FEASIBILITY OF BIO-CCS IN CHP PRODUCTION – A CASE STUDY OF BIOMASS CO-FIRING PLANT IN FINLAND

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Contents

Keywords: CCS, biomass, CHP, oxy-fuel, feasibility

Abstract

This paper briefly describes implications of applying Bio-CCS in power production sector through a case study for a Finnish CHP-plant using biomass fuels. Effect of carbon capture and storage on greenhouse gas balance and operation economics of the CCS plant with different biomass and fossil fuel ratios are compared to the base case plant production with varying parameters of plant operation. In the study it is assumed that the economic incentive for negative CO_2 emission is included in EU ETS.

The studied fuel-shares with and without CCS consisted of pure biomass, pure peat and biomass-peat co-firing and these options were compared in the same operational environments. In general, co-firing biomass with fossil fuels represents one combination of renewable and fossil energy utilisation that derives the greatest benefit from both fuel types. Co-firing is typically favoured in large scale when supply of large volumes of biomass can be difficult to arrange. Co-firing capitalises on the large scale investment while requiring only a relatively modest investment to include a fraction of biomass in the fuel. The benefit of the large scale in co-firing is emphasised in the case of CCS where the investment is higher and the CO_2 transport costs are highly size-dependent

The case study for economic and environmental implications of Bio-CCS is based on greenfield 482 MW_{fuel} CHP-plant situated on the coast of the Gulf of Bothnia and emitting approximately 1.5 Mton / year. The plant is equipped with a modern CFB-boiler which is using oxy-fuel technology in the CCS applications. The effects of CCS on the local CHP-system were included within the studied system boundary in order to evaluate the economics and emissions from investor's (local energy company) point of view. Oxy-fuel and carbon capture processes were modelled using Aspen Plus process modelling software and the results were used to estimate CO_2 emission reduction possibilities and carbon abatement costs. Regarding the emission balances, besides the site emissions, the main effects on global GHG-emissions are also taken into account by using system modelling and streamlined LCA.

The results showed that the costs for CCS are heavily dependent not only on the characteristics of the facility and the operational environment but also on the chosen system boundaries and assumptions. In the case of Bio-CCS the feasibility of CCS is dependent on the CO_2 allowance price level shift into biomass prices. In combined heat and power plants, significant improvements can be achieved with heat integration, especially, in the production of district heat. In the near future particularly large, new combined heat and power (CHP) plants, which can burn coal, biomass or peat, are seen as promising candidates for CCS in Finland.

1 Introduction

It has been generally stated that climate change is one of the most serious environmental threats that humankind is facing and that greenhouse gas emissions (GHG's) should be reduced in every field of activities. In general, about 2°C raise in global average temperature is presented as a maximum acceptable level. In several scenarios presented to achieve this challenging target, global GHG emissions are turned to decrease in near future and despite of that global overall net emissions should be replaced by net carbon sinks (or negative emissions) in global scale at the end of this century (IPCC). One of the rare solutions for negative emissions is Bio-CCS, which is defined in this paper as capturing CO_2 from biomass combustion and storing it constantly isolated from atmosphere. In addition to that, significant improvements on the energy production efficiency are needed. One of the key solutions for that is combined heat and power (CHP, a.k.a co-generation) where over 90 % process efficiency is achievable if large heat distribution system and relatively continuous heat consumption in that system exist.

In Finland, both biomass and CHP has been utilised for decades in industry and for district heating. Boilers fired or co-fired with biomass are generally based on fluidized bed combustion technology and in Finland there are over 120 fluidized bed boilers in operation. Despite of fluidized bed technology's flexibility regarding the fuels, in the case of biomass combustion some challenges exist. When co-firing risky biomass with fossil fuels (or peat) in fluidised bed boiler designed for fossil fuels it can be expected that SO_2, NO_x and CO_2 emissions decrease, but bed material agglomeration, the rate of deposit formation and risks for high temperature corrosion usually increase. Also the variations in the moisture content of biomass fuels set demands e.g. for combustion process and the auxiliary equipment (e.g. flue gas fans) of the boiler. Due to these operational problems boiler efficiency and production can decrease and the operating and maintenance costs increase influencing on the total economy of the plant (Orjala et al. 2003). Some of these challenges may be emphasized in the case of utilization of CCS. For example with oxy-fired fluidized bed boilers even small concentrations of chlorine in the fuel can lead to deposits of harmful alkaline and chlorine compounds on boiler heat transfer surfaces due to components enrichment in the flue gas because of flue gas re-circulation.

In this paper, the results from a study where new CHP plant with and without CCS is applied to existing CHP environment are presented. Several case studies including different fuel mixes and costs for biofuels, CO_2 emission allowances and electricity were modelled. The considered power plant, modelled cases and operational environment (local energy system) are presented in Chapter 2, results of the study in Chapter 3 and discussion and conclusions in chapter 4.

2 Methods

2.1 System description and boundaries of evaluation

The case study is based on greenfield 482 MW_{fuel} CHP-plant situated on the coast of the Gulf of Bothnia and emitting approximately 1.5 Mton / year. The plant is equipped with a modern CFB-boiler which is using oxy-fuel technology in the CCS applications. The effects of CCS on the local CHP-system, including usage of the existing 295 MW_{fuel} CHP plant, were included within the studied system boundary in order to evaluate the economics and emissions from investor's (local energy company) point of view. District heat selling within the studied system boundary is kept constant in every case (1400 GWh/a) but the net electricity production is allowed to vary from case to case. Net electricity production of the economic system boundary is sold by given electricity market price. Based on the economics and emissions within this boundary, *break even prices* (BEP) for CO_2 emission allowances in EU ETS, by which CCS turns feasible over the respective base case, can be defined. CO_2 leaves from the system boundary either in the flue gases from power plant or it is shipped to a permanent underground storage. Regarding the emission balances, besides these direct emissions from combustion, the main effects on global GHG-emissions were also taken into account using system modelling and streamlined LCA. In LCA calculations, the studied system was expanded from direct emissions to include GHG emissions also from replaced electricity production (estimated to replace condensing electricity production by coal), fuel production, construction of new plant with and without CCS and CO_2 transport (ship construction, fuel consumption and CO_2 cooling splits. These emissions are taken into account for example when *costs of avoided CO_2 emissions* (COA) are estimated.

The characteristics of the power plant and operational environment are based on the real application built in Finland in 2010 with the exception of location of the plant. In this study, the plant is located on the coast of Finland, as CO_2 transportation for long distance from the inland of Finland to the coast for ship transportation has proved to increase transportation costs significantly (Teir et al. 2011).

2.2 Case descriptions

Effect of carbon capture and storage on greenhouse gas balance and operation economics of the greenfield CHP plant with different biomass and fossil fuel ratios are compared to the base case greenfield plant without CCS and to the reference case (without new CHP plant) in different cases. In the reference case the existing CHP-plant produces district heat and back-pressure electricity with maximum load (utilization rate 6000 h/a) and number of heavy-oil fired district heating plants provide the additional heat needed within the system for example during the winter peak load hours. In other cases existing CHP-plant and the new plant produce district heat and back-pressure electricity with given utilization rates and condensing electricity is produced at the new plant depending on the given utilization rate. At cases with CCS the utilization of heat recovered from CCS is dependent on the given utilization rates of the plants. In every case the existing plant is fired with 50 % peat and 50 % biomass. The studied fuel-shares with and without CCS for the new plant consisted of pure biomass (consisting of logging residues at average moisture of 50 %), pure peat (at average moisture of 45 %), and biomass-peat co-firing and these options were compared in the same operational environments. The studied cases are named as follows:

1. **Reference**: No new plant.
2. **100 % peat w/o CCS**: The new plant is fired with 100 % peat and it runs without CCS.
3. **100 % peat with CCS**: The new plant is fired with 100 % peat and it runs with CCS.
4. **co-firing w/o CCS**: The new plant is fired with 50 % peat and 50 % biomass and it runs without CCS.
5. **co-firing with CCS**: The new plant is fired with 50 % peat and 50 % biomass and it runs with CCS.
6. **100 % bio w/o CCS**: The new plant is fired with 100 % biomass and it runs without CCS.
7. **100 % bio with CCS**: The new plant is fired with 100 % biomass and it runs with CCS.

Large variation in the fuel mix affects on plant design, investment and operational parameters. These are described in chapter 2.4. The plant fuel power (nominal capacity 482 MW), designed live steam values (160 kg/s, 164 bar, 560 °C with final superheating at the loop seal) of the boiler and the amount of heat supplied to district heating network are assumed to remain constant in all cases and the use of biomass is assumed to increase the plant investment and plant operating costs. In the case of CHP plant and especially in the case of combusting significant amount of biomass, designing CCS plant to for example equal electricity production than base case (resulting larger fuel consumption and heat production) is not reasonable.

2.3 Processing, logistics and storing

As there is no storage capacity in Finland the captured CO_2 has to be transported and stored abroad. The storage phase in this study is evaluated according to Teir et al. (2011) and the CO_2 transportation including costs related are assumed according to Kujanpää et al. (2010).

Ship transportation from Finland is the most promising first phase solution for transporting of CO_2 to a storage site outside Finland. For ship transportation CO_2 has to be pressurized and cooled down to approximately 6,5 bar and -52°C. To reach these conditions with normal cooling water temperatures CO_2 compression and flash purification is needed in several stages. When CO_2 is flashed, part of it is evaporated. This evaporated part is circulated back to the corresponding compression stage. Compression is done in several stages, to enable efficient heat recovery. Isentropic efficiency used in the compressors is 0.8. Most of the energy in CO_2 compression is used to liquefy CO_2. In addition to the vaporized CO_2 recirculation, this is why compression power for ship transportation is not significantly smaller than for significantly higher pressures for pipeline transportation.

CO_2 stream has to be cooled between the compression stages and some of the heat can be recovered for district heating. CO_2 is cooled down to 15°C between the compression stages. Some of this low temperature level heat can be utilized to preheat the return stream from district heating network.

2.4 Cost and emission balance estimation

In order to estimate costs and emission balances of the overall CCS chain excel-based system model was developed. The goal was to evaluate annual cash flows within the system boundary described in chapter 2.1. In different CCS cases and compare the balances with the base cases without CCS. The costs are defined as investor's/ operator's point of view including following main categories within the system boundary:

- District heat and electricity production from both CHP plants
- CO_2-allowances (later ETS-costs)
- CO_2 transport and storage
- Capital costs
- Other fixed operating costs (personnel, maintenance etc.)
- Variable operating costs (chemicals, water, flue gas cleaning, etc.)[1]

In the study it is assumed that the economic incentive for negative CO_2 emission is included in EU ETS. Oxy-fuel and carbon capture processes were modelled using Aspen Plus process modelling software. Results from the process models are served as inputs into the cost model as well as general data received from the plant operator and from public literature. The most important parameters, in terms of economic feasibility of CCS, are the cost of CO_2 emission allowances, fuel purchase prices and the price of electricity and these parameters were varied in the study to obtain results in different market situations.

Because there are only few oxy-CFB based CCS-approaches available in the literature, the overall additional investment due to CCS is based on the presentation given by Simonsson et al. (2009) which represents similar and thus well suitable comparison of CHP plant based on CFB technology with and without oxyfuel. The baseline investment for new plant without CCS is based on the information from local newspaper. This value was used as an investment for peat firing plant, even though up to 30 % biomass can be utilised also with that design if sufficient biomass sources with applicable properties (e.g. in terms of fuel handling and feeding) can be found. The additional investment due to CCS [M€] is scaled to represent the capacity of studied plant by the equation 1.

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[1] Note: Own electricity consumption of the CCS-plant is evaluated separately.

$$I = \left(\frac{P_{fuel}}{P_{fuel,ref}}\right)^{CF} \cdot \left(I_{CCS} - I_{w/o\ CCS}\right), \tag{eq. 1}$$

where

P_{fuel}	Fuel power of studied plant
$P_{fuel,ref}$	Fuel power of CCS plant by Simonsson (2009)
CF	Capacity factor 0.65 (Green and Perry, 2008)
I_{CCS}	Investment presented for plant with CCS by Simonsson (2009), 1074 M€
$I_{w/o\ CCS}$	Investment presented for plant w/o CCS by Simonsson (2009), 741 M€

Due to biomass share increase in the studied co-firing and 100 % biomass cases in comparison to 100 % peat firing, the investment of the plant and the fixed and variable operating costs are increased, both in air- and oxymodes. The investment increase in air fired co-firing case is 15 M€ and 25 M€ in 100 % biomass case. Incremental costs are mainly derived from additional fuel handling systems, higher quality boiler materials, extra soot-blowers and higher volumes in the flue gas path including increased capacity fans. Some savings in comparison to 100 % peat firing can be achieved from decreased ash handling and limestone systems. The fixed and variable operating costs in the air firing mode are increased in comparison to 100 % peat firing mainly because of e.g. fuel handling operations, increased maintenance work, extra consumption of boiler tube materials and make-up bed material. Also the use of in-house electricity consumption is increased due to fuel handling and larger flue gas fans etc. Some savings in comparison to 100 % peat firing can be again achieved in operations related to ash handling and limestone systems.

The overall additional investment due to CCS is slightly different in the studied co-firing case (3 % increase in investment) and 100 % biomass case (5 % increase in investment) in comparison to 100 % peat firing. This is mainly based on increased ASU capacity (increased air demand in biomass firing), more advanced boiler materials due to e.g. chlorine enrichment in oxy-fuel and increased capacity of the CO_2 compression stage. Also some savings in comparison to 100 % peat firing can be achieved. For example, as the amount of sulphur compounds in biomass is typically very small, savings in the sulphur removal system especially in the case of 100 % biomass firing are possible. However, the need for additional sulphur removal unit due to CCS is still inconsistent in the case of oxy-fuel as sulphur removal may be possible in CPU. In addition, in the case of CFB, in-situ sulphur removal by limestone addition in bed may eliminate the need for additional scrubbers. Simonsson et al. (2009) did not include additional sulphur removal into investment and therefore neither savings for that investments cannot be calculated. However, in the case of 100% biomass even the limestone systems needed for in-situ sulphur removal can be avoided resulting some cost savings.

The additional fixed and variable operating costs due to CCS in the studied co-firing and 100 % biomass cases in comparison to 100 % peat oxy firing are estimated to be equal. The captured CO_2 is shipped to North Sea by special CO_2 ships. The transport is purchased as service from a separate service provider in these studies. The storage is saline aquifer and the overall storage price is set to 11–12 €/t CO2 (McKinsey & Co 2008).

3 Results

The goal was to evaluate annual cash flows within the system boundary in different CCS cases and compare the balances with the base cases without CCS and also to reference case without any investments on new power generation.

With the earlier described process parameters and the costs for electricity, district heat and CO_2 emission allowances foreseeable in on-going (second) EU ETS period, the following figure about the costs from the operator point of view can be calculated. With the costs presented in following figures, it is estimated that the peak load utilisation rate of new plant is 7000 h/a for all the cases with and w/o CCS. The utilisation rate of existing plant is estimated to be 5500 h/a for all the cases which means that a lot of electricity is produced also in condensing mode in all the cases especially during summer time.

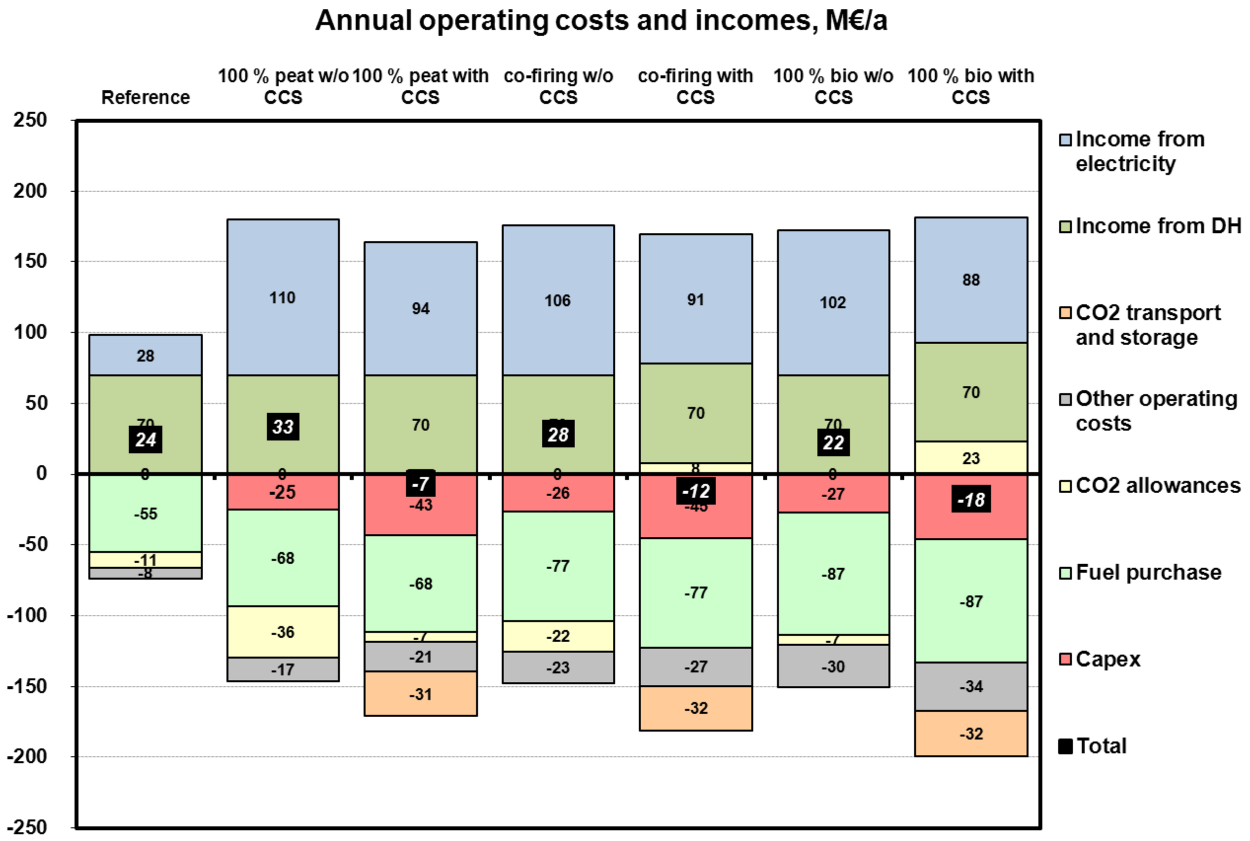

Figure 1. The cost structure with EU-ETS price of 23 €/tn,CO_2, electricity price of 60 €/MWh and district heat price 50 €/MWh for different cases if fuel purchase prices are 12 €/MWh for peat and 18 €/MWh for biomass. CCS is not feasible in comparison to respective base cases with the given input values. The highest profit is gained by 100% peat firing. However, all the cases without CCS are economically profitable, mainly due to good economics of CHP in general.

From figure 1 it can be seen that with the chosen parameters the most significant cost categories in terms of CCS economics are income from electricity (effect of energy penalty), CO_2 transport and storage, CO_2 allowances (which appears as incomes in the case of Bio-CCS) and Capex (additional investment). If electricity price and CO_2 allowance price are increased, the significance of these two categories obviously increases. CCS is estimated to become economically feasible at future costs of CO_2. If CO_2 price is high, it is probable that also price of electricity is high. In figure 2, the profit of studied operator is presented with future costs of CO_2 and electricity. Another line presents the profit in the case that biomass price is increased due to increased local consumption. As it can be seen, in terms of Bio-CCS feasibility, it is essential how CO_2 costs and increased biomass consumption are reflected in biomass prices. However, the higher is the cost from CO_2 emissions, the more profitable is Bio-CCS in comparison to other studied alternatives.

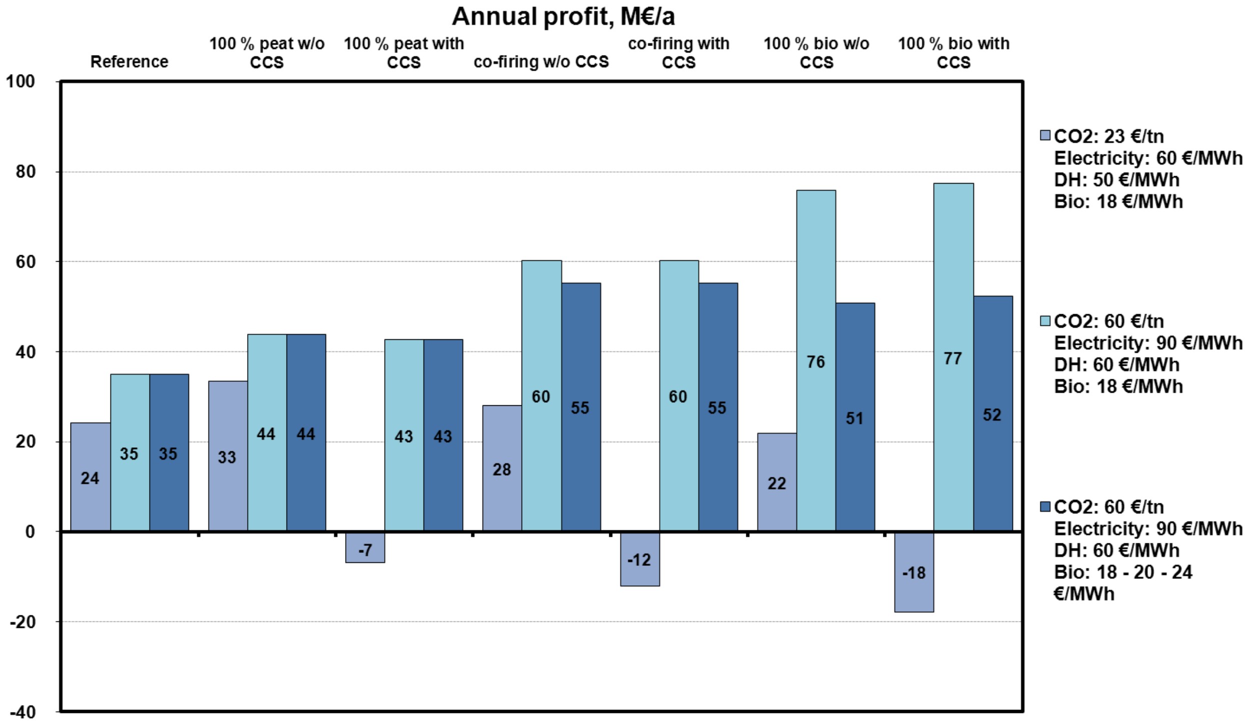

Figure 2. The profit with different economic variables for different cases. Bio-CCS is clearly the most profitable option if potential increase in biomass price is not taken into account. If biomass cost is expected to increase as a function of local consumption (18 €/MWh for reference plant in the case of 100% peat consumption in new plant, 20 €/MWh for co-firing case and 24 €/MWh for dedicated biomass firing), co-firing is the most profitable option.

Effect of CCS on GHG emissions is not directly depended on the fuel costs etc. variables used in this study. However, economics affect on the utilisation of the plants and thus also on emissions. In Figure 3, the effect of CCS on GHG emissions with earlier presented utilisation rates are presented.

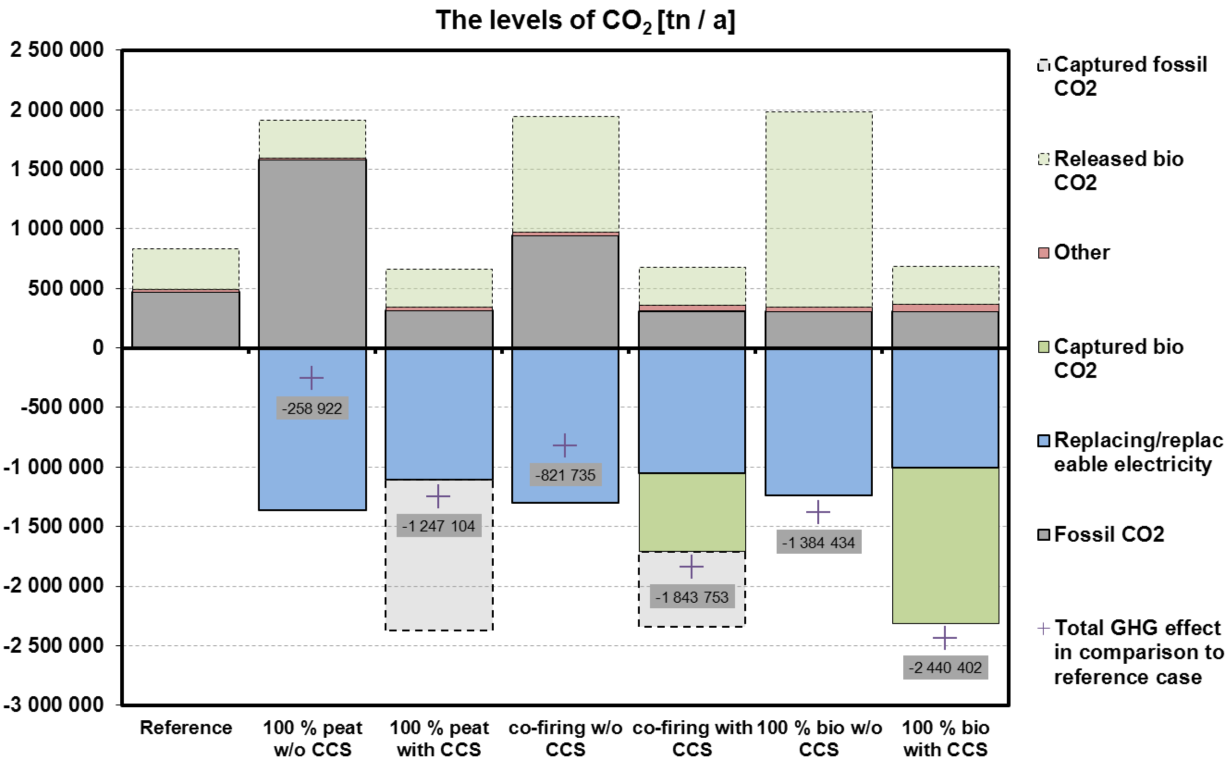

Figure 3. The effect of CCS on GHG emissions. Dashed lines indicate emissions that are often neglected when accounting emissions (i.e. CO2 emissions from biomass combustion and stored CO2 from fossil fuel combustion). In comparison to reference case, all of the studied alternatives reduce GHG emissions trough substitution credits gained from replaced electricity production.

The most economical solution is depended on for example electricity prices, CO_2 and fuel costs and estimated peak load hours, which all are uncertain. In table 1, the break even prices (defined in chapter 2.1) are presented. As can be seen, CCS in connection to CHP and biomass combustion results relatively low break even prices compared for example with break-even prices defined for condensing power plants. For Finnish condensing power plants break even prices of 70 – 100 €/tn are presented by Teir et al. (2011) even if plant size is larger in condensing case. Even though the most profitable CCS option is in the case of co-firing, the lowest BEP can be achieved with Bio-CCS.

Table. Break even prices (BEP) and costs of CO2 avoided (COA), €/tn, in different CCS cases in comparison with respective base cases with two sets of price parameters.

Case:	**100 % peat with CCS**		**co-firing with CCS**		**100 % bio with CCS**	
	BEP	COA	BEP	COA	BEP	COA
CO_2: 23 €/tn, Electricity: 60 €/MWh, DH: 50 €/MWh, Bio: 18 €/MWh	**55**	**70**	**54**	**68**	**53**	**66**
CO_2: 60 €/tn, Electricity: 90 €/MWh, DH: 60 €/MWh, Bio: 18 €/MWh	**61**	**78**	**60**	**76**	**59**	**73**

4 Conclusion and discussion

The results showed that the costs for CCS are heavily dependent not only on the characteristics of the facility and the operational environment but also on the chosen system boundaries and assumptions. The optimal solution from an investor's point of view depends on multiple factors, electricity price and EU-ETS price being the dominant ones. In general, it can be concluded the EU-ETS price and electricity prices prospected in the near future do not make the CCS investment yet easily feasible. In the case of Bio-CCS the investment and operational costs (excluding CO_2 emission allowances) are probably higher than in the case of fossil fuels. Increasing CO_2 prices benefit Bio-CCS faster than other CCS options. Feasibility of Bio-CCS is dependent heavily on the CO_2 allowance price level shift into biomass prices. In general, feasibility of CCS is also dependent heavily on the CO_2 allowance price level shift into electricity price. The feasibility can, however, be optimised by using the new operational options that CCS brings. For instance, CO_2 capture could be bypassed during periods of peak electricity prices. In combined heat and power plants, significant improvements can be achieved with heat integration, especially, in the production of district heat. Economically the most feasible CCS solutions are achieved in the cases where heat from CCS plant can be utilized in district heating network but plant can be operated also in condensing mode to achieve high peak load hours, which are necessary in terms of investment payback time.

There are large CO2 emissions in Finland originating from biomass combustion, both in energy production and industry. However, the current EU ETS do not recognize negative emissions, and thus no economical incentive exist for capturing CO2 from biomass installations. As far as biomass and biogenic emissions are concerned in power plants, most potential and straight forward applications would be in facilities co-firing biomass with peat. Biomass firing plants are not seen as primary places to apply CCS in the initial phase, since these facilities do not currently need to reduce their CO2 emissions. CCS would also mean additional environmental and economical risks and concerns for the facility. In addition, biomass firing plants are generally of moderate size and often situated in central Finland, which makes them less attractive due to large distances to potential ship terminals. In the near future particularly large, new and flexible combined heat and power (CHP) plants, which can burn coal, biomass or peat, are seen as promising candidates for CCS in Finland. Oxy-fuel combustion is seen as a promising technology for Finland, both in terms of domestic CCS applications and as an opportunity for Finnish technology developers.

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