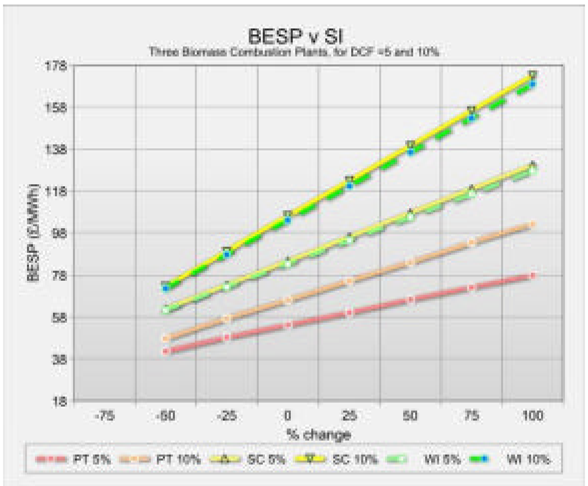


4.4 Economic Sensitivity Analyses

4.4.1 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 8 (for DCF of 5% and 10%) for the three CFBC and BFBC models.

Figure 8 BESP versus Percentage Change in Specific Capital Investment (SI) for daf wood cost of £50/tonne. (Again SC and WI practically overlap).

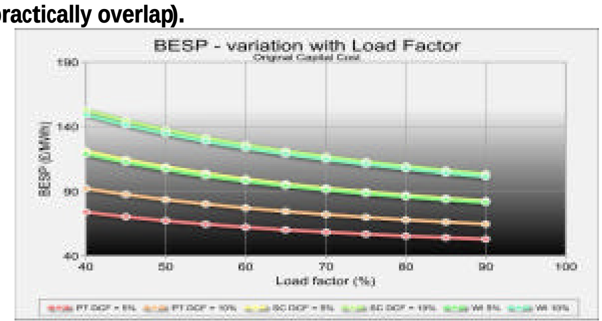


4.4.2 Sensitivity of BESP to the Variation in Load Factor

The Port Talbot power plant is conceived as a base load system, operating for around 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. 9.

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 9 Variation of Cost of Electricity with Load Factor with a Wood Cost of £50/daf tonne (Again SC and WI practically overlap).



5. CONCLUSIONS

In Table V, some of the nominal data (from literature and websites) are compared with the results of the simulations and with data from coal-fired power plants. The costs of electricity generation are also compared in Fig. 11.

Table V Comparison of biomass and coal power plants

	Efficiency	CO_2 emissions	Net Output	SI	BESP
	LHV, %	g/kWh	MWe	£/kW	£/MWh
WIN	n/a	n/a	30	2000	n/a
WIS	30.2	1287	34	2068	83.8
SCN	~31.3	n/a	44	2136	n/a
SCS	28.9	1321	43.6	2136	84.6
PTN	~36	n/a	350	1182	n/a
PTS	35.2	1090	351	1182	54.2
G	39.0	841	250	1227*	45.9**
PF	44.0	760	600	969*	35.7**

(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 [20])

(* 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, which significantly reduces the net electricity output. 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. 11 and Table V 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.

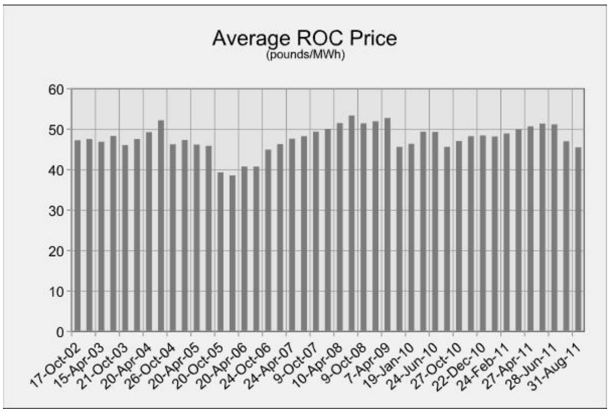
The smaller BFBCs suffer from this too, and also from their lower superheated steam conditions. Their capital costs are also significantly higher, as shown by their Sis being almost double those of the larger biomass CFBC and the coal-fired plants.

5.2 Effect of ROCs 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 [21] as shown in fig 10 below. Assuming one ROC is available for each unit of electricity generated from biomass, then a 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 Figure 10.

Figure 10 Average ROC value over time

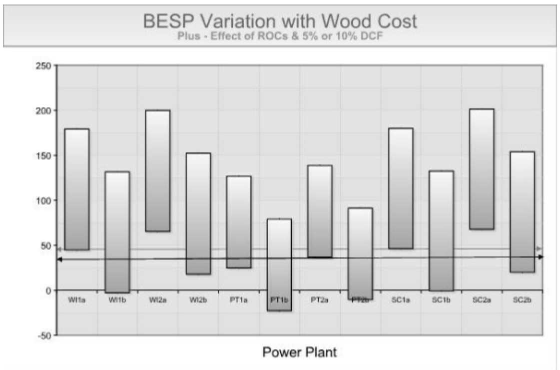


The average ROC value over the period in this figure was 47.56 £/MWh.

Figure 11 shows the variation of BESP with wood cost for 3 power plants – Wilton 10, Port Talbot and Steven's Croft. Each vertical column shows how it varies as the wood cost changes from 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 BESP for coal-fired power plants. The upper (BESP = 45.9 £/MWh) is for the Gardanne type CFBC, and the lower (BESP = 35.7 £/MWh) is for an average supercritical PF plant.

Figure 11 BESP v Wood Cost for the three plants. Effect of ROCs at different DCF values.



Scenarios with subscript 'b' in Fig. 11 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. Without ROCs the BFBC plants are only competitive at near zero wood cost, and the CFBC at low wood costs.

It can be seen that the 2 BFBC plants have very similar economics. Both plants are not only 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! The Port Talbot CFBC can do this as well, even with the DCF of 10%. 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.

6. ACKNOWLEDGEMENTS

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