The Economics of Reducing Carbon dioxide Emissions by the Use of Biomass Co-Combustion

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Abstract
The use of biomass, which is considered to produce no net CO_2 emissions in its life cycle, can reduce the effective CO_2 emissions of a coal-fired power generation system, when co-fired with the coal, but can also reduce system efficiency and increase electricity selling price. An analysis of the system, using only coal, only biomass and a coal-biomass mixture can identify the economic cost of reducing CO_2 emissions through the replacement of coal with biomass.

The technical feasibility of burning biomass or certain wastes with pulverised coal in utility boilers has been well established. Co-firing had also been found to have little effect on efficiency or flame stability, and pilot plant studies had shown that co-firing could reduce NOx and SOx emissions.

The technical, environmental and economic analysis of such technologies, using the ECLIPSE suite of process simulation software, is the subject of this study. System efficiencies for generating electricity are evaluated and compared for the different technologies and system scales. The capital costs of systems are estimated for coal-firing, and also any additional costs introduced when biomass is used. The break-even electricity selling price is calculated for each technology, taking into account the system scale and fuel used. Since CO_2 emissions are reduced when biomass is used, the effect of the use of biomass on the electricity selling price can be found and the penalty for emissions reduction assessed.

Several technologies could be applied to the co-combustion of biomass or waste and coal. The assessment studies here examine the potential for co-combustion of a) a 600 MWe pulverised fuel (PF) power plant, (i) co-firing coal with straw and sewage sludge and (ii) using straw derived fuel gas as return fuel; b) a 350 MWe pressurised fluidised bed combustion (PFBC) system co-firing coal with sewage sludge; c) 250 MWe and 125 MWe circulating fluidised bed combustion (CFBC) plants co-firing coal with straw and sewage sludge; d) 25 MWe CFBC systems co-firing low and high sulphur content coal with straw, wood and woody matter pressed from olive stones (WPOS); e) . 12 MWe CFBC co-firing low and high sulphur content coal with straw; and f) 12 MWe bubbling fluidised bed combustion (BFBC), also co-firing low and high sulphur content coal with straw.

In the large systems the use of both straw and sewage sludge resulted in a small reduction in efficiency (compared with systems using only coal as fuel) and an increase in investment costs. However, the high cost of straw led to a significant

increase in the electricity selling price. In the PFBC there was no penalty found in using dewatered sewage sludge.
In the small-scale systems the high moisture content of the wood chips chosen caused a significant efficiency reduction. However, the capital cost of wood fuel processing is lower than for straw. This, together with the high cost of straw means that wood-fired CFBC electricity selling prices are significantly lower than the equivalent straw based systems.

Introduction

Power generation is a major user of fossil fuels and the demand for electricity is growing steadily throughout the developed world and dramatically in the less developed countries. The replacement of all or part of these fossil fuels by renewable energy sources, such as biomass and waste, is an attractive means of reducing greenhouse gas emissions. Biomass and waste are also attractive because they are indigenous fuels, providing local employment and a boost to the rural economy. Conventional ways of disposing of waste, such as landfilling and dumping to sea are also becoming more difficult, more expensive and are no longer an acceptable solution.
The European Commission has fostered interest in co-firing coal and biomass or waste through some of its energy R&D programmes. The APAS Clean Coal Technology Programme showed that it was technically feasible to co-combust certain wastes or biomass with coal in utility boilers. Co-firing was also found to have little effect on combustion efficiency or flame stability. In addition, pilot plant tests showed that co-firing could reduce NO_x and SO_x emissions. However, there was concern that the impurities in some biomasses and wastes, particularly the alkali metals and halogens, could cause operational problems with regard to slagging, fouling or corrosion. There was also concern about the disposal of the ash, which in normal coal combustion can be used in construction applications, and about the emission of heavy metals and toxic organic compounds. A further project, known as OPTEB[1], addressed all of these areas.
The role of the Energy Research Centre (NICERT) of the University of Ulster in OPTEB was to provide an overall techno-economic assessment of the systems examined, which is published elsewhere[2]. The information put forward in this paper is also derived from the same project, and here is used to assess the cost of CO_2 reduction by co-firing.

Method and Scope of Assessment

The process simulation package, ECLIPSE[3], 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[4] and fuel cells integrated with biomass gasification[5].
A variety of power generation technologies, a range of sizes of power plant and a number of blends of coals/biomasses/wastes as feedstocks were considered. The power generation technologies studied were pulverised fuel firing (PF), pressurised fluidised bed combustion (PFBC) and atmospheric pressure circulating fluidised bed combustion (CFBC). The power plant sizes ranged from 600MWe for the PF plants, to 12MWe for the smallest of the CFBC plants. A low and a high sulphur bituminous coal was used blended with straw, wood, the woody matter from pressed olive stones (WPOS) and sewage sludge. The analysis of these feedstocks is given in Table 1.

Federal coal was taken as the standard coal in these studies. It has a relatively high sulphur content, so limestone was considered to be necessary as an absorbent for capturing 95% of the sulphur. For some of the studies a low-sulphur coal (*Bellambi*) was also assessed.

Feedstock	**Federal Coal**	**Bellambi Coal**	**Wheat Straw**	**Wood**	**WPOS**	**Sewage Sludge**
Water (% ar)	6.30	6.00	14.2	33.3	13.5	4.0
Ash (% db)	6.62	13.83	4.55	0.9	10.0	21.88
HHV (MJ/kg daf)	35.64	36.18	19.90	18.73	20.89	22.94
LHV (MJ/kg daf)	34.25	35.00	18.20	17.37	19.77	21.13
Ultimate Analysis (% daf)						
Carbon	84.0	87.6	48.84	51.0	52.06	53.92
Hydrogen	5.70	4.70	7.08	6.0	6.04	7.85
Nitrogen	1.50	1.90	1.28	0.1	3.59	5.06
Sulphur	2.60	0.80	0.16	<0.1	0.64	0.89
Chlorine	0.14	0.01	0.28	0	0	0.38
Oxygen	6.06	4.99	42.36	42.9	37.67	31.90

Table 1 Analysis of Feedstocks Used

A total of 25 processes, as outlined below, were studied in this work.

PF Combustion Systems

All the studies using a PF combustion system were based upon the Amer 9 power station at Geertruidenberg in the Netherlands[6]. This is a 600MW supercritical PF coal fired power station with flue gas desulphurisation (FGD)[78].

Four processes were based around this technology. The first process (Process Number One - PN1) was the standard process as described elswhere[9], using the standard coal. The second process (PN2) involved replacing one level of coal burners with straw burners so that 20% of the total thermal input to the boiler could be changed from coal to chopped processed straw. No other changes were required to the process apart from balancing flows to the steam cycle and the FGD system. The third process (PN3) involved replacing one level of coal burners with sewage sludge burners so that 20% of the total thermal input to the boiler could be changed from coal to dried sewage sludge cake. Again no other changes were required to the process apart from balancing flows to the steam cycle and the FGD system.

The fourth process (PN4) was based on the use of fuel gas from a straw gasifier as a reburn fuel. Reburn technologies achieves a NO_x emission reduction of about 50% by staging the combustion within the furnace.

PFBC Combustion Systems

The first of the two PFBC systems uses only the standard coal (PN5) whereas the second system (PN6) is co-combusted with a mixture of 80% standard coal and 20% dried sewage sludge. Both are based on a 350 MW system described elsewhere[10]

CFBC Combustion Systems

The following assessment studies were based on the CFBC systems.

PN7	250MWe CFBC	Federal Coal Only
PN8	250MWe CFBC	Federal Coal + 20% Straw
PN9	250MWe CFBC	Federal Coal + 20% Sewage Sludge
PN10	125MWe CFBC	Federal Coal Only
PN11	125MWe CFBC	Federal Coal + 20% Straw
PN12	25MWe CFBC	Federal Coal Only
PN13	25MWe CFBC	Federal Coal + 50% Straw
PN14	25MWe CFBC	Federal Coal + 50% Wood
PN15	25MWe CFBC	Federal Coal + 50% WPOS
PN16	25MWe CFBC	Bellambi Coal Only
PN17	25MWe CFBC	Bellambi Coal + 50% Straw
PN18	25MWe CFBC	Bellambi Coal + 50% Wood
PN19	25MWe CFBC	Bellambi Coal + 50% WPOS
PN20	25MWe CFBC	Wood Only
PN21	25MWe CFBC	Straw Only
PN22	12MWe CFBC	Federal Coal Only
PN23	12MWe CFBC	Federal Coal + 50% Straw
PN24	12MWe CFBC	Bellambi Coal Only
PN25	12MWe CFBC	Bellambi Coal + 50% Straw

The superheated steam inlet conditions at the high-pressure steam turbine for the different processes are given in Table 2. The system technologies are described more fully elsewhere, as before.

Plant Size	**Pressure (bar)**	**Temperature (°C)**	**Reheat**
12 MWe	80	480	None
25 MWe	92	495	None
125 MWe	160	538	Reheat to 538C
250 MWe	160	538	Reheat to 538C

Table 2 Superheated Steam Conditions for the CFBC Systems

Technical Results

A full description of the technical, environmental and economic features of these systems has been described elsewhere (as before), but only the key indicators of performance are needed to assess the effects of using biomass or wastes on CO_2 emissions reduction.

The indicator of technical performance is taken to be the LHV Net Electrical Efficiency (Efficiency, %). The CO_2 emission level is taken as a measure of the environmental performance (total CO_2). Where biomass is used as the fuel, the CO_2 released by the biomass can be offset from the total CO_2 emissions (net CO_2).

Process Number	Technology, Fuel	Efficiency (%)	Total CO_2 (g/kWh)	Net CO_2 (g/kWh)
PN1	600MWe PF, 100% Federal Coal	44.0	759	759
PN2	600MWe PF, 20% Straw	43.8	773	610
PN3	600 MWe PF, 20% Sewage Sludge	43.8	765	765
PN4	600 MWe PF, 20% Straw (reburn)	43.2	818	625

PN5	350 MWe PFBC, 100% Federal Coal	41.2	783	783
PN6	350 MWe PFBC, 20% Sewage Sludge	41.1	792	634
PN7	250MWe CFBC, 100% Federal Coal	39.0	841	841
PN8	250MWe CFBC, 20% Straw	38.7	858	678
PN9	250MWe CFBC, 20% Sewage Sludge	39.0	866	866
PN10	125MWe CFBC, 100% Federal Coal	39.0	841	841
PN11	125MWe CFBC, 20% Straw	38.7	859	678
PN12	25MWe CFBC, Federal Coal Only	30.2	1107	1107
PN13	25MWe CFBC, Federal Coal + 50% Straw	29.5	1163	558
PN14	25MWe CFBC, Federal Coal + 50% Wood	28.2	1266	552
PN15	25MWe CFBC, Federal Coal + 50% WPOS	29.2	1172	580
PN16	25MWe CFBC, Bellambi Coal Only	30.2	1095	1095
PN17	25MWe CFBC, Bellambi Coal + 50% Straw	29.6	1157	550
PN18	25MWe CFBC, Bellambi Coal + 50% Wood	28.2	1259	543
PN19	25MWe CFBC, Bellambi Coal + 50% WPOS	29.2	1166	566
PN20	25MWe CFBC, Wood Only	26.5	1433	0
PN21	25MWe CFBC, Straw Only	29.1	1213	0
PN22	12MWe CFBC, Federal Coal Only	29.5	1132	1132
PN23	12MWe CFBC, Federal Coal + 50% Straw	28.9	1192	600
PN24	12MWe CFBC, Bellambi Coal Only	29.5	1120	1120
PN25	12MWe CFBC, Bellambi Coal + 50% Straw	28.8	1182	590

Table 3 Technical and environmental indicators for all systems

Economic Results

The economic indicators for a system are taken to be: a) the Total Capital Investment (TCI) in M€; b) Specific Capital Investment (SCI) i.e. Capital Investment per Installed Net kWe, in €; and c) the Break-even Electricity Selling Price (BESP) in €/MWh.

Process Number	Technology, Fuel	TCI	SCI	BESP
PN1	600MWe PF, 100% Federal Coal	515	856	31.5
PN2	600MWe PF, 20% Straw	535	891	37.4
PN3	600 MWe PF, 20% Sewage Sludge	523	872	See text
PN4	600 MWe PF, 20% Straw (reburn)	609	1017	39.7
PN5	350 MWe PFBC, 100% Federal Coal	355	984	36.9
PN6	350 MWe PFBC, 20% Sewage Sludge	368	1026	See text
PN7	250MWe CFBC, 100% Federal Coal	271	1080	40.1
PN8	250MWe CFBC, 20% Straw	283	1140	46.2
PN9	250MWe CFBC, 20% Sewage Sludge	280	1118	See text
PN10	125MWe CFBC, 100% Federal Coal	167	1330	46.4
PN11	125MWe CFBC, 20% Straw	176	1400	53.3
PN12	25MWe CFBC, Federal Coal Only	41	1700	56.1
PN13	25MWe CFBC, Federal Coal + 50% Straw	46	1980	79.1
PN14	25MWe CFBC, Federal Coal + 50% Wood	43	1920	67.8
PN15	25MWe CFBC, Federal Coal + 50% WPOS	42	1810	60.4
PN16	25MWe CFBC, Bellambi Coal Only	40	1660	54.0
PN17	25MWe CFBC, Bellambi Coal + 50% Straw	46	1960	77.9

PN18	25MWe CFBC, Bellambi Coal + 50% Wood	43	1900	66.6
PN19	25MWe CFBC, Bellambi Coal + 50% WPOS	42	1790	59.2
PN20	25MWe CFBC, Wood Only	45	2110	79.3
PN21	25MWe CFBC, Straw Only	49	2110	99.0
PN22	12MWe CFBC, Federal Coal Only	24	1910	61.5
PN23	12MWe CFBC, Federal Coal + 50% Straw	28	2260	86.4
PN24	12MWe CFBC, Bellambi Coal Only	24	1870	59.2
PN25	12MWe CFBC, Bellambi Coal + 50% Straw	28	2230	84.8

Table 4 Economic indicators for all systems

Whilst every effort is made to validate the capital cost estimation data, using published information and actual quotations from equipment vendors, the absolute accuracy of this type of capital cost estimation procedure has been estimated at about ±25-30%. However, although the absolute accuracy of a single cost estimate may be only ±25-30%, what has been done in these studies is to compare families of similar technologies, composed of similar types of equipment. Therefore, the comparative capital cost estimates, which are based on the accurate calculation of a difference in a basic design by the mass and energy balance program, should be valid. The economic data shown here were collected in 1998, but the comparisons should still retain their validity.

The Effect on Economics of Biomass Co-Combustion Systems of CO2 Emissions Reduction

As can be seen from the tables 3 and 4 above, all of the systems that involved co-combustion of biomass with coal have a negative impact on the efficiency, capital cost and electricity generation cost (BESP). However, they all give a reduction in net CO_2 emissions and they should be given a credit for this. One way of comparing the economic performance of the different biomass co-combustion systems is to look at the cost of reducing the emissions by 1 tonne of CO_2. These figures are presented in Table 5 and Figure 1. Of the three biomass feedstocks studied straw is the least attractive biomass for reducing CO_2 emissions, because of its high moisture content, its high capital cost for reception, storage and feeding and its high purchase price of 60€/tonne in Denmark. WPOS is the most attractive biomass basically because of its good feedstock properties and its low price in Greece. Wood is not as attractive as WPOS due to its high moisture content and its slightly higher purchase price.

Co-combustion System	**PN2**	**PN8**	**PN13**	**PN14**	**PN15**	**PN20**	**PN21**	**PN20**	**PN21**
System Compared with	PN1	PN7	PN12	PN12	PN12	PN12	PN12	PN1	PN1
Increase in BESP (€/MWh)	5.9	6.1	23	11.7	4.3	23.2	42.9	47.8	67.5
Reduction in CO_2 Emissions (g/kWh)	149	163	540	515	535	1107	1107	759	759
Cost €/t CO_2	39.5	37.4	42.6	22.7	8.0	21.0	38.8	63.0	88.9

Table5 Cost of Reduction CO_2 Emissions

For small-scale combustion of wood (PN20) to compete with large-scale production of electricity for sale on the open market (PN1) a credit of 63 €/tonne of CO_2 emission avoided is required. When looking at small scale CFBC systems (PN12) the credit required for co-combustion (PN14) is very similar to direct combustion (PN20), it increases slightly from 21.0 to 22.7 €/tonne CO_2 avoided. This is due to the lower capital cost penalty incurred for receiving, storing and feeding the wood chips compared with straw. Therefore to encourage small industrial scale CFBC combustion of wood or co-combustion of coal with wood a credit of about 22 €/tonne CO_2 avoided would be required. WPOS requires only a small credit of 8 €/tonne of CO_2 emission avoided to encourage its use.

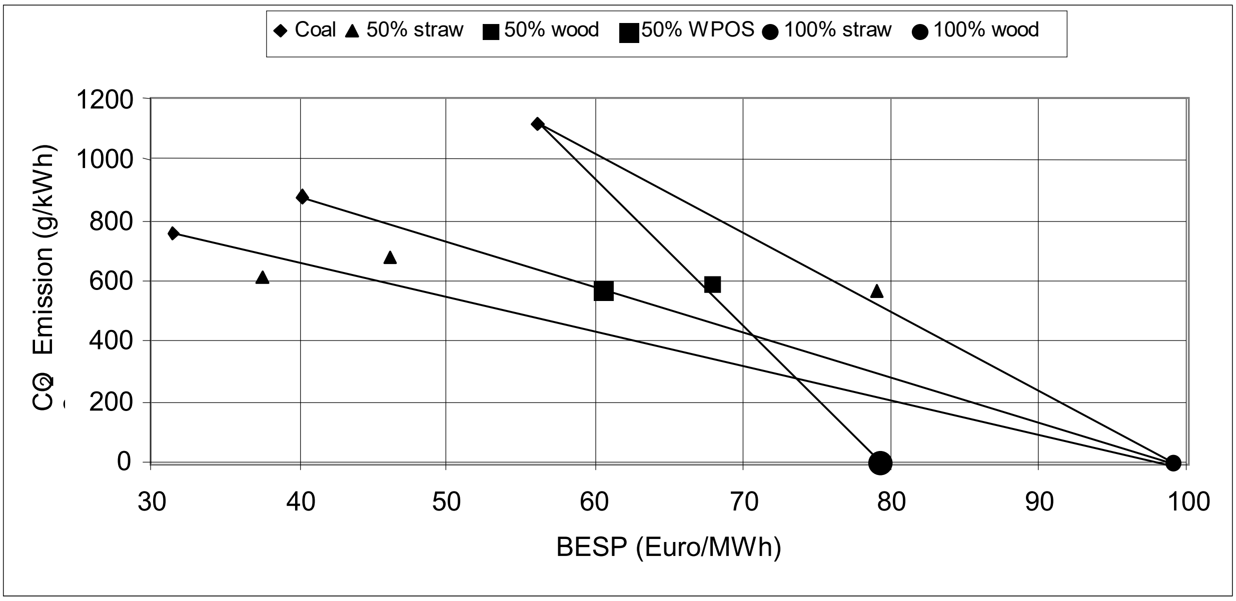

Figure 1 Economics of CO_2 Emission Reduction

For small scale combustion of straw (PN21) to compete with large scale production of electricity for sale on the open market (PN1) a credit of 88.9 € is required for each tonne of CO_2 emission avoided. Co-combustion of straw with coal in either a PF boiler system (PN2) or a large scale CFBC system (PN8) is a much more attractive means of reducing CO_2 emissions as a lower credit of 39.5 and 37.4 € respectively is required for each tonne of CO_2 avoided. When looking at small scale CFBC systems (PN12), which are not competing with large scale electricity production on the open market, then co-combustion (PN13) is not as attractive as direct combustion (PN21) and the credit required increases from 38.8 to 42.6 €/tonne CO_2 avoided. This is due to the additional capital cost incurred in receiving, storing and feeding two different feedstocks for this small size of power plant. However, these figures show that a credit of about 40€/tonne CO_2 avoided would encourage large-scale co-combustion of straw with coal and also small industrial scale CFBC combustion of straw or co-combustion of coal with straw. Not shown in the table is the figure for 12MWe CFBC plant, but the figure here for co-combustion of coal with straw is 45 €/tonne CO_2 avoided.

Conclusions

Straw

Straw has a negative effect on the overall performance due to its high moisture content, the high capital cost of straw processing equipment and the high purchase price of the straw feedstock.

With large scale PF co-combustion of coal and 20% straw the overall efficiency was reduced by 0.2%, the capital costs increased by 20 M€ and the electricity selling price (BESP) increased by 5.9 €/MWh. However the use of straw reduced the net CO_2 emissions by about 20%. To make PF co-combustion competitive with similar coal only systems a credit of 39.5 €/tonne CO_2 avoided is required.

When using gasified straw as a reburn fuel in a PF boiler the overall efficiency was reduced by 0.8%, the capital costs increased substantially by 94 M€ and the BESP increased by 8.2 €/MWh. However this reduced the NO_x emissions by 50% and the net CO_2 emissions by about 20%. It is difficult to justify the increased costs involved in this system in comparison with coal-over-coal reburn technology and co-combustion with straw unless there are substantial operational benefits.

With large scale CFBC co-combustion of coal and straw the overall efficiency was reduced by 0.3%, the capital costs increased by 12 M€ and the BESP increased by 6.1 €/MWh. The use of straw reduced the net CO_2 emissions by about 20%. To make CFBC co-combustion competitive with similar coal only systems a credit of 37.4 €/tonne CO_2 avoided is required.

The co-combustion of coal with 50% straw in a 25MWe CFBC system reduced the overall efficiency by 0.7%, increased the capital costs by 5 M€ and increased the BESP by 23 €/MWh. The use of straw reduced the net CO_2 emissions by about 50%. To make small scale CFBC co-combustion competitive with similar coal only systems a credit of 42.6 €/tonne CO_2 avoided is required. The use of a low sulphur coal had a small beneficial effect on the performance of the CFBC systems studied. The economic advantage depends on the relative price differential between the low and high sulphur coal.

Sewage Sludge

In this study sewage sludge is considered to be a waste, not a renewable energy source, and therefore what is important is the cost of disposing of this waste not the reduction in CO_2 emissions. To calculate the cost of disposing of the sewage sludge it was assumed that the BESP for the three processes using sewage sludge, PN3, PN7 and PN10 is the same as the BESP for the equivalent coal only systems. An economic analysis was then performed to determine the price that could be paid for the sewage sludge to give this BESP.

The addition of 20% sewage sludge to a PF boiler reduced the efficiency by 0.2% and increased the capital cost by 8 M€. To make PF co-combustion of sewage sludge

competitive with similar coal only systems a price of 13.6€/tonne could be paid for the dried sewage sludge compared to 32 €/tonne for the coal.
The addition of 20% sewage sludge to a PFBC system reduced the efficiency by 0.1% and increased the capital cost by 13 M€. To make PFBC co-combustion of sewage sludge competitive with similar coal only systems a price of 6.5 €/tonne could be paid for the sewage sludge. However, the PFBC is a slurry fed system therefore wet sewage filter cake could also be used without any economic penalty.
The addition of 20% sewage sludge to the large scale CFBC reduced the efficiency by 0.2% and increased the capital cost by 9 M€. To make CFBC co-combustion of sewage sludge competitive with similar coal only systems a price of 11.8 €/tonne could be paid for the sewage sludge. There is a penalty of 20 €/dry tonne if wet sewage filter cake is used in this system instead of dried sewage sludge.
However, PF, PFBC and CFBC are all potentially attractive routes for co-combusting coal and sewage sludge, especially as under normal circumstances a gate fee would be available to take the sewage sludge.

Wood
Wood has quite a high negative impact on efficiency, due to its higher moisture content, but less of an impact on the capital cost due to its easier reception, preparation and feeding compared with straw. The co-combustion of coal with 50% wood in the 25MWe CFBC systems reduced the overall efficiency by 2.0%, increased the capital costs by 2 M€ and increased the BESP by 11.7 €/MWh. The use of wood reduced the net CO_2 emissions by about 46%. To make CFBC co-combustion of wood competitive with similar coal only systems a credit of 22.7 €/tonne CO_2 avoided is required. The co-combustion of coal with WPOS in the 25MWe CFBC system reduced the overall efficiency by 1.0%, increased the capital costs by 1 M€ and increased the BESP by 4.3 €/MWh. The use of WPOS reduced the net CO_2 emissions by about 50%. To make CFBC co-combustion of WPOS competitive with similar coal only systems a credit of 8 €/tonne CO_2 avoided is required.

Biomass Feedstock comparisons
Of the three biomass feedstocks studied straw is the least attractive biomass for reducing CO_2 emissions, because of its high moisture content, its high capital cost for reception, storage and feeding and its high purchase price of 60€/tonne in Denmark. WPOS is the most attractive biomass because of its good feedstock properties and its low price of 23€/tonne in Greece. Wood is not as attractive as WPOS due to its high moisture content and its slightly higher purchase price. A credit of about 40€/tonne CO_2 avoided would encourage large scale PF and CFBC co-combustion of straw with coal and also small industrial scale CFBC combustion of straw or co-combustion of coal with straw. To encourage small industrial scale CFBC combustion of wood or co-combustion of coal with wood a credit of about 22€/tonne CO_2 avoided would be required. WPOS requires only a small credit of 8 €/tonne of CO_2 emission avoided to encourage its use. These figures are heavily dependent on the price paid for the biomass.

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