Effects of carbon capture on gas fired power plant

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Abstract

Climate change is one of the biggest challenges of our time, and carbon capture and storage (CCS) is expected to play a significant role in reducing carbon dioxide emissions worldwide and abating climate change. This study analyses how the integration of pre-combustion carbon capture technology in the gas-fired combined heat and power (CHP) plant affects the efficiency, power-to-heat ratio, CO_2 emissions and costs of the power plant. The study shows that carbon capture reduces the efficiency of the combined cycle gas turbine power plant by 11%-points. Same time, the power-to-heat ratio increases due to the fact that carbon capture reduces heat production of the plant more than electricity production. The investment in greenfield gas turbine combined cycle CHP power plant with pre-combustion carbon capture technology would not be a reasonable investment with the current prices of electricity, heat, and emission allowances.

Background

The concern over the climate change has crown in the last decades. It is one of the biggest challenges of our time. Human activities have increased the concentration of greenhouse gases in the atmosphere, which are considered to have a significant impact on the climate. The European Union has set target for reducing its greenhouse gas emissions by at least 20 % by 2020. Carbon capture and storage (CCS) is expected to play a significant role in reducing carbon dioxide emissions worldwide. Figure 1 below shows the key technologies for reducing CO_2 emissions.

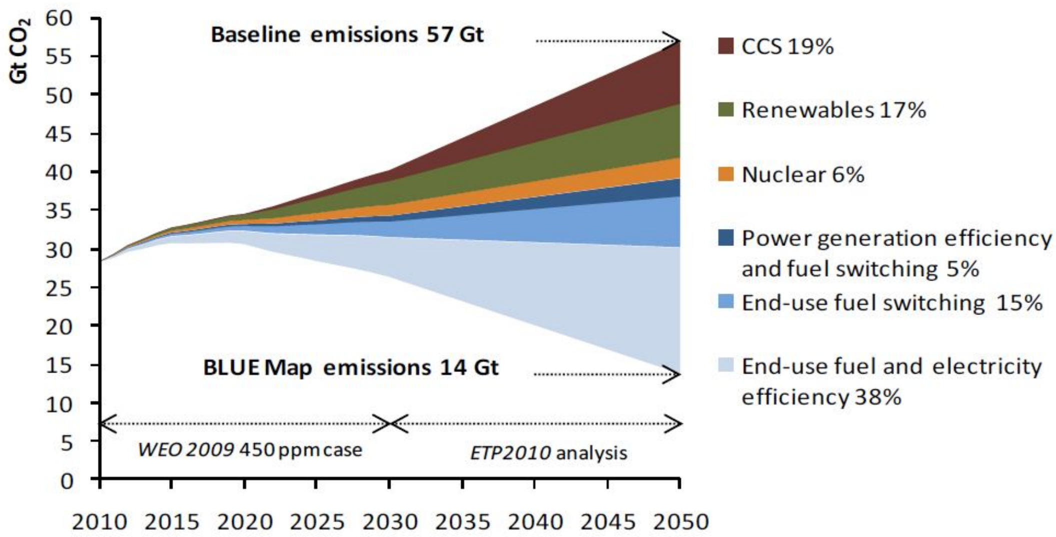

Figure 1. Key technologies for reducing CO_2 emissions according to the International Energy Agency's (IEA) BLUE Map Scenario for 2050 [1].

Carbon capture and storage is widely studied in Europe and in the USA. European commission encouraged the member states to research and to develop the CO_2 capture and storage technologies so that in the year 2020 it would be feasible to use in new fossil fuel power plants [2]. For promoting the development of CCS technology the European Commission created a financial instrument managed jointly by the European Commission, the European Investment Bank, and Member States. This instrument is known as NER300 – Finance for installations of innovative renewable energy technology and CCS in the EU [3]. Financing is provided by 300 million emission allowances, which are given without charge for the installations [3].

Even though the majority of the CCS projects plan to use coal and biomass as a fuel, there are also natural gas fuelled projects under way. A gas and coal-fired post-combustion carbon capture pilot plant is due to start operation in 2012 in Technology Centre Mongstad in Norway. The CO_2 separation rate in the plant will be approximately 85% [4]. The Don Valley Power Project and CCS project at Peterhead are two natural gas-fired CCS projects in the UK. A pre-combustion carbon capture technology will be used in the Don Valley Power Project. The separation rate in the project is approximated to be 90% [5]. The CCS project at Peterhead is a post-combustion carbon capture project. The carbon capture facilities will be retrofitted into an existing combined cycle gas turbine power plant [6]. In addition to the individual projects, Energy Technologies Institute in the UK launched a CCS for gas plant projects [7]. Based on Global CCS Institute [8] no CCS projects in related to the CHP power plants seem to be on-going.

In Finland, carbon capture and storage is studied under the CCSP program of CLEEN Ltd. CLEEN Ltd is a Finnish Energy and Environment Competence Cluster owned by companies and research institutes. The objective of the program is to develop CCS related technologies and concepts that would lead to essential pilots and demonstrations by 2014-2015 and commercial CCS concepts available from ca. 2020 onwards promoting development of Finnish CCS innovations [9]. The CCSP program includes the work package in which CCS concepts are studied. Under this work package Gasum has studied the effects the carbon capture technologies have on a greenfield combined cycle gas turbine power (CCGT) plant in producing both electricity and heat. The results of this study have been reported more detailed in the Master's thesis of Leena Pirhonen [10]. This article sums up the main findings of the thesis.

Aims

The aim of this research is to study how CCS affects combined heat and power (CHP) plant. This is an interesting question in the Nordic countries where large-scale CHP is widely applied in energy production. In Finland, 32% [11] of consumed electricity was produced by CHP in 2010. The share of CHP in the district heating production was as high as 71% [12].

The carbon dioxide capture technologies were studied from the perspective of a greenfield combined cycle gas turbine (CCGT) power plant producing both heat and power. The objective of the study was to found out how a carbon capture technology affects the power plant i.e. overall efficiency of the power plant, electric efficiency, power-to-heat ratio, fuel input and CO_2 emissions. In addition, cost effect such as costs of electricity and heat production, were studied.

Methods

There are currently three primary technologies to reduce CO_2 emissions. The technologies which decarbonise the fuel prior to combustion are known as pre-combustion technologies. In technologies know as post-combustion, CO_2 is separated from flue gases. Combustion can also be re-engineered in such a way that it produces only CO_2 and water that can be condensed after combustion. This capture technology is called oxy-fuel combustion. In oxy-fuel combustion the fuel is combusted in pure oxygen. There is also significant modification of oxy-fuel combustion, known as chemical looping. [13, 14]

Different carbon capture technologies were first compared by evaluating the strengths, weaknesses, opportunities and threats (SWOT analysis). Based on the comparison a pre combustion technology seemed most appealing from the perspective of a greenfield combined cycle gas turbine power plant. The SWOT-analysis of pre-combustion technology is presented in table 1 below.

Table 1. Pre-combustion SWOT [10, 13, 14, 15, 16]

Strengths • Relatively high CO_2 concentration before separation→ lower energy demand for CO_2 capture and compression • When increasing CO_2 capture rate, the specific energy requirement does not greatly increase • Separation of CO_2 from H_2 is easier than from N_2	**Weaknesses** • Temperature and efficiency issues associated with hydrogen-rich gas turbine fuel • Increase of NO_x emissions due to increased flame temperature
Opportunities • Development of H_2 fueled gas turbine • High development potential owing to the combined power cycle	**Threats** • Difficult to retrofit • Complex technology has to be used

The main advantage of pre-combustion technology is high efficiency. However, the level of maturity is lower than that of some other technologies. The pre-combustion technology is estimated to need 6–10 years of development [17].

Pre combustion technologies are used commercially in various industrial applications such as the production of hydrogen and ammonia. In the figure 2 the block diagram for pre combustion CO_2 capture in CCGT is presented. In natural gas fuelled power plant the fuel must be reformed and sifted to generate a mixture of hydrogen and CO_2. Then either the CO_2 is removed using sorbents or the hydrogen is removed using membranes.

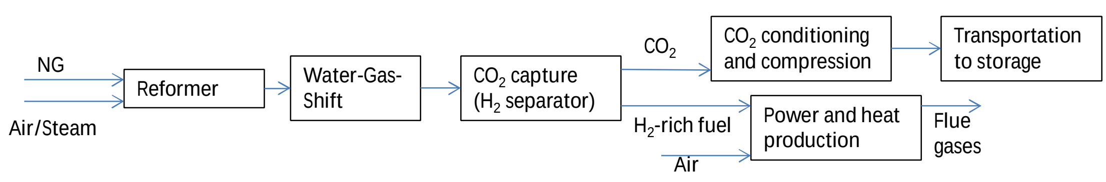

Figure 2. Block diagram for pre-combustion CO_2 capture [10].

The combined cycle gas turbine power plant producing both heat and electricity with pre combustion carbon dioxide capture was modelled, and the modelling results were compared to the reference plant without carbon capture. The reference plant without CO_2 capture was modelled with Solvo ®, that is a power plant design and optimisation tool developed by Fortum Oyj. The power plant with CO_2 capture was built with three programs: the base components of the power plant were modelled with Solvo ®, the reforming process with Microsoft Excel ® and the absorption system with Aspen Plus ®. The input data of modelling is based on previous studies available and process information. The system boundaries and integration between the different models are presented in figure 3. The operation of the power plant was modelled with three different CO_2 capture rates: 97%, 90%, and 80%.

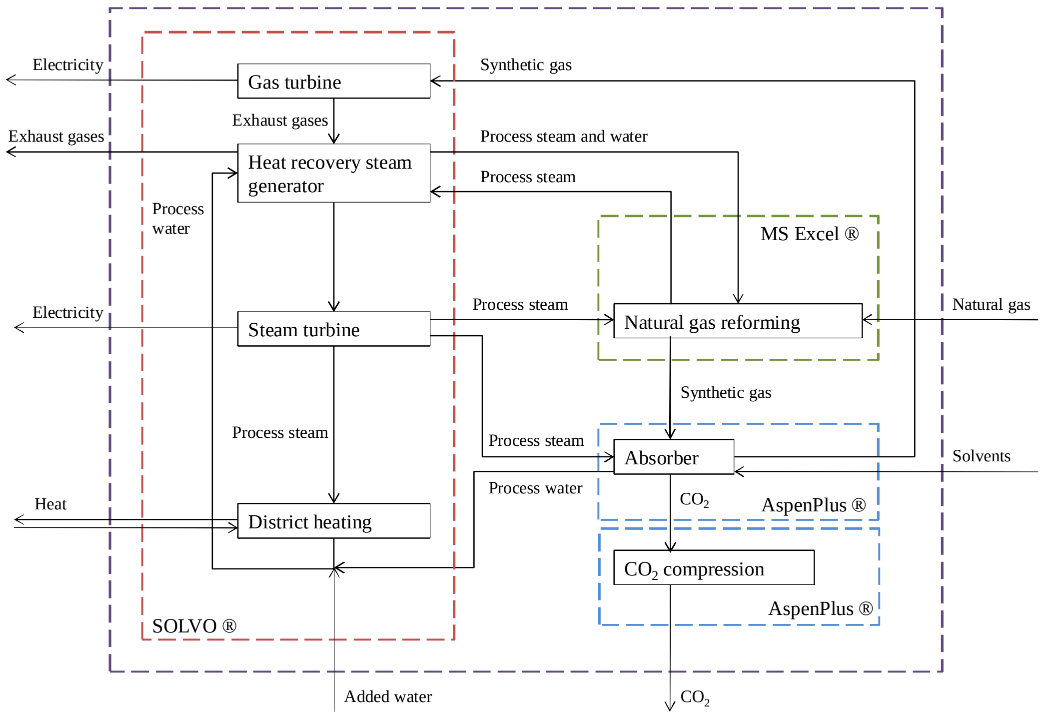

Figure 3. Power plant model [10].

In this study the overall efficiency of the power plant will be calculated as follows:

$$\eta_{tot} = \frac{\text{Electric Power Sold} + \text{District Heat Sold}}{\text{Purchased Natural Gas}} \qquad (1)$$

Electric Power Sold does not include the auxiliary electricity used by the power plant. Also the heat produced to the reformer and absorber is not included in the District Heat Sold.

The power-to-heat ratio is defined as follows:

$$\text{Power} - \text{to} - \text{Heat Ratio} = \frac{\text{Electric Power Sold}}{\text{District Heat Sold}} \qquad (2)$$

In this study the peak operation time of 4,776 hours per year is used. This figure is based on the real operation profile of typical CCGT power plant. Table 2 shows the investment costs of the power plant.

Table 2. Investment costs of the CCGT plant with CCS. [10, 18, 19]

TOTAL INVESTMENT COST	**M€**
Power plant (2 GT+HRSG, ST, DH)	303
CO_2 removal, compression and liquefaction	156
Reformer	508
Balance of plant	168
TOTAL	1,135

The investment cost of a CCGT plant, based on the same gas turbines without carbon capture, for power and heat production is expected to be €270 million [18]. The power plant unit cost with pre-combustion carbon capture is estimated to be 1.12 times the conventional power plant cost [19]. This is mainly due to the modifications that have to be made to the gas turbine for hydrogen combustion.

In the early stage of the process development there are significant uncertainties related to the investment costs. Especially, the reformer investment cost is high compared to the other components. However, it can be assumed that the reformer technology in power plant use is in an early stage in the learning curve. Thus, it can be assumed that the cost of the reformer will decrease in the future.

Operating costs used as an input data of this study is presented in table 3 below. Methyldiethanolamine (MDEA) and diethanolamine (DEA) are amines used to absorb CO_2 from synthetic gas in the absorber.

Table 3. Operating costs of the of the CCGT plant with CCS [10].

	Price
Natural gas	€31 / MWh (taxes excluded) €45 / MWh (taxes included)
MDEA	€3,830 / tonne
DEA	€1,000 / tonne
Raw water	€0.102 / 1,000 l
CO_2 transport	€15 / CO_2-tonne
CO_2 storage	€11 / CO_2-tonne
Labor	€56,500 / employee
Maintenance	3% of total investment costs
Overhead changes	30% of labor costs

Results

The summary of the plant performance with a capture rate of 90% is compared to the reference plant in table 4 below. In this comparison the heat output is kept almost unchanged because the heat load is the factor that states the size of the CHP plant. Because capturing carbon needs additional energy the fuel input increases around 19% compared to the reference case. Therefore, the overall plant efficiency decreases.

Table 4. Plant performance [10].

PLANT THERMAL INPUT	**CCGT CHP with CO_2 capture**	**CCGT CHP without CO_2 capture**
Thermal Energy of Natural Gas	1,003 MW	841 MW
PLANT ELECTRICAL OUTPUT		
Electric Power Output at Generator		
Gas Turbine	294 MW	273 MW
Steam Turbine	152 MW	130 MW
Total	446 MW	403 MW
Gross Electrical Efficiency	0.44	0.48
Auxiliary Electrical Consumption	21 MW	1,7 MW
Net Electrical Output	425 MW	401 MW
Net Electrical Efficiency	0.42	0.48
PLANT THERMAL OUTPUT		
District Heating	353MW	351 MW
Absorber Unit Heat Consumption	96 MW	-
OVERALL PLANT EFFICIENCY		
	0.78	0.89
POWER TO HEAT RATIO		
	1.20	1.14

The efficiency of the power plant modelled was 11%-points lower than the reference power plant without carbon dioxide capture. The efficiency was the higher the lower the carbon dioxide capture rate. In previous studies the efficiency drop for CCGT power production without heat production has been 5–8% units [17, 20]. This means a 9%–15% drop in efficiency. Here, the total drop in total plant efficiency is 11%. The drop in electrical efficiency is 6% units, which is 13% from the net electrical efficiency of the CCGT CHP without CO_2 capture. This falls into the same range as in the previous studies of CO_2 capture in a CCGT without heat production.

The power-to-heat ratio for a modern CCGT CHP is higher than 1.00. In the reference case, the power-to-heat ratio is 1.14. The relatively high power-to-heat ratio in the reference case is due to the added condensing unit of the steam turbine, where part of the steam is not extracted to district heating heat exchangers, thus it expands to the condenser pressure, producing more electricity. This is done because the reference plant is fixed to produce roughly the same amount of heat for being comparable to the CCS case.

In the case of CCS the power to heat ratio was 1.2 i.e. 6 %-units higher than in the reference power plant without carbon capture. Thus, the decrease in efficiency influences more in the heat than electricity production. This can be explained by the large steam extraction made from the steam turbine to the absorber in the CO_2 removal unit. The extraction is made around the same pressures as the extractions to the district heating heat exchangers. This reduces the production of district heat. The CCGT CHP with CO_2 capture produces more electricity in the steam turbine because the mass flow in the steam turbine is larger than in the reference case. The mass flow is larger because steam is produced in both the heat recovery steam generator (HRSG) and the reformer.

The electricity output and heat output reduce when the capture rate is increasing. The mass flow of the steam extracted from the steam turbine to natural gas reforming is larger the higher the capture rate is. The electricity production of the gas turbine is the same in every capture rate case but the electricity production of the steam turbine is decreasing. Table 5 shows the results of this sensitivity analysis.

Table 5. Results from the sensitivity analyses related to different carbon capture rates [10].

	Capture rate 97%	**Capture rate 90%**	**Capture rate 80%**	**Without CO_2 capture**
Gas turbine electrical output	294 MW	294 MW	294 MW	273 MW
Steam turbine electrical output	147 MW	152 MW	154 MW	130 MW
District heating	348 MW	353 MW	357 MW	351 MW
Absorber unit heat consumption	103 MW	96 MW	86 MW	-
Power-to-heat ratio	1.20	1.20	1.20	1.14

Captured and actual CO_2 emissions are presented in the figure 4 below. The total amount of actual and captured emissions increases with the increasing capture rate, because due to increasing efficiency loss more fuel is needed to produce the same heat output.

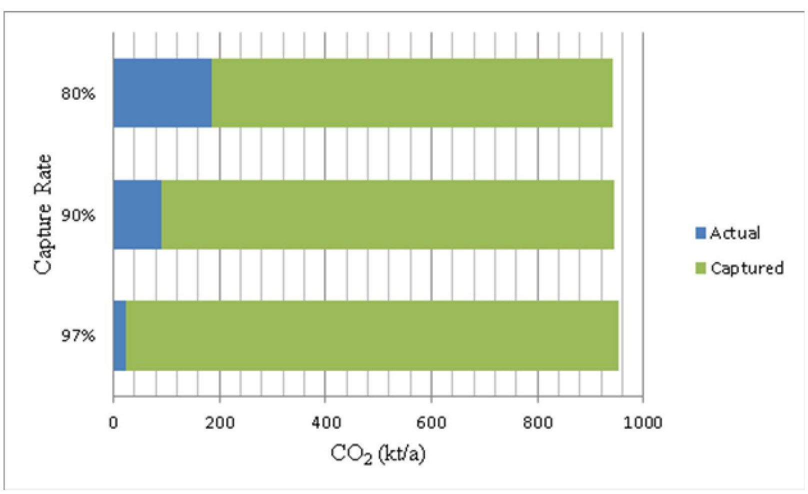

Figure 4. CO_2 emissions with different capture rates [10].

The costs of the power plant with carbon capture are much higher than the power plant without carbon capture. Especially, the investment cost of the reformer is high compared to the other components. In addition, increased fuel consumption increases the operation costs. The total annual cost in the case of the capture rate of 90% is €308 Million. The cost of energy is calculated by dividing the total annual cost by the energy produced. It is divided for heat and electricity by using the coefficient 0.9 for heat produced, and then using the energy method. The factors are 0.59 for electricity and 0.41 for heat. Table 6 shows the production cost of energy in the CCGT power plant with the carbon capture rate of 90 %. The production cost is compared the actual electricity and heat prices in Finland in 2010.

Table 6. Cost of energy [10].

Parameter	Production cost (€ / MWh)	Energy price (€ / MWh)
Cost of energy	82	
Cost of electricity	90	57
Cost of heat	75	55

Carbon capture and storage increases the energy production costs 36..58% above the market prices in 2010. There should be remarkable changes in the energy and carbon markets that the energy production in the CCGT plant with CCS would be feasible. Based on our estimation the price of emission allowance should be at least €80 / t CO_2 that energy production could be profitable.

Summary/Conclusions

Carbon capture is an interesting option to reduce CO_2 emissions from natural gas use in energy production.

The CCGT power plant with carbon capture studied here is not feasible. The costs are high, and to cover the costs of CO_2 capture the emission allowance prices should be extremely high. It is concluded that CCGT CHP with pre-combustion technology would not be a reasonable investment with the current prices of electricity, heat, and emission allowances. The main strengths of the plant were low rate of emissions and increased power-to-heat ratio. The main weaknesses were high investment costs and decreased efficiency.

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