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Techno-Economic Evaluation of Biomass Fired or Co-Fired Power Plants with Post Combustion CO_2 Capture

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Abstract

The use of biomass in power generation is a key option to reduce greenhouse gas emissions. Specifically, the co-firing of biomass with coal could be regarded as a common feature of any new build power plant if a sustainable supply of biomass fuel is readily accessible. Currently, there is an on-going discussion on what could be the pros and cons of incorporating CO_2 capture and storage (CCS) to any type of biomass-fired power plant. The discussion has primarily centred on how to consider the CO_2 emitted from biomass-fired power plants, if it is counted as "CO_2 neutral" and if stored, whether it could be considered as a "negative" CO_2 emission. One of the main questions addressed in this study was "What should be the CO_2 emission cost that would make CCS an attractive option to be incorporated into a biomass fired power plant assuming that the stored CO_2 from a biomass fired power plant could generate an additional revenue as CO_2 credit"

The study, carried out by Foster Wheeler for the IEA Greenhouse Gas R&D Programme (IEA GHG), aimed to address these questions, and investigated and evaluated the different options and techno-economic performance of a biomass-fired power plant or a coal power plant co-fired with biomass, based on current state-of the art boiler and steam generation equipment incorporating post-combustion CO_2 capture based on MEA solvent. Specifically, the study evaluated the following cases comparing the performance and techno-economics of the power plants with and without CO_2 capture.

- Case 1: nominal 500 MW_e (net) co-firing of biomass and coal in pulverised fuel (PF) power plant.
- Case 2: nominal 500 MW_e (net) co-firing of biomass and coal in CFB power plant.
- Case 3: nominal 250 MW_e (net) circulating fluidized bed standalone biomass power plant.
- Case 4: nominal 75 MW_e (net) bubbling fluidized bed standalone biomass power plant.

To evaluate the potential impact of any incentives from the "Green Certificate" or the "ETS Mechanism", four different scenarios for all cases were assumed, which are briefly described below.

[1] Scenario 01 – The calculation of the Levelised Cost of Electricity does not include any revenues from the Green Certificate nor from ETS mechanism.
[2] Scenario 02 – The calculation of the Levelised Cost of Electricity only allows the revenues from the Green Certificate. For the reference case, the Green Certificate is given a price of 50 € / MWh.
[3] Scenario 03 – The calculation of the Levelised Cost of Electricity only allows the revenues from the ETS mechanism. For the reference case, the Green Certificate is given a price of 14 € / t CO_2.
[4] Scenario 04 – The calculation of the Levelised Cost of Electricity considers the revenues from both the Green Certificate and ETS mechanism.

This study presents the following results:

- Performance of the power plants
- Techno-economic assessment of the power plant assuming no incentives from the "Green Certificate" or the "ETS Mechanism".
- Sensitivity of the economics to the inclusion of the "Green Certificate" and "ETS Mechanism" incentives

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1. Background to the Study

The use of biomass in power generation is one of the key ways in reducing greenhouse gas emissions. Specifically, the co-firing of biomass with coal could be regarded as a common feature of any new-build power plant if a sustainable supply of biomass fuel is readily accessible.

Currently, there is an on-going discussion on what could be the pros and cons of incorporating CO_2 capture and storage (CCS) to any type of biomass-fired power plant. The discussion has primarily centred on how to consider the CO_2 emitted from biomass-fired power plants; if it is counted as "CO_2 neutral" and if stored, whether it could be considered as a "negative" CO_2 emission. This study aims to address this discussion by investigating the potential application and feasibility of incorporating CO_2 capture technologies to a biomass fired or co-fired power plant.

2. Basis of the Study

The study aimed to investigate options and evaluate the techno-economic performance of a biomass-fired, or coal co-fired with biomass, power plant, based on current state of the-art-boiler and steam generation equipment incorporating CO_2 capture technology. It is expected that the study should provide the performance of the plant assuming the need to capture at least 90% of the total CO_2 emissions.

The current study evaluated the techno-economic performance of incorporating CO_2 capture in a biomass fired or co-fired power plant on the following four cases namely:

- Case 1: nominal 500 MW_e (net) co-firing of biomass and coal in PF power plant.
- Case 2: nominal 500 MW_e (net) co-firing of biomass and coal in CFB power plant.
- Case 3: nominal 250 MW_e (net) circulating fluidized bed standalone biomass power plant.
- Case 4: nominal 75 MW_e (net) bubbling fluidized bed standalone biomass power plant.

All cases are evaluated without and with the consideration of capturing CO_2 using the standard MEA solvent. The CO_2 capture rate is assumed to be at least 90% of the total CO_2 emissions.

3. Power Plant Performance and Cost Assessments Criteria

Assessment Criteria

The performance and costs of power plants with CO_2 capture were estimated based on the assumption that power plants were to operate at base load with a load factor of 90% (for reference power plants cases without CO_2 capture) and 88% (for power plant cases with CO_2 capture). The economic evaluation was based on a 10% annual discount rate and 2-year operating life.

The biomass fuel used for this study is based on virgin wood and is assumed to be supplied sustainably. For the co-firing option, the coal used for this study is based on Eastern Australian Coal with a lower heating value (LHV) equal to 25,870 kJ/kg and a sulphur content equal to 1.1% wt (dry ash free). The reference coal price was assumed to be €2.90/GJ, whilst for biomass fuel price was assumed to be €8.39/GJ (bone dry basis).

The plant costs were estimated in Euros (May 2009) based on the location of the power plant to be built at a coastal site in The Netherlands. Conversion of Euros to US Dollars was assumed to be 1.35$ to 1.00€. The accuracy of the cost estimate is set at ±30%.

Further details of the assessment criteria are describe in the IEAGHG report [1].

Economic Assessment and Consideration to the Impact of the Green Certificate and ETS Mechanism

The economic assessment incorporated the potential benefit of a Green Certificate and the benefit or penalty of the CO_2 ETS price (assuming that power plant operator will be required to buy the ETS certificates necessary for the plant).

To evaluate the potential impact of any incentives from the Green Certificate or the ETS Mechanism, four different scenarios for all cases were assumed, which are briefly described below.

[1] Scenario 01 – The calculation of the Levelised Cost of Electricity does not include any revenues from the Green Certificate nor from ETS mechanism.

[2] Scenario 02 – The calculation of the Levelised Cost of Electricity only allows the revenues from the Green Certificate. For the reference case, the Green Certificate is given a price of 50 € / MWh.
[3] Scenario 03 – The calculation of the Levelised Cost of Electricity only allows the revenues from the ETS mechanism. For the reference case, the Green Certificate is given a price of 14 € / t CO_2.
[4] Scenario 04 – The calculation of the Levelised Cost of Electricity considers the revenues from both the Green Certificate and ETS mechanism.

For the reference cases, the Green Certificate is assumed to be €50 per MWh, whilst for the CO_2 ETS price was assumed to be fixed at € 14 per tonnes of CO_2 emitted. It should be noted that for simplicity, the revenues from the Green Certificate and ETS mechanism were assumed to be constant over the whole 25-year economic life of the power plant. This should reflect the average revenues necessary during the economic life of the power plant to achieve the breakeven cost. The levelised cost of electricity was calculated based on these values, setting the net present value of the power plant to zero (i.e. NPV = € 0).

4. Description of the Cases

Table 1 presents the key features of the power plants and the choice of technology for the flue gas clean-up necessary to achieve the regulatory requirements related to emissions or requirements of the CO_2 capture plant.

It should be noted that for all cases evaluated, it was assumed that the same size boiler would be used for power plants both with and without CO_2 capture. As a consequence, the power plant with CO_2 capture units would produce less electricity at the gate as compared to power plants without CO_2 capture.

5. Summary of Results

The performance and cost of the biomass-fired or co-fired power plants are summarized in Tables 2.

Figures 1 and 2 present the levelised cost of electricity (based on NPV = 0) for Cases 1A to 2B and Cases 3A to 4B respectively without any consideration for the possible benefit of the Green Certificate or the possible benefit or penalty of the ETS CO_2 price.

Table 3 presents a summary of the CO_2 emissions of the power plant which indicates the CO_2 contribution from biomass and coal. The overall capture efficiency based on the total CO_2 emission is also provided. The amount of CO_2 avoided was also presented and this was calculated based on the CO_2 emissions from both coal-fired power plant and Natural Gas Combined ycle (NGCC) without CO_2 capture as reference plant.

Table 4 presents a summary of the CO_2 credits and potential revenues that could be obtained from the Green Certificate and ETS mechanism. It should be noted that it was assumed that no free ETS certificate allowance will be provided to the power plant operator; therefore any subsequent CO_2 emissions from coal would require the purchase of the ETS certificate. Table 5 summarises the results from the different scenarios for the reference cases.

Figures 3 and 4 illustrate the levelised cost of electricity for Case 1 and Case 3 indicating the price of ETS that would place CO_2 capture from a biomass-fired or co-fired power plants on cost parity to the non-CO_2 capture cases and the impact of the Green Certificate to the levelised cost of electricity (assuming combined incentives are provided).

6. Discussion of Results

Power Plant Performance – Impact of the CO_2 Capture Plant

The net power outputs of the power plants are lower in all CO_2 capture cases (Cases 1B, 2B, 3B and 4B). This is due to the installation of the same size boiler as compared to their corresponding power plants without CO_2 capture, thus the lower power output reflects the energy penalty of the CO_2 capture unit.

The thermal efficiencies for the power plants without CO_2 capture were all within the range of 36 - 45% based on a lower heating value (LHV), which are consistent with the expected performance of state-of-the-art power plants for supercritical and subcritical units.

For power plants with CO_2 capture, the thermal efficiency ranges from as low as 23% for the smaller bubbling fluidized-bed boiler to 34.5% for the supercritical PC boiler co-fired with biomass. This reflects the significant penalty incurred by the subcritical units (a penalty ranging between 12-16% based on LHV) vs the supercritical units (a penalty ranging between 10-12% based on LHV).

The following points summarise the key features that affect the performance of the power plant evaluated in this study:

- It should be noted that for Case 1A, a supercritical boiler for the pulverised coal-fired power plant was used instead of the more advanced ultra-supercritical units. The primary concern was due to the slagging and fouling issues which are common with co-firing of biomass. Currently, there is no experience or a reference plant where co-firing of biomass in an ultra-supercritical PC boiler has been demonstrated; therefore this study concluded that the use of supercritical PC boiler co-fired with biomass would be more conservative in design to maintain the confidence in achieving the necessary availability.
- It could be illustrated in this study that a coal-fired power plant co-fired with biomass at nominal 500MWe net output, the CFB case – Case 2A (45.1%) – would have higher net efficiency than the PC case – Case 1A (44.8%). The better performance of Case 2A than Case 1A was due to the absence of the external FGD and the introduction of the special plastic heat exchanger that could maximise the heat recovery from the flue gas downstream the ID fan for Case 2A. It should be noted that this type of heat exchanger cannot be applied if an external FGD or CO_2 capture units are installed. Therefore this type of equipment, that helped improved the performance of the power plant, was only implemented for Case 2A and 3A. For the BFB case (Case 4A), the special heat exchanger was not installed due to its high cost and minimal benefits in relation to its possible performance gain.
- As presented in Tables 2, it could be noted that there is a significant loss in net efficiency for all cases when the CO_2 capture units were installed. This should be expected due to the steam and power requirements for CO_2 capture units and the compressors to deliver the CO_2. However, it should be further noted that a higher loss in net efficiency could be observed for cases using a "standalone" biomass-fired power plant (i.e. Case 3B and 4B). The higher loss in net efficiency could only be due to the following factors:
  - Installation of additional flue gas clean-up equipment (i.e. for Case 2B – the addition of an external FGD; introduction of limestone injection into the furnace for Case 3B and 4B) to achieve the required quality of the flue gas before introduction to the CO_2 capture units increases the loss of net efficiency of the power plant.
  - The installation of the Direct Contact Cooler, which is necessary to reduce the particulate matter introduced into the CO_2 capture plant, does not allow the recovery of low grade heat that could be used by the power plant.
  - It should be highlighted that the lower LHV of the biomass with respect to coal has an impact to the exhaust flue gas. Biomass-fired power plants make more heat at low temperature therefore penalising any power plants with CO_2 capture units where low temperature heat recovery cannot be introduced.
  - Furthermore, the volume of flue gas from a "standalone" biomass-fired power plant to be handled by the CO_2 capture unit is proportionally larger than a similar sized coal-fired boiler, therefore requiring larger process equipment which increases the auxiliary power requirements. Additionally, the concentration of CO_2 from a "standalone" biomass power plant is lower than the CO_2 concentration of flue gas from a same sized coal fired boiler.

Cost Implication of the CO_2 Capture Plant

Power Plant Co-Fired with Biomass

As shown in Figure 1, the difference in the levelised cost of electricity (COE) between the PC and CFB case with CO_2 capture is higher than its corresponding cases without CO_2 capture. The COE for the PC with CO_2 capture is about 7% lower s compared to the CFB case with CO_2 capture. This result is a consequence of a lower investment cost of the PC boiler in addition to the small advantage in efficiency when the CO_2 capture unit was installed.

In terms of the specific capital cost, as shown in Table 2, the installation of the CO_2 capture unit resulted in an increase of ~63% for the PC Case 1B with respect to Case 1A, and of ~73% for the CFB Case 2B with respect to Case 2A. Most of the increase in the specific capital cost could be attributed to the installation of the CO_2 capture unit and the compression unit. However, the higher increase in the capital cost in the CFB case as compared to the PC case could be attributed to the additional cost associated with the installation of the external flue gas desulphurisation which was not required for the CFB power plant without CO_2 capture.

Power Plant Fired with 100% Biomass

As shown in Figure 2, the percentage increase in the COE for both CFB and BFB power plants with CO_2 capture is very similar to their corresponding cases without CO_2 capture (about 80-85% increase). However, if compared to the co-fired cases, which have about a 50-60% increase in their COE when capturing the CO_2, the increase in COE for "standalone" biomass power plants is significantly greater; and could be a primary consequence of the higher cost of the biomass fuel as compared to coal (on energy basis). Likewise, to some extent, the increase in COE is also due to the increase in the capital cost. Additionally, the higher performance penalty when capturing CO_2 from "standalone" biomass power plants also contributed to the higher increase in the COE.

In terms of specific capital cost as shown in Table 2, an increase of 126% and 114% could be noted for the "standalone" 250MWe CFB (Cases 3A and 3B) and 75MWe BFB (Cases 4A and 4B) biomass power plants respectively. For both cases, the increase in the specific capital cost is primarily due to the cost associated with the CO_2 capture unit and the compression unit. The magnitude of the increase in the capital cost of a "standalone" biomass case as compared to the co-fired cases is higher and this could be also be due to the proportionally larger volume of flue gas and slightly diluted CO_2 concentration needed to be processed by the CO_2 capture unit.

Impact of ETS and Green Certificate

To evaluate the benefits that could be gained from the ETS Certificate, it was assumed that there will be no free allocation of ETS credit provided. Thus, for all cases, the power plant would need to buy the necessary ETS credit to cover its CO_2 emissions. The calculation of the CO_2 emissions and annual revenues for the ETS and Green Certificates is illustrated in Tables 3 and 4.

For the four reference scenarios, it was assumed that ETS and Green Certificates will have a reference price of 14€/t CO_2 and 50€/MWh respectively. Furthermore, it was assumed that these prices would be constant over the whole economic life of the power plant. This means that if the price goes below the assumed value, then a negative NPV value results.

The cost implication of the ETS and Green Certificate is illustrated in Figures 3 and 4. These figures clearly show that both the Green and ETS certificates are needed to make the capture of CO_2 from a biomass-fired or co-fired power plant competitive.

Also, it is noted that the price of the ETS certificate could provide the benefits to make the COE of the power plant with CO_2 capture comparable to the COE of the power plants without CO_2 capture. However, the benefit of the Green Certificate is also necessary to bring down the COE of the power plant with or without CO_2 capture and make it comparable to the COE of the power plant without CO_2 capture for Scenario 1 - if no incentives from ETS or Green Certificate are considered.

A case in point is shown in Figure 3, for the PC co-fired with biomass case (Case 1A and 1B), where the price of the ETS certificate should be about 48€/t CO_2 to make the power plant with CO_2 capture comparable to the power plant without CO_2 capture. Furthermore, Figure 3 also illustrates that both the ETS (at 48€/t CO_2) and the Green Certificate (at 312€/MWh) would be needed to bring down the COE of the power plant to the same level as the COE of the power plant without capture when no incentives are considered (i.e. Scenario 1).

7. Concluding Remarks

This study evaluated the techno-economics of four different cases of power plants fired with biomass under four different economic scenarios considering the impact of ETS and Green Certificates. The following could be concluded from this study:

Power Plant Performance

a. For the PC co-fired with biomass cases, the study examined the use of a supercritical boiler instead of the more advanced ultra-supercritical boiler due to the concern over the USC's plant's availability and reliability. The study has indicated that there is a significant technology gap that needs to be overcome when using ultra-supercritical power plant co-fired with biomass. This is still to be demonstrated in the larger scale to achieve the necessary confidence. Specifically, the technology gaps exist in the slagging and fouling area when a boiler is co-fired with biomass and operated under ultra-supercritical conditions.
b. Without CO_2 capture, the net efficiency of the 500MWe CFB co-fired with biomass is higher than its counterpart PC case. However, this was reversed when CO_2 capture units were installed. This is due to the higher performance penalty incurred by the CFB because of the additional FGD needed and the absence of advanced flue gas heat recovery equipment downstream of the ID fan.
c. This study illustrated that "standalone" biomass-fired cases experience a higher performance penalty when CO_2 capture was included. It was noted that the main reasons for the additional performance penalty in the full biomass-fired power plant was due to the larger volume needed to be processed by the CO_2 capture plant, a slightly diluted CO_2 concentration, and in some cases, the additional flue gas clean-up equipment required.

Cost of the Power Plant

a. The higher cost of the biomass fuel as compared to the coal price on a unit energy basis has a significant impact to the cost of electricity of the "standalone" biomass-fired power plants. This study illustrated that for power plants without CO_2 capture, the COE is about twice for the 250MWe CFB (Case 3A) and triple for the 75MWe BFB (Case 4A) when compared to the 500MWe PC or CFB co-fired with biomass cases (Case 1A or 2A).

b. In terms of the specific capital cost, the installation of the CO_2 capture unit resulted in an increase of ~63% for the PC case (Case 1B vs. Case 1A), of ~73% for the CFB case (Case 2B vs. Case 2A), an increase of ~126% and ~114% for both "standalone" biomass-fired power plants (Cases 3A vs. 3B and 4A vs. 4B) respectively. Most of the increase in the capital cost was due to the CO_2 capture units and the compression units. However, additional capital cost increase was also due to the equipment needed for flue gas clean up, especially for the CFB and BFB cases.

Cost of Electricity with ETS and Green Certificate

a. There are three factors that could make the biomass-fired or co-fired power plant with CO_2 capture competitive as compared to power plants without CO_2 capture; this includes the benefits that could be gained from the ETS and the Green Certificate; and the sensitivity to the price of the biomass fuel.
b. To make the biomass-fired or co-fired power plant comparable to their counterparts without CO_2 capture, an ETS price of ~48 – 55 €/t CO_2 is necessary for the 500MWe co-fired with biomass cases (Case 1 and 2). ETS prices of ~65€/t CO_2 and ~76€/t CO_2 are necessary for the "standalone" biomass-fired 250MWe CFB (Case 3) and 75MWe BFB (Case 4) respectively.
c. It can be concluded that Green Certificates alone will not make biomass-fired power plants with CO_2 capture cost competitive. Both ETS and Green Certificate mechanisms need to be in place to make the COE for CO_2 capture cases comparable to non-CO_2 capture cases.

8. References

[1] IEA Greenhouse Gas R&D Programme (IEA GHG). "Techno-Economic Evaluation of Capturing CO2 from Biomass Fired or Co-Fired Power Plant". *IEA GHG Report No. 2009/9*. November 2009.

9. Figures and Tables

Table 1: Summary and Key Features of the Power Plants Evaluated in this Study

Case	Boiler Technology	Steam Parameter	Fuel	Key Technology Features	CO_2 Capture	DeSOx	DeNOx
1A	PC	supercritical	90% Coal / 10% Biomass	None	No	FGD	SCR
1B	PC	supercritical	90% Coal / 10% Biomass	None	Yes	FGD	SCR
2A	CFB	supercritical	90% Coal / 10% Biomass	Inclusion of special plastic HEX for flue gas heat recovery	No	Limestone Injection in Furnace	None
2B	CFB	supercritical	90% Coal / 10% Biomass	None	Yes	Limestone Injection in Furnace & FGD	None
3A	CFB	subcritical	100% Biomass	Inclusion of special plastic HEX for flue gas heat recovery	No	None	None
3B	CFB	subcritical	100% Biomass	None	Yes	Limestone Injection in Furnace	None
4A	BFB	subcritical	100% Biomass	None	No	None	None
4B	BFB	subcritical	100% Biomass	None	Yes	Limestone Injection in Furnace	None

Table 2: Summary of Performance and Cost of the Biomass Fired or Co-Fired Power Plants

	Biomass Thermal Input	Net Power Output	Net Efficiency (LHV)	Total Investment Cost	Capital Cost
	%	MW	%	MM €	€/kWe net
SC PC boiler co-fired with biomass					
Case 1A (without CO_2 capture)	10	518.9	44.8	657.2	1266.5
Case 1B (with CO_2 capture)	10	398.9	34.5	824.3	2066.5
SC CFB boiler co-fired with biomass					
Case 2A (without CO_2 capture)	10	521.4	45.1	707.3	1356.5
Case 2B (with CO_2 capture)	10	390.5	33.8	918.4	2351.8
Sub CFB boiler fired with biomass					
Case 3A (without CO_2 capture)	100	273.0	41.7	370.3	1356.4
Case 3B (with CO_2 capture)	100	168.9	25.8	519.7	3077.2
Sub BFB boiler fired with biomass					
Case 4A (without CO_2 capture)	100	75.8	36.0	185.4	2446.1
Case 4B (with CO_2 capture)	100	48.9	23.2	256.2	5240.1

Table 3: Summary of CO2 Emissions of the Biomass Fired or Co-Fired Power Plant

	Actual CO_2 Emissions	CO_2 from Coal	CO_2 from Biomass	Total CO_2 Captured	Equivalent CO_2 Emissions	CO_2 avoided wrt SCPC	CO_2 avoided wrt NGCC
	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh
SC PC fired boiler (w/o CO_2 capture)	722.8	722.8	-	-	722.8	-	-
NGCC (without CO_2 capture)	359.0	359.0	-	-	359.0	-	-
SC PC boiler co-fired with biomass							
Case 1A (without CO_2 capture)	748.5	649.7	98.8	0.0	649.7	73.1	-290.7
Case 1B (with CO_2 capture)	973.7	845.2	128.5	876.4	-31.3	754.1	390.3
SC CFB boiler co-fired with biomass							
Case 2A (without CO_2 capture)	748.2	649.4	98.8	0.0	649.4	73.4	-290.4
Case 2B (with CO_2 capture)	999.0	867.1	131.9	899.1	-32.0	754.8	391.0
Sub CFB boiler fired with biomass							
Case 3A (without CO_2 capture)	1081.3	0.0	1081.3	0.0	0.0	722.8	359.0
Case 3B (with CO_2 capture)	1747.8	0.0	1747.8	1573.1	-1573.1	2295.9	1932.2
Sub BFB boiler fired with biomass							
Case 4A (without CO_2 capture)	1257.3	0.0	1257.3	0.0	0.0	722.8	359.0
Case 4B (with CO_2 capture)	1948.9	0.0	1948.9	1754.6	-1754.6	2477.4	2113.7

Table 4: Summary of the Annual Credit from ETS or Green Certificate for Biomass Fired or Co-Fired Power Plants

	Net Power	Operating Hours	Power from Biomass	Annual Green Certificate Credit[1]	Total CO_2 Emissions (Overall)	CO_2 Emission Credit	CO_2 Emission Penalty	Annual ETS Credit (Penalty)[2,3]
	MW	h	MW	MM €	t/h	t/h	t/h	MM €
SC PC boiler co-fired with biomass								
Case 1A (without CO_2 capture)	518.9	7884	51.9	**20.5**	388.4	0.0	337.1	**-37.2**
Case 1B (with CO_2 capture)	398.8	7710	39.9	**15.4**	38.8	12.5	0.0	**1.4**
SC CFB boiler co-fired with biomass								
Case 2A (without CO_2 capture)	521.5	7884	52.1	**20.6**	390.1	0.0	338.6	**-37.4**
Case 2B (with CO_2 capture)	390.5	7710	39.0	**15.1**	39.0	12.5	0.0	**1.4**
Sub CFB boiler fired with biomass								
Case 3A (without CO_2 capture)	273.0	7784	273.0	**107.6**	295.2	0.0	0.0	**0.0**
Case 3B (with CO_2 capture)	168.9	7710	168.9	**65.1**	29.5	265.7	0.0	**28.7**
Sub BFB boiler fired with biomass								
Case 4A (without CO_2 capture)	75.8	7784	75.8	**29.9**	95.3	0.0	0.0	**0.0**
Case 4B (with CO_2 capture)	48.8	7710	48.8	**18.9**	9.5	85.8	0.0	**9.3**

[1] Green Certificate = 50 € /MWh
[2] ETS Price = 14 € / t CO_2
[3] If value is (-) then this indicates that the power plant operator is required to buy the ETS certificate.

Table 5: Summary of Results – Levelised Cost of Electricity (based on IRR = 10%)

	Scenario 01	Scenario 02	Scenario 03	Scenario 04
Green Certificate (€/MWh)	**0.0**	**50.0**	**0.0**	**50.0**
ETS CO2 Certificate Price (€/t CO_2)	**0.0**	**0.0**	**14.0**	**14.0**
	Levelised Cost of Electricity (COE)			
	€ / MWh	€ / MWh	€ / MWh	€ / MWh
SC PC boiler co-fired with biomass				
Case 1A (without CO_2 capture)	60.95	55.95	70.05	65.05
Case 1B (with CO_2 capture)	93.50	88.50	93.07	88.07
SC CFB boiler co-fired with biomass				
Case 2A (without CO_2 capture)	63.85	58.85	72.95	67.95
Case 2B (with CO_2 capture)	101.24	96.24	100.79	95.79
Sub CFB boiler fired with biomass				
Case 3A (without CO_2 capture)	119.61	69.61	119.61	69.61
Case 3B (with CO_2 capture)	221.43	171.43	199.41	149.41
Sub BFB boiler fired with biomass				
Case 4A (without CO_2 capture)	167.03	117.03	167.03	117.03
Case 4B (with CO_2 capture)	300.95	250.95	276.39	226.39

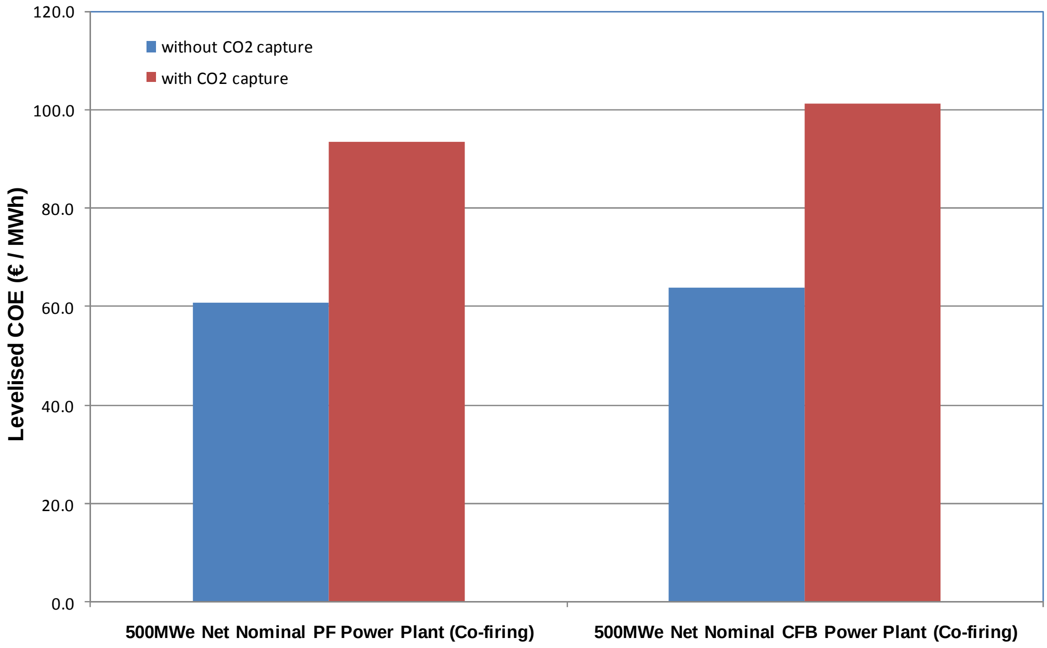

Figure 1: Levelised Cost of Electricity (COE) at 10% IRR for Coal Co-Fired with Biomass Power Plants (COE does not include any incentives or penalty from ETS CO_2 price or Green Certificate)

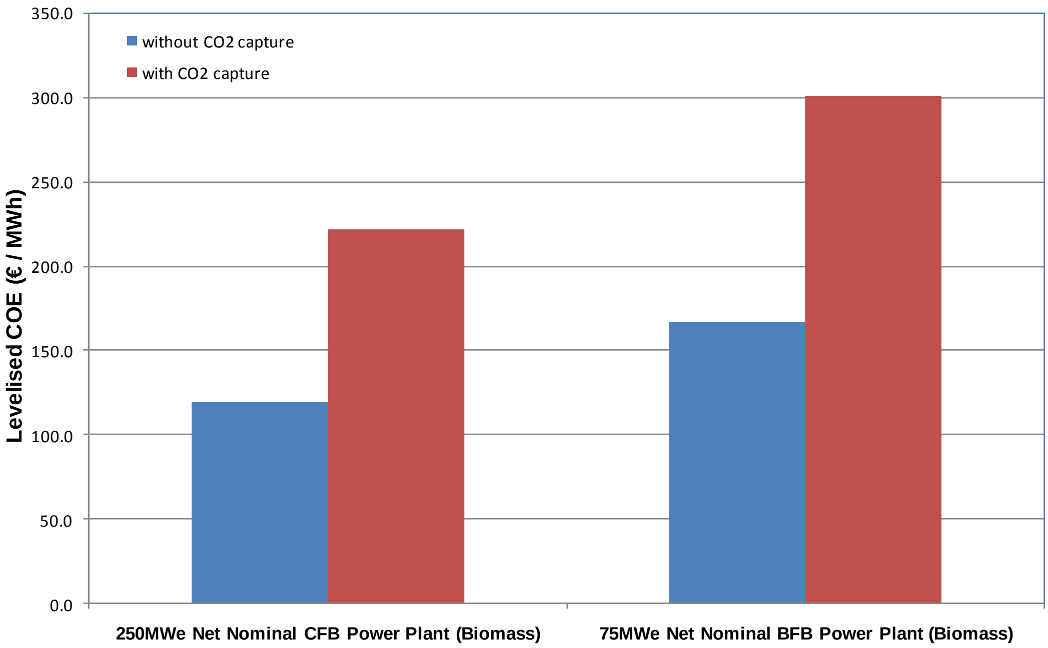

Figure 2: Levelised Cost of Electricity (COE) at 10% IRR for "Standalone" Biomass Fired Power Plants (COE does not include incentives or penalty from ETS CO_2 price or Green Certificate)

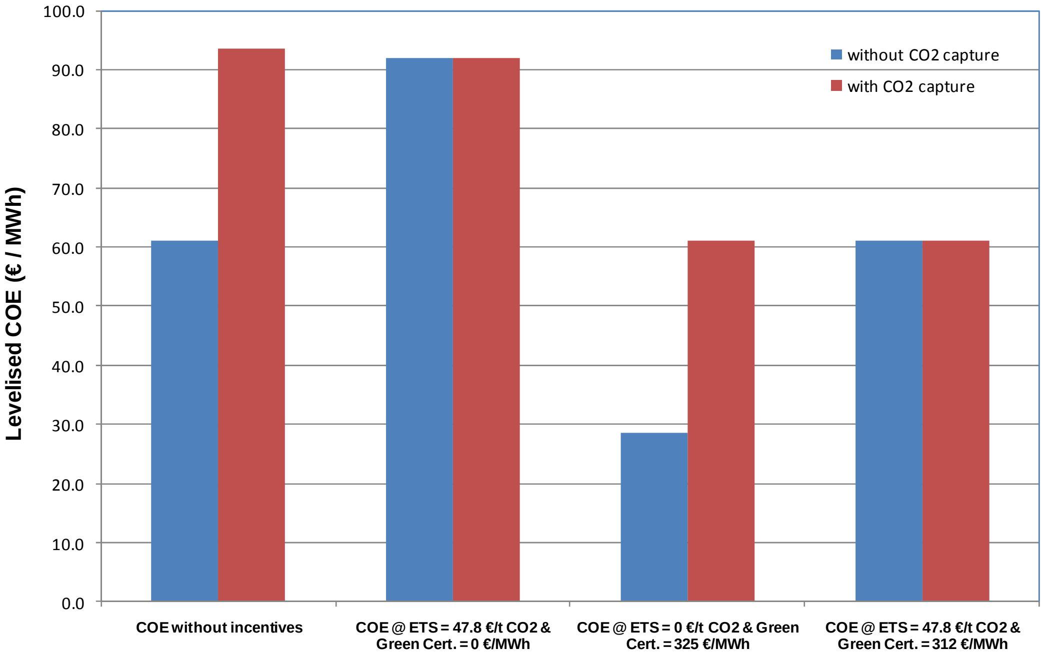

Figure 3: Levelised COE at 10% IRR for a nominal 500MWe Pulverised Coal Power Plants Co-Fired with Biomass (Figure illustrating the impact of ETS and Green Certificates)

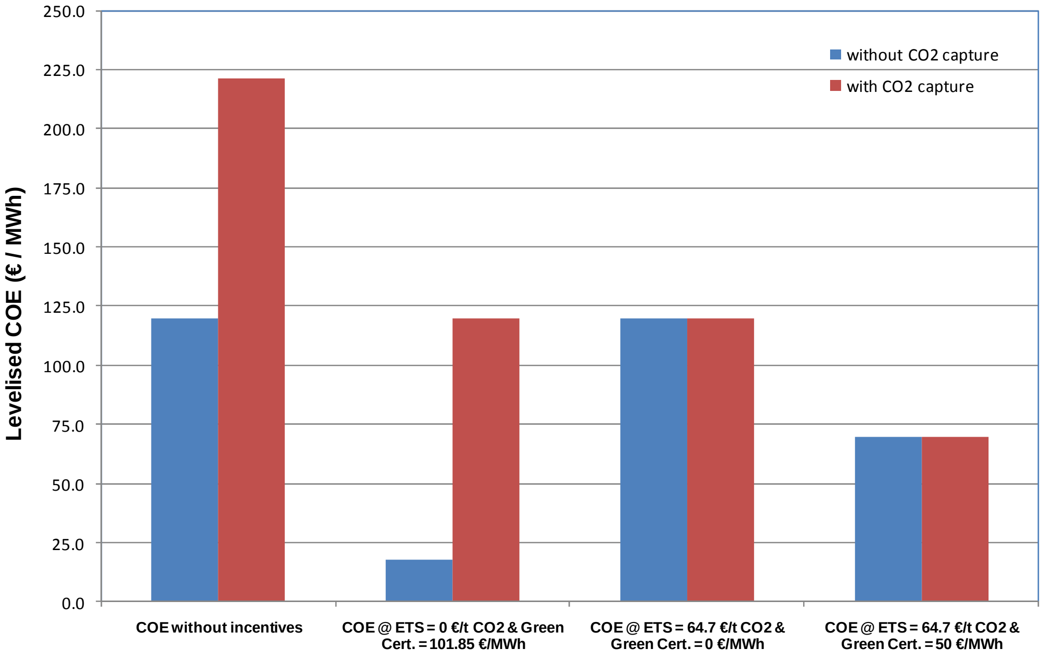

Figure 4: Levelised COE at 10% IRR for a nominal 250MWe Biomass Fired CFB Power Plant (Figure illustrating the impact of ETS and Green Certificates)