Czech Technical University in Prague

Faculty of Mechanical Engineering

Department of Power Engineering

Post-combustion carbon capture for fossil fuel power plants

Bachelor Thesis - June 2015

Author

Raul Pinto da Costa

Supervisor

Ing. Monika Vitvarova

Declaration of authorship

I, Raul Leal Pinto da Costa, declare that I have written this thesis on my own under de tutoring of Ing. Monika Vitvarova and have cited all published works consulted in references.

Acknowledgement

I would like to thank my supervisor Ing. Monika Vitvarova for her teachings and good spirits , my mother Maria Eugénia for her patience, Radhika Chartterjee for her support, my grandfather Gúi Pinto da Costa for making me curious about knowing things and all my family and friends for their support during this time.

A big thanks to all the professors that along the years in Czech Technical University in Prague passed their knowledge on Mechanical Engineering and keep on doing it.

Abstract

This thesis explains the types of Carbon Capture and Storage methods focusing on post-combustion capture technology capture technology for fossil fuels power plants. It analyzes the levels of carbon dioxide emitted in Europe and the tendency of the big gas emitters in recent year and the European system created around carbon trading to cause its reduction.

We analyze the impact of post-combustion technologies in a Natural Gas Combined Cycle Power Plant and in a Pulverize Coal Power Plant on the cost of energy, investment cost, efficiency, and carbon dioxide capture. Than in the case of Natural Gas Combined Cycle Power Plant we see how post-combustion technologies influence performance on different size plants.

After studying the current status of the post-combustion technology we check future projects in Europe and what are the developments being done in PCC for the future so it can be more efficient in Pulverized Coal Power Plants and in Natural Gas Combined Cycle Power Plants.

Keywords

Post-combustion, CCS, capture, CO_2, emissions, cost, fossil fuels, PC, NGCC

Content

1. Introduction 7
2. Carbon Capture and Storage methods (CCS technologies) 8
3. Carbon Capture Fundamental Methods 9
   - 3.1. Pre-Combustion 9
     - 3.1.1. Advantages and Disadvantages of CO_2 Pre-combustion Capture 10
   - 3.2. Oxy-fuel Process 11
     - 3.2.1. Advantages and Disadvantages of Oxy-fuel Capture 12
   - 3.3. Post-Combustion 12
     - 3.3.1. Advantages of post-combustion CO_2 capture over pre-combustion and oxy-fuel 13
4. Different Technologies of Post-combustion Capturing 14
   - 4.1. Absorption 14
     - 4.1.1. Detailed Amine Solvent Solution Capture Process 15
     - 4.1.2. Detailed Chilled Ammonia Capture Process 15
   - 4.2. Adsorption 15
     - 4.2.1. Vacuum Swing adsorption (Developing Technology) 16
   - 4.3. Membranes 16
     - 4.3.1. Polymeric Membrane in CO_2 Capture from Post Combustion 17
   - 4.4. Comparison between post-combustion capture technologies 17
5. Carbon Dioxide Emissions from Electrical Power Plants in Europe 19
   - 5.1. European Countries with Highest Carbon Dioxide emissions from Consumption of Energy 20
   - 5.2. The European Union Emission Trading System (EU ETS) 21
6. Impact of CCS technology integration into fossil power plants 23
   - 6.1. Basis of this Data 23
   - 6.2. Efficiency 23
   - 6.3. Investment Cost 24
   - 6.4. Cost of Electricity 25
   - 6.5. Avoided CO_2 and Cost of Avoided CO_2 26
   - 6.6. Summary 27
7. Plant size economic impact on Natural Gas Combined Cycle with and without post-combustion capture technologies 28
   - 7.1. COE vs Electrical Output 28
   - 7.2. Capital Required vs Electrical Output 29
   - 7.3. Capital Required vs CO_2 Emissions 30
8. Techno-economic Impact of PCC technology integration into fossil power plants in Europe 31
   - 8.1. Net Power Output and Net Efficiency 32
   - 8.2. Relative Decrease in Net Efficiency 33
   - 8.3. Investment Cost and CO_2 Emission Levels 34

8.4. CO2 capture cost and EU ETS carbon price 35
9. Future PCC projects in Europe 36
9.1. ROAD Project 37
9.2. Peterhead CCS Project 37
10. Assessment of the applicability of PCC technologies in fossil fuels power plants in Europe 39
10.1. Type of PCC Technology 39
10.2. Type of Fossil Fuel 40
10.3. Efficiency Losses 41
11. Conclusion 42
Reference 43
Abbreviations 45
List of Figures 47
List of Graphs 48
List of Tables 49
Appendix A 50

1. Introduction

The reduction of carbon dioxide and others greenhouse gases emitted into the atmosphere is one of the major concerns today in the power production industry. The increase of the world's population and subsequently increase of energy demand makes the total emissions of CO_2 reach really high levels all over the world. Facing this facts, the introducing of legislation in Europe for use of renewable cleaner energies, together with making the current fossil fuels power plants more clean, by introducing CCS technologies, was imperative having in account the consequences that those gases have on Earth and for the last 20 years many developments have been done so that this technologies become more appealing in cost and efficiency.

The goals of this thesis is introduction of the carbon capture fundamental methods (pre-combustion, oxyfuel and post-combustion capture) applicable into fossil power plants with focusing on post-combustion capture (PCC) technologies and evaluation of impacts (technical and economical) for power plant.

2. Carbon Capture and Storage methods (CCS) [1, 2, 5, 6]

Carbon Capture and Storage (CCS) is a technology that can capture carbon dioxide (CO_2) emissions produced from the use of fossil fuels in electricity generation and industrial processes, preventing the carbon dioxide from entering the atmosphere and causing global warming and climate change.

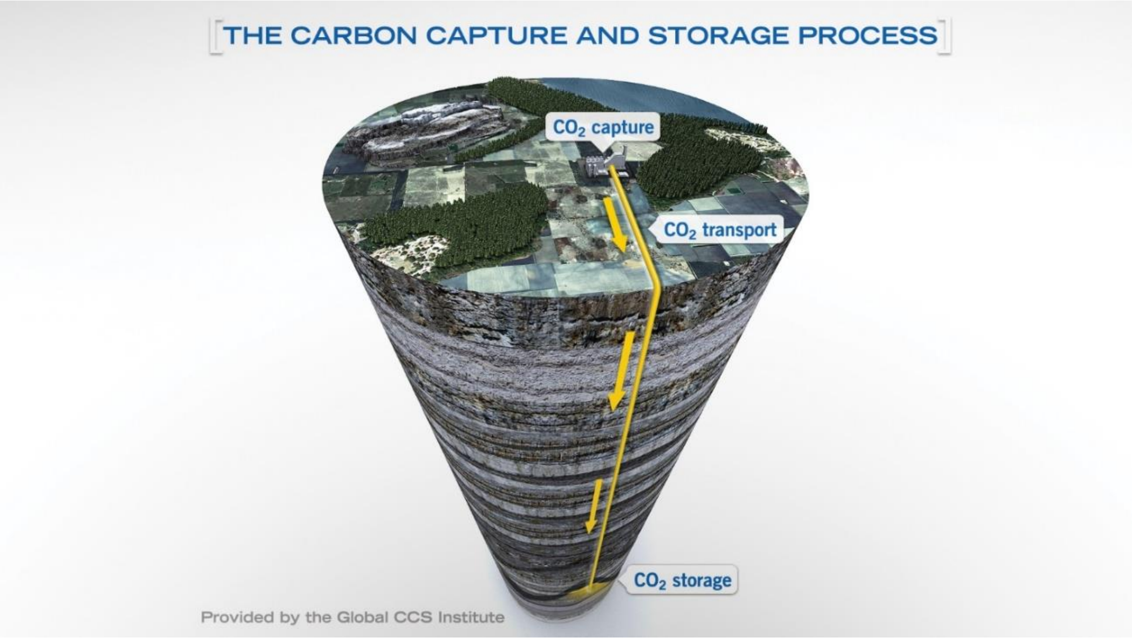


Figure 1: Carbon Capture and Store Technology [1]

The CCS technology consists of three basic parts shown in Figure 1: capture of the CO_2 emissions from energy production or industrial processes, transport of the CO_2, using pipeline or shipping, and storage of the CO_2 emissions, into deep underground geological formations.

An upcoming branch of CCS technology is the Carbon Capture Utilization and Storage (CCUS) which after capturing CO_2 either reuses or stores it. Putting the captured CO_2 into use creates a market and overall beneficial situation for CCS technologies and for a clean the environment. [2]

3. Carbon Capture Fundamental Methods [3, 20]

Capture of CO_2 from fossil fuels can be done before or after combustion. There are 3 ways that this capture occurs in the power generating sector: pre-combustion, post-combustion and oxyfuel. These categories are shown next in Figure 2.

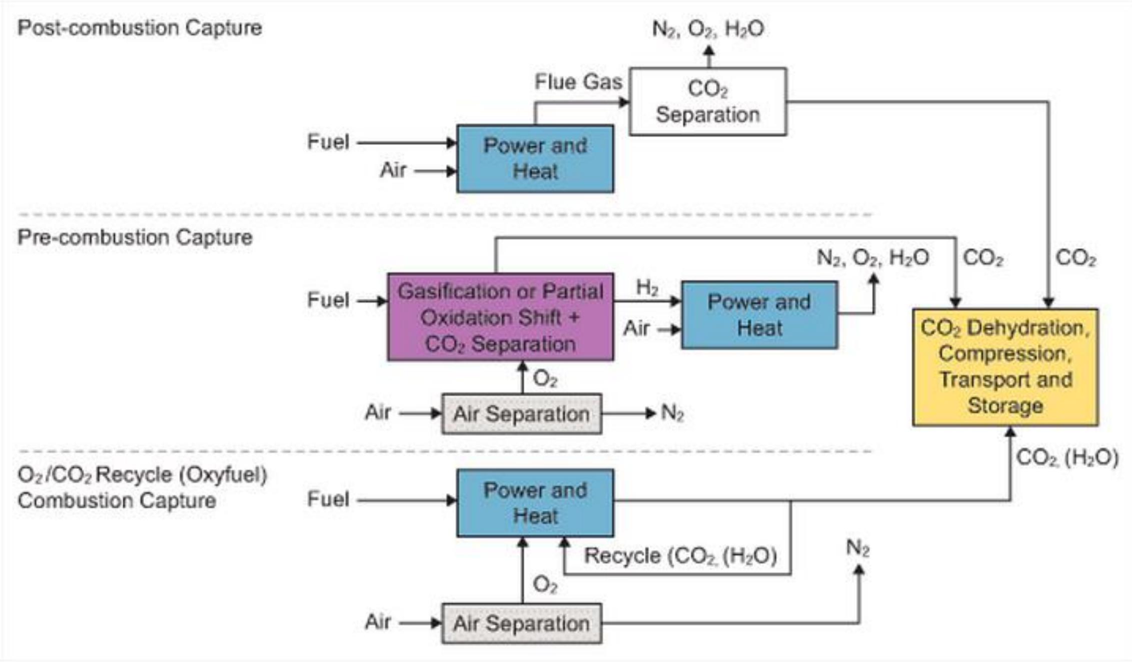


Figure 2: Carbon dioxide capture methods [3]

In Pre-Combustion the fuel goes through a process of gasification. Oxygen, which was separated from air, flows to the Gasifier and reacts with the fuel creating Syngas which than goes to a Shift Reactor where steam is added to create CO_2.The CO_2 is than captured to be dehydrated, compressed and ready to transport and storage. The remaining components of the fuel after gasification are use in another cycle to produce heat and power and/or send to the atmosphere.

On the case of Oxy-fuel oxygen is separated from air and then added to the fuel in a boiler at the right amount so that combustion is complete. Part of the resultant water and carbon dioxide produce in the combustion is reused to maintain the right temperatures in the process and the rest is dehydrated, compressed and ready for transporting and storage.

In the same way as Oxy-fuel, Post-combustion capture method captures CO_2 after combustion (as the name suggests) but using air as the oxidizing agent. The resultant flue gas from the combustion goes through a process of separation (Adsorption, Absorption or using Membranes) that captures only the CO_2 particles which than can be dehydrated, compressed and ready to transport and storage. This bachelor thesis focuses on this last technology – Post-combustion CO_2 Capture.

3.1. Pre-Combustion [4,8]

In Pre-combustion (Figure 3) air is injected into an Air Separation Unit removing nitrogen and creating a stream of almost pure oxygen (around 95% oxygen, 4% nitrogen and 1% argon and other gases), than the oxygen stream reacts with the fuel in a Gasifier at high temperatures to form Syngas (which is a mixture of water (H_2O), hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons, such as methane (CH_4)).

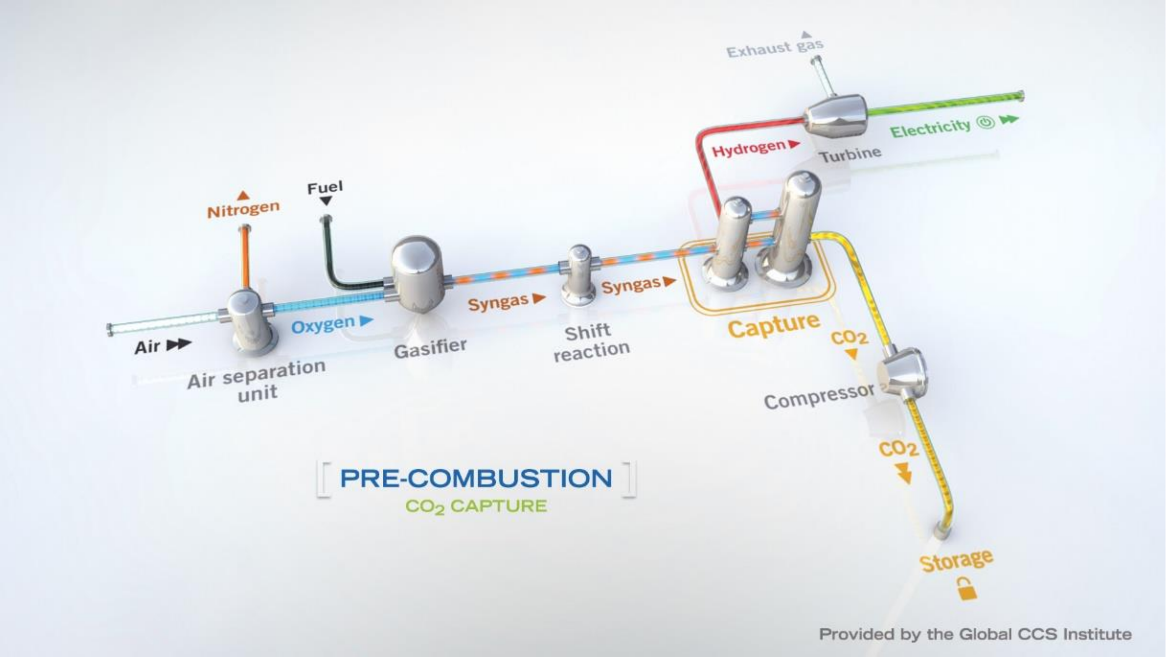


Figure 3 : Pre-combustion Carbon Dioxide Capture [4]

This Syngas is cooled down to less than 40ºC so it can be cleaned from impurities and acid gases ,such as hydrogen sulfide, to than go into a Shift Reactor, where steam is added, converting the CO and water, to CO_2 and H_2.

H_2 is used to generate electricity in gas turbines and the excess heat is recovered and used to power steam turbine, making the power output more efficient.

CO_2 created is removed from the fuel gas by getting in contact with a liquid in which CO_2 dissolves, i.e. absorption process., being than compressed and dehydrated for transport and storage.

3.1.1. Advantages and Disadvantages of CO_2 Pre-combustion Capture

If we check some of the differences in pre-combustion CO_2 capturing in comparison with the current processes in oxy-fuel CO_2 capture and post-combustion CO_2 capture there are some advantages for its implementation on industry processes and in power plants.

The gasification process is done at high pressures and the partial pressure of CO_2 in the flue gas is higher compared with post-combustion methods, this makes the regeneration of the adsorbent process easier since it can be done with the drop of pressure to 101kPa (atmospheric pressure) instead of using high amounts of energy.

Also the separation of CO_2 and H_2 is easier to be done than CO_2 and N_2 in a molecular level and should be a factor on the evolution of pre-combustion over, for example, other adsorbents for post-combustion capture and oxy-fuel capture not forgetting that it is still in a development stage, making some of the advantages only reachable in long-term. Another factor of pre-combustion capture is that it's harder to implement in an already existing power plant making post-combustion more favorable.

3.2. Oxy-fuel Process [5,9,24]

In oxy-fuel process the fuel is combust in pure oxygen in the right amount so that complete combustion happens. As we can see in Figure 4, the air is first injected into an Air Separation Unit were nitrogen is separated from oxygen which than is put in to a Boiler together with the fuel for combustion to occur.

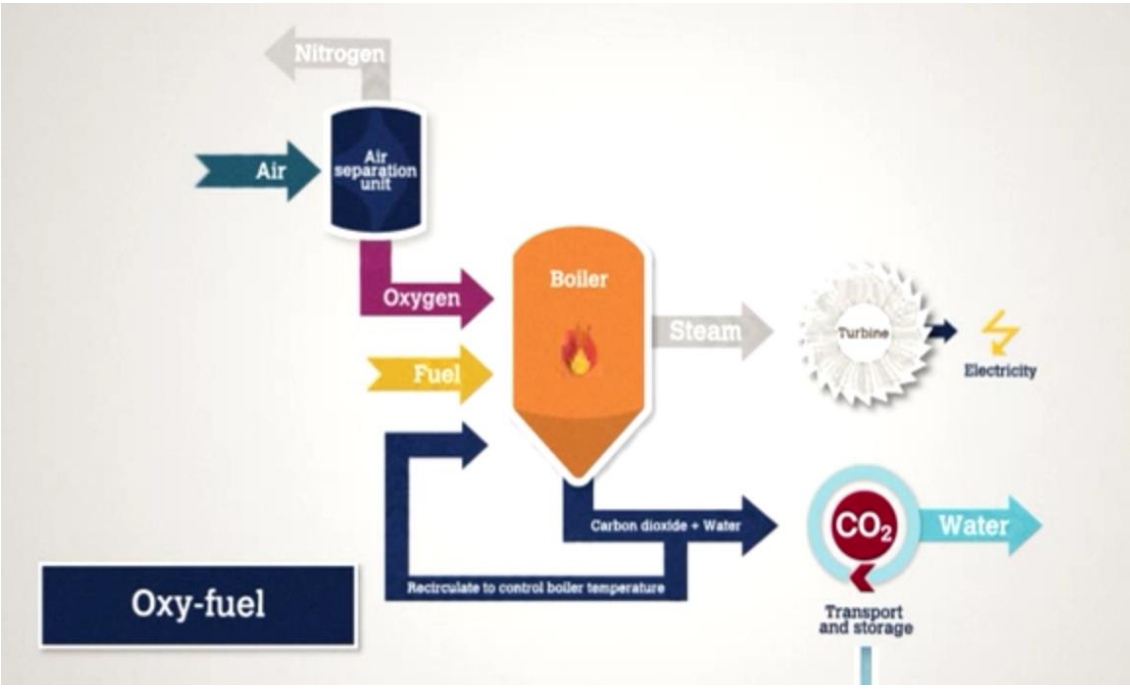


Figure 4: Oxy-fuel Carbon Dioxide Capture [5]

Steam is generated and used for electrical production and the flue gas, containing mostly CO_2 and Water, is partially recirculated to control the boiler temperature and the rest is compressed and dehydrated to be transport and stored.

3.2.1. Advantages and Disadvantages of Oxy-fuel Capture

Oxy-fuel emits really low amounts of NO_x due to the fact that it uses oxygen in combustion instead of air (to achieve complete combustion) and also because the flue gas is reused. This fact also has a negative impact on the power plant efficiency, reducing it to around 15%, mainly due to the large amounts of energy necessary for the Air Separation Unit , thus increasing the cost of electricity.

The technology is advancing to lower the energy used in the air separation department and also in the energy needed to reuse the flue gas but due to the fact that it is a complex process and no commercial operating plants exist (so more conclusions could be taken from it) it's harder to improve

3.3. Post-Combustion [5,7]

Has shown in Figure 5 in post-combustion process the fuel and air are injected to a Boiler for combustion.

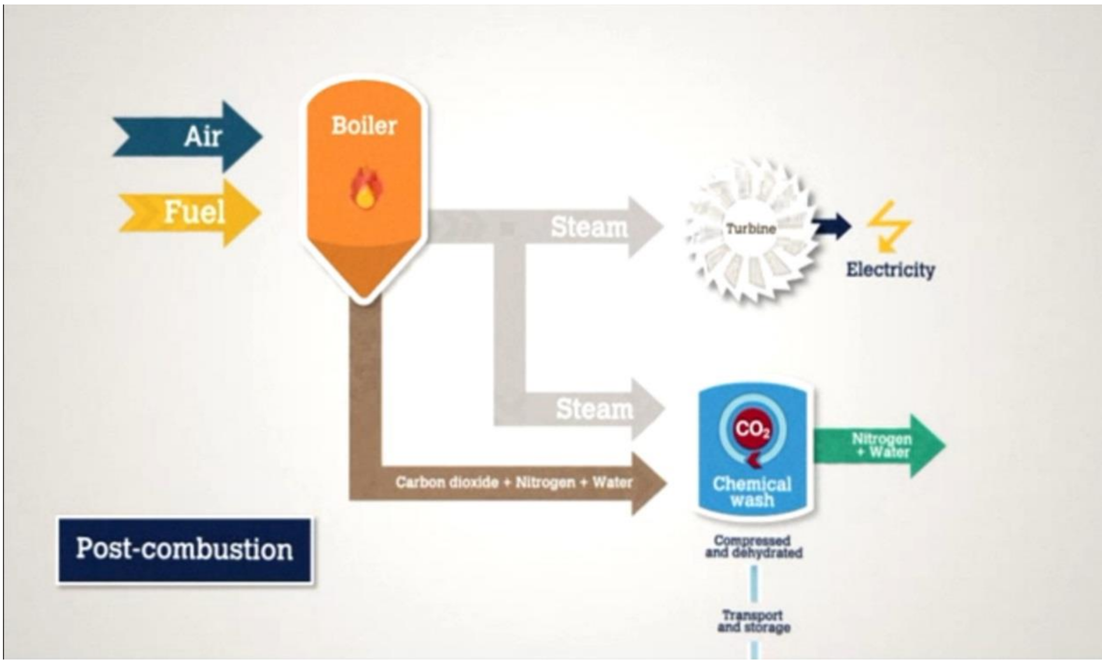


Figure 5: Post-combustion Carbon Dioxide Capture [5]

From the heat generated in combustion, steam is produce to generate power in a turbine and the flue gas containing carbon dioxide, nitrogen and water go in a chemical wash separating the CO_2 from nitrogen and water. This separation of CO_2 can be done with 3 main different methods of post-combustion capture that will be further explained.

The captured CO_2 is than compressed and dehydrated to be transport and stored in a proper place.

3.3.1. Advantages of post-combustion CO_2 capture over pre-combustion and oxy-fuel

Mature technology

A big advantage of post-combustion CO_2 capture is that the technology is much more mature than the alternatives of pre-combustion capture and oxyfuel combustion with CO_2 capture.

CO_2 capture in pilot plants for many years and testing in laboratory has shown that it works making it an attractive technology to use in future plans in the world

The relative well advanced maturity of amine absorption is big factor to construct power plants with post-combustion CO_2 capture.

Introducing in already existing CO_2 emission sources

Post-combustion CO_2 capture technologies can put in already operating facilities with CO2 emissions sources. Almost no changes to the already existing facility are required for introducing post-combustion CO_2 capture to a coal/gas power plant or industrial factory with large CO_2 emissions.

Pre-combustion and oxyfuel CO_2 capture technologies need to be planned and already integrated in process that generates the CO_2 emissions from the start. Therefore, even if pre-combustion and oxy-fuel CO_2 capture evolve to more efficient results than post-combustion technologies it would still be better to introduce post-combustion CO2 capture in to already existing facilities such as power plants or factories

4. Different Technologies of Post-combustion Capturing [7,12,20]

The three main PCC processes are:

- **Absorption:** the uptake of CO_2 into the bulk phase of an absorbent. Most PCC processes under development are absorption based.
- **Adsorption:** the selective uptake of CO_2 molecules onto a solid surface.
- **Membranes:** the separation of CO_2 from flue gas by selectively permeating it through a membrane material.

4.1. Absorption

The flue gas is injected to the Absorber and when the CO_2 present in the flue gas gets in contact with the selective absorbent, that reacts with CO_2, creates a new stable compound. The remaining components in the flue gas don't react with the absorbent and are send to the atmosphere with a low CO_2 content that didn't react.

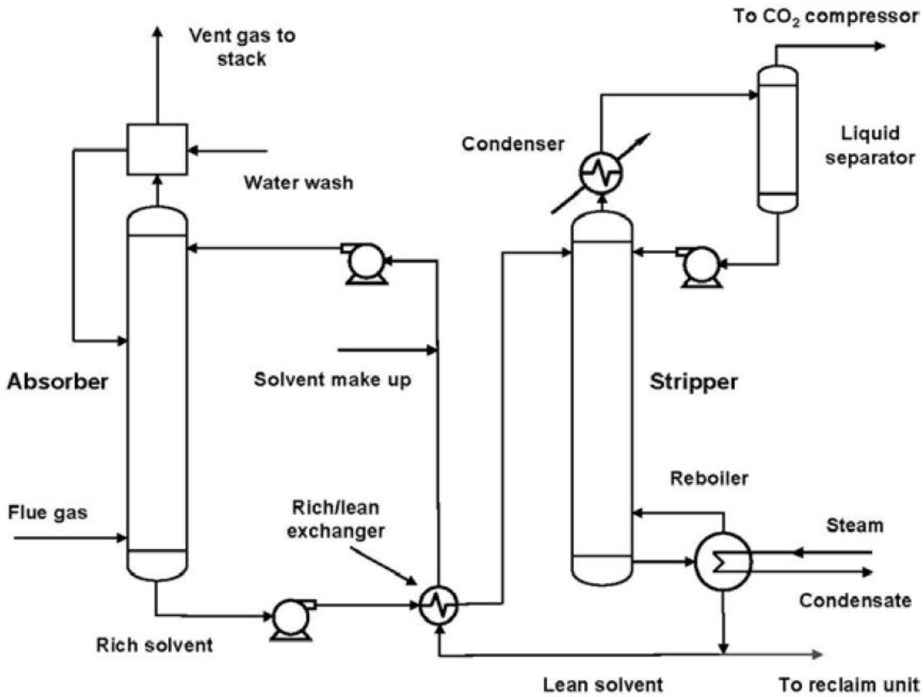


Figure 6: PCC Absorption Technology [7]

After this process, as shown in Figure 6, the rich solvent (CO_2 and absorbent solution) is pumped to a Regenerator Vessel (Stripper) where, after being heated, the absorbent is separated from the CO_2 and sent back to the Absorber while the gaseous CO_2 is compressed and transported to be stored. Using this post-combustion CO_2 capture technology close to 90% of CO_2 can be prevented of going into the atmosphere.

The list of used absorbents includes Amine based, Ammonia based, Ionic liquid based, among others. [18]

4.1.1. Detailed Amine Solvent Solution Capture Process

. Flue gas with less than 15% of CO_2 at ambient temperature is injected on the bottom of an Absorber Vessel and from the top lean amine solution is showered down reacting with the CO_2. From this chemical reaction a weak acid is formed and a water soluble salt while the other remaining gases from the flue gas that didn’t react get vent out from the top of the Absorber Vessel.

The absorber together with the captured CO_2 is pumped to a Stripper (or Regenerator) were the solution is heating to 110ºC reversing the reaction from the Absorber. CO_2 and water vapor are collected from the top of the Stripper to be dehydrated compressed and transported and the now regenerated solvent returns to the Absorber Vessel so that the process can be done once again.

4.1.2. Detailed Chilled Ammonia Capture Process

Ammonia is used a lot for desulphurization in power plants but it can also be used as an efficient CO_2 capture process by reacting with CO_2 and forming Ammonia bicarbonate. In chilled ammonia capture process the flue gas is first cooled to 1º C, to reduce its volume and to reduce the ammonia release in the absorber, and infected from the bottom of the absorber while ammonia is injected from the top. The slurry of ammonia with CO_2 is pumped to the stripper were the ammonia and CO_2 are stripped with the advantage that this regenerative process can be done at high pressures and moderated temperatures, making compression for transportation cheaper.

In comparison with other solvents ammonia is abundant and cheap with a good CO_2 capacity and little degradation during the absorption and regeneration process, making it a really viable absorbent for CO_2 capture.

4.2. Adsorption

Adsorption refers to adhering CO_2 molecules onto the surface of another material and as shown in Figure 7, it occurs due to weak Van der Waals forces, in case of physisorption or stronger covalent bonding in case of chemisorption.

In case of Fluidized Bed the flue gas is injected from the bottom going up at a speed such that the adsorbent particles are suspended in the gas flow. The adsorbent selectively adsorbs CO_2 from the flue gas and can be reutilized by increasing the temperature making the adsorbent release the collected CO_2, so by using 2 Packed Beds and alternating the flue gas between them CO_2 can be constantly removed by being adsorbed in one packed bed while the other is releasing gaseous CO_2 from the adsorbent. The adsorbent is regenerated and the process repeats.

Nowadays some of the used adsorbents include Zeolite, metal-organic and carbonaceous materials [18]

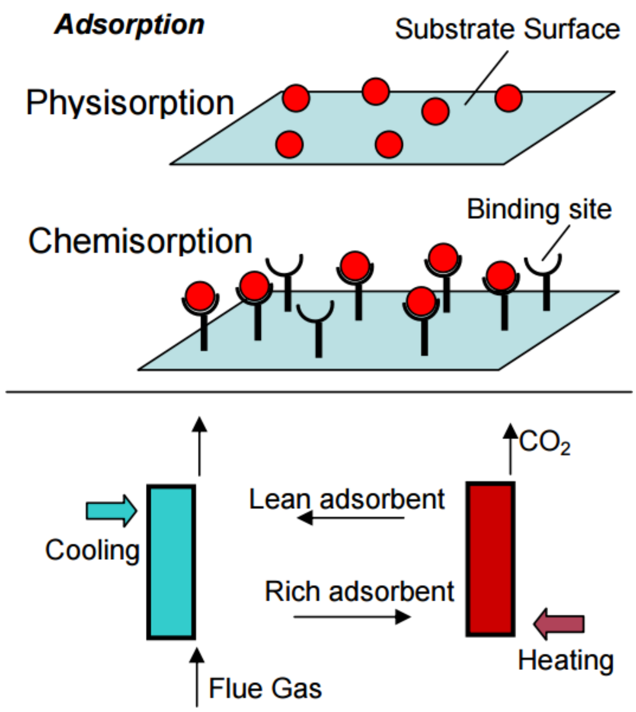


Figure 7: PCC Adsorption Technology [7]

Potential disadvantages for adsorbents include particle attrition, handling of large volumes of sorbent and thermal management of large-scale adsorber vessels.

4.2.1. Vacuum Swing adsorption (Developing Technology) [11]

Post-combustion vacuum swing adsorption (VSA) process uses a metal-organic adsorbent, named UiO-66, and is been tested with flue gas containing 15% or less of CO_2 with and without 9% water vapor.

It operates at a near ambient temperature and pressure were the adsorbent selectively adsorbs CO_2 than it swings to a vacuum to regenerate the adsorbent.

Based on the data from this developing technology, the VSA cycle shown a CO_2 capacity reduction close to 25% when water vapor is present, making it a big factor on the technology efficiency.

4.3. Membranes

As illustrated below in Figure 8 the Flue Gas is pressurized through a selective membrane material that will make CO_2 permeate the membrane due to CO_2 having a higher permeability (chemicals can be added to enhance the membrane selectivity for CO_2). Permeability is the product of solubility and diffusivity, in the membrane relative to the components in the flue gas.

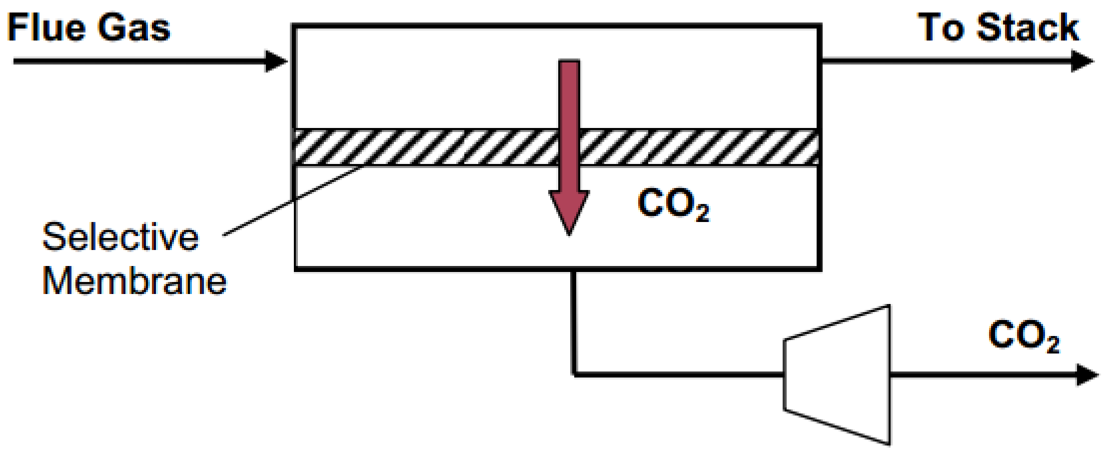


Figure 8: PCC Membrane Technology [11]

Depending on the level of selectivity of the membrane multiple membranes can be added to increase the separation of CO_2 from the flue gas. The CO_2 collected is than compressed, transport and finally stored.

Membranes have the potential being a low energy CO_2 capture technology but are still on a testing phase. There is not much data available, relatively to pre-combustion capture and post-combustion capture, so it's a technology in more of a laboratory and testing phase with most of the focus being put on improving the membrane properties to maximize its efficiency

4.3.1. Polymeric Membrane in CO_2 Capture from Post Combustion [10]

Polymeric Membranes separation of CO_2 is a simple membrane process to capture CO_2 that can fit different plant sizes making it a great technology for PCC of CO_2 with the improvement of prior membranes that it may be exposed to temperatures as high as 170˚C with high selectivity. However it can have more complications in comparison to processes such as adsorbing using amine, because it uses more energy, uses slower flow rates and can be damage by high temperatures from the flue gas, it is therefore a technology with lots of room to improve, for example using multiple membranes in different stages and changes of pressure and vacuum can improve the mass transfer rate.

4.4. Comparison between post-combustion capture technologies [19]

To compare different PCC technologies a study in end of 2014 by the Global Carbon Capture and Storage Institute was made having in account several factors such as economic viability, integration in current operating systems, development stage and environmental impact and based on this factors a Technology Readiness Level (TRL) is given as described on Table 1 below.

Table 1: Technology Readiness Level scale meaning

TRL value	Meaning
1 to 2	Idea is shown theoretically or just basic principles in a laboratory
2 to 5	Idea is tested in laboratory using main components to show the functionality
5 to 7	Pilot-scale testing with sensitive analysis
7 to 9	Process implemented fully and plant operates taking in account all operating conditions in a commercial scale

This different TRL show the phase that each technology is at the moment, from just an early concept that is being develop until a full implemented process that can run in a commercial scale having in account all the conditions necessary.

On PCC technologies many technologies are emerging, on Table 2 we can see the main ones:

Table 2: Evaluation of development state of emerging PCC Technologies

PCC Technology	**TRL value**
Amine based solvents	7 to 9
Advanced amine based solvents	5 to 7
Aqueous Ammonia solvent	7 to 9
Catalysed enhanced solvents	2 to 5
Ionic Liquids	2 to 5
Temperature or Pressure Swing Adsorption	5 to 7
Membranes	5 to 7
Cryogenic CO_2 separation	2 to 5

The developments in all PCC technologies have the objective of lowering the economic impact in industrial processes and power plants by evolving the technologies on a chemical level, on the design and equipment used.

In Absorption, Advance amino based solvents show great results in pilot-scale showing a reduction in energy penalty around 25% by using effectively the wasted heat of the power plant, although the technology is still in a development state the results are encouraging. Also, in an earlier stage of development, ionic liquids and catalysed enhanced solvents are starting pilot-scale testing.

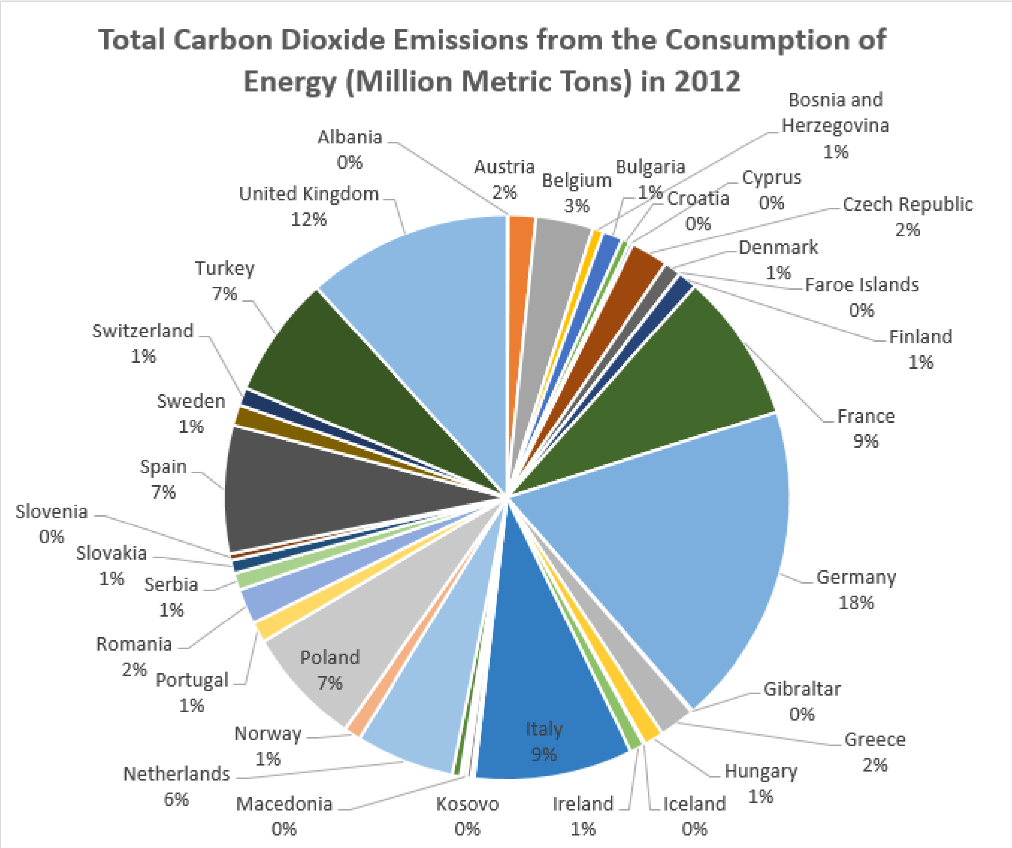
Adsorption technologies are using temperature or pressure swing mechanisms are also going to be tested in pilot scale, one project will test this technology at National Carbon Capture Central (NCCC) with 1 MWe output.

In the Membrane development, because the CO_2 in the flue gas are relatively low, they are evolving into hybrid systems where a solvent is used prior to the membrane. This systems are been tested at the moment with multiple stage membranes, at the NCCC.

Finally, Cryogenic CO_2 Separation, a technology that just been develop in the most recent year that separates CO_2 from flue gas by cooling and condensation is going to start being tested in a small unit of kWe using real flue gas.

5. Carbon Dioxide Emissions from Electrical Power Plants in Europe [13]

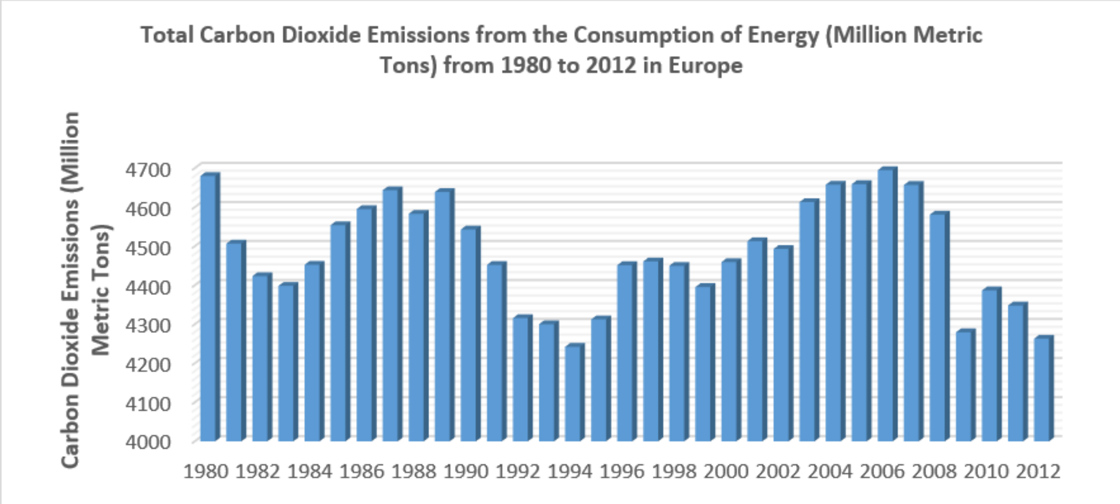
CO_2 emissions from energy consumption in Europe are around 4263 million metric tons (Appendix A). We can see on Graph 1 that the largest emissions of CO_2 come from United Kingdom, France, Turkey, Italy, Netherlands, Poland and Germany which alone emits 18% of all CO_2 from energy consumption in Europe.



Graph 1: Total Carbon Dioxide Emission from Electrical Production in Europe in 2012

The total amount of emissions of CO_2 from electrical production is now decreasing each year due to emission reductions policies in the main polluting countries, this tendency can be seen in Graph 3 which follows the European tendency shown in Graph 2.

In Graph 2 we can examine that levels of CO_2 emissions raised steadily from 1995 with 4242 MMT until 2007, peaking at 4694.9 MMT and after that, due to implementation of greenhouse gas emissions reduction policies and increase use of renewable energies, the values drop to a trough at 4263 MMT in 2012. The increase of population and energy demand is a big factor that makes some of this values fluctuate but it is clear that the introduction of environmental laws such as more use of renewable energies and application of CCS technologies reduced drastically the CO_2 emissions from energy consumption in Europe.



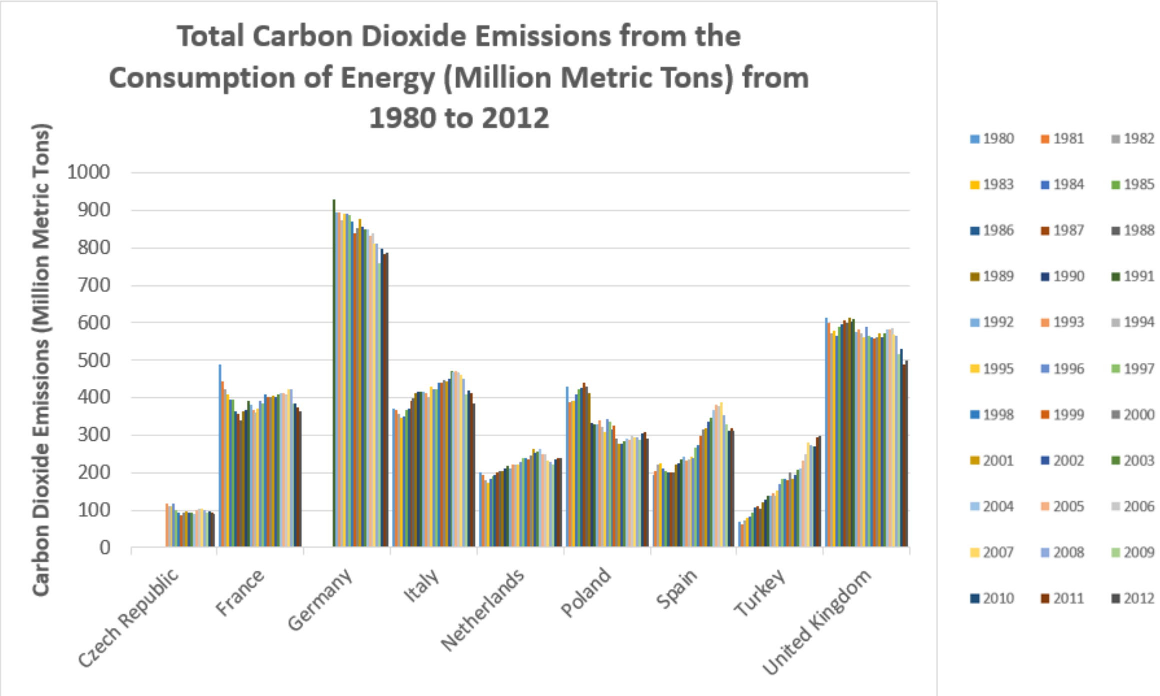
Graph 2: Total Carbon Dioxide Emission from Electrical Production in Europe from 1980 to 2012 [13]

5.1. European Countries with Highest Carbon Dioxide emissions from Consumption of Energy

Graph 3 shows the change on the CO2 emission from the consumption of energy on the countries that contribute the most for it (for the exception of Czech Republic which is there as a reference point) from 1980 to 2012. We can observe that countries like Italy, Netherlands, Spain, France and the United Kingdom have a peek around 2007 and then a decline. This change in values occurred due to implementation of internal policies for this effect following the tendency of overall European values.

In the case of Germany and Poland the emissions levels decrease almost constantly during the years, although Germany shows the highs CO2 emission levels from energy production in Europe representing 18% of total CO2 emissions.

The only case of constant rising levels of CO2 emissions comes from Turkey that been increasing from 63 MMT in 1980 to 296.9 MMT in 2012 at a constant rate every year and according to a 2009 report by Bahçeşehir University Center for Economic and Social Research in Turkey, the country has not yet made any commitment to reducing greenhouse gas emissions.



Graph 3: Total CO_2 Emission from Electrical Production in Largest Emitters in Europe from 1980 to 2012

5.2. The European Union Emission Trading System (EU ETS) [14]

The European Union Emission Trading System is policy introduced so that greenhouse gas emissions are reduce by creating a trading market around emissions allowances. It is used for more than 11 000 power plants and industrial plants in 31 countries.

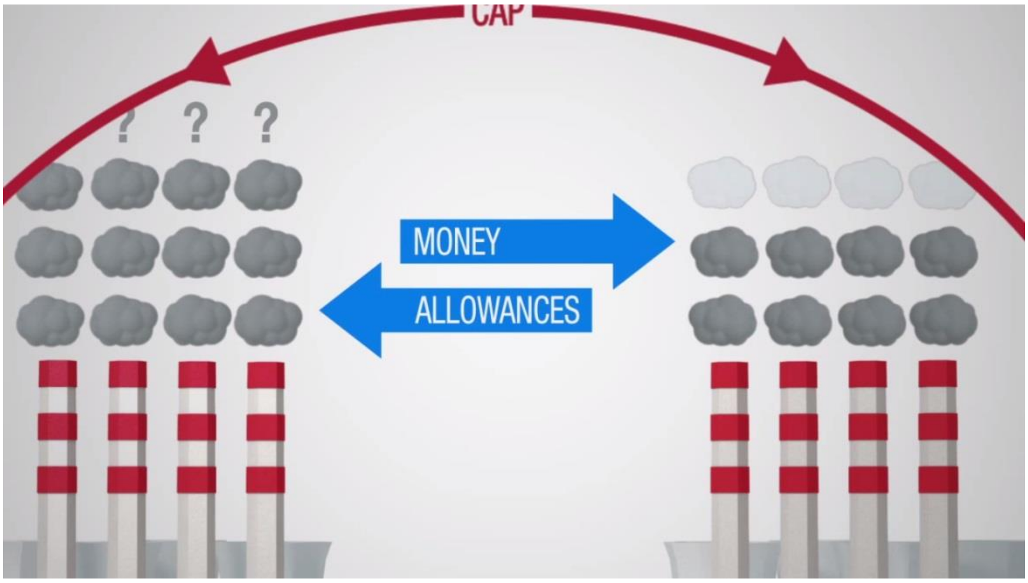


Figure 9: The European Union Emission Trading System [14]

The EU ETS sets a limit on the total amount of greenhouse gases emitted by a power plant or factory per year. Regular measures are taken and then verified if the emission levels where higher or lower than the allowance levels. If the emission levels are higher than the allowance, the companies that emitted those greenhouse gases have to pay heavy fines or buy the allowance of a company that did not reach the allowance limit, meaning that if the emission levels of greenhouse gases are lower than the allowance you can sell those margins and profit from it (Figure).

Also the cap on the greenhouse gas emissions decreases every year so that the total emissions fall over time. And since this system start in 2005 we can see the impact it had on the CO_2 emissions from Energy consumption in Europe (Graph og Europe)

Putting a value on pollutant emissions and creating a regulated marked around it promotes the development of new CCS technologies, Renewable Energy and overall a cleaner environment. It is expect that in 2020 the countries using EU ETS will have 21% lower levels of emissions compared to 2005 and in 2030 it should be 43% lower.

6. Impact of CCS technology integration into fossil power plants [15]

CCS technology causes an increase of their own consumption of energy in a power plant (the highest cost being associated with the capture of CO_2 from all CCS technology costs), therefore reducing efficiency. This additional use of energy goes mainly for the compression of CO_2 removed to than by transported and stored. In the case of post-combustion capture technologies a lot of energy also goes to regenerate the absorbent (in case of absorption) where high heat requirements are needed.

6.1. Basis of the Data

The basic technical data from international study about operational conditions of power plants are shown in Table 3.

Table 3: PC and NGCC parameters

	Pulverize Coal Power Plant (PC)	Natural Gas Combined Cycle (NGCC)
Operation Time [h/year]	7800	8000
Amortization Time [year]	30	30
Availability [%]	90	92
Construction Time [year]	4	2

The results presented are all based on the same ambient conditions (15ºC, 1.013 bars and 60% relative humidity). Concerning fuels, the coal used is a standard international quality steam coal (LHV = 26 MJ/kg, 7% humidity, 15% ash and 1% sulfur) costing 2.26 EUR/GJ HHV and for natural gas the cost is 6.29 EUR/GJ

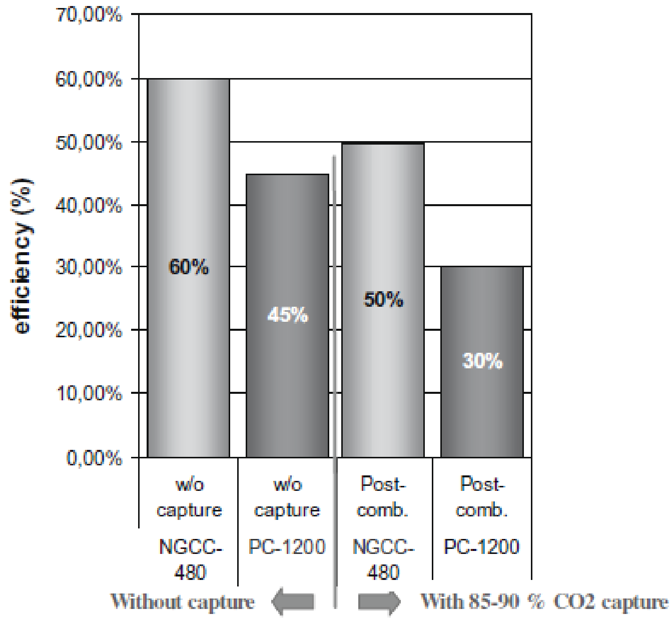
The economic estimates use discount rate of 11% and use relative costs to pulverized coal power plant without CO_2 capture (used as reference) due to the absolute cost values may be quite inaccurate compared with 2008 prices.

All relative costs exclude transport and storage costs of CO_2.

6.2. Efficiency

From Graph 4 we can see that the introduction of a PCC technology has a big effect in the overall efficiency of the power plant reducing it by 10% in the case of NGCC-480 and by 15% in the case of PC-1200. Meaning that higher amounts of fuel need to be used to produce the same energy and, by consequence, producing more CO_2 than in a power station without use of PCC technology with the advantage of capturing 85% to 90% of the emitted CO_2. This relation is called "Avoided CO_2" (Figure 10) and will be talked about further on.

In the case of NGCC-480 with post-combustion capture technology the drop in efficiency (10%) is better than in PC-1200 (15%) making it look more suitable for that kind of power plant, nevertheless we should also take in to account that post-combustion technologies can be integrated into pulverized coal plants already operating without CCS technologies.

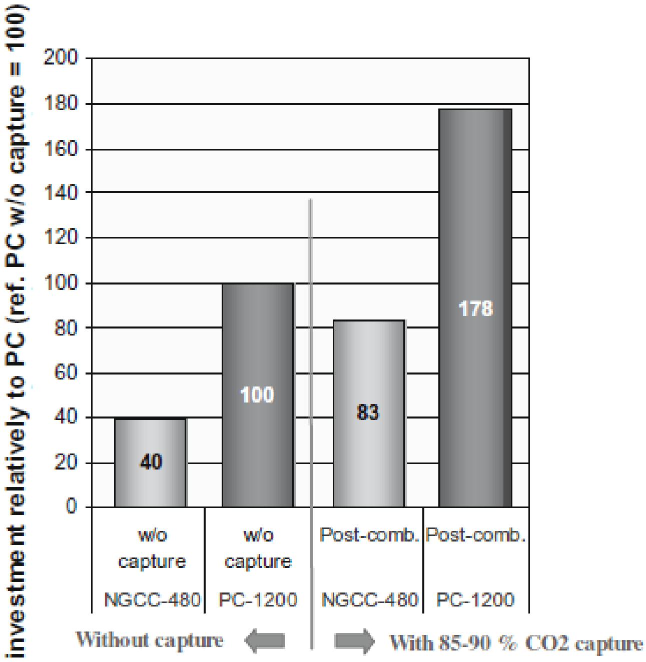


Graph 4: Efficiency without and with CO2 post-combustion capture [Adapted from ref. 15]

6.3. Investment Cost

From the investment cost (Graph 5) we can analyze that NGCC with or without post-combustion capture is cheaper than the investment of PC without post-combustion capture (reference point) having an increase of 43% when the PCC technology is used.

In the case of the PC the increase is much higher when the PCC technology is installed, being in the order of 78% and almost doubling the initial cost.

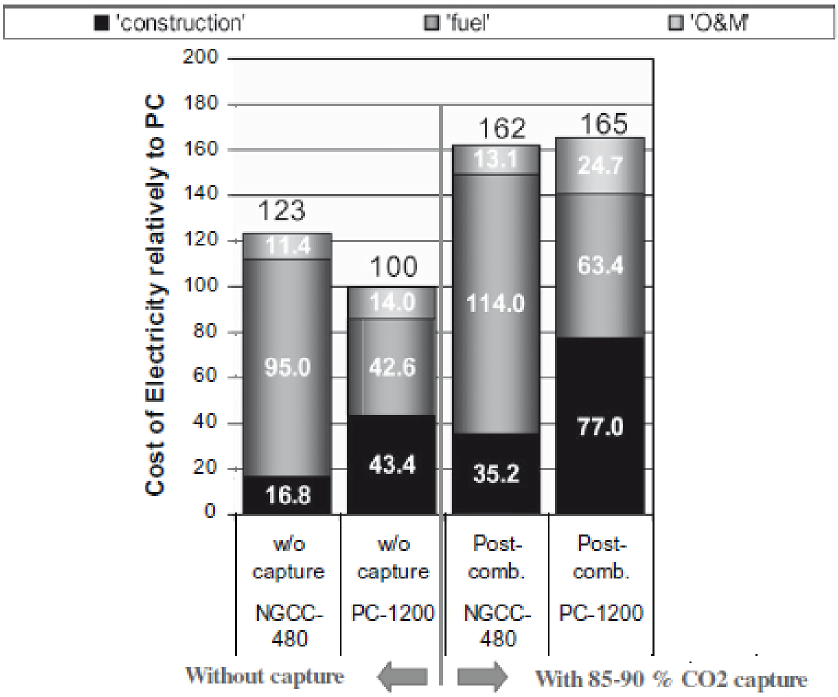


Graph 5: Investment cost without and with capture of CO2 relatively to PC without CO2 capture (11% discount rate) [Adapted from ref. 15]

6.4. Cost of Electricity

The electricity production (Graph 6) cost in the case of NGCC raises 39% when PCC technology is installed due mainly to construction and fuel costs. In the case of PC the cost increases 65% when PCC technologies are introduced making electricity cost more expensive than NGCC, which was cheaper without the use of PCC technologies.

The increase cost of electricity when PCC technology is installed, both in NGCC and PC, comes half from construction showing the huge impact it has, not only in consumption of the power plant own electricity but in the construction of the infrastructures. In NGCCC the increase from construction is of 18.4% relative to NGCC and in PC with PCC technology the increase from construction is of 33.6% relative to PC.



Graph 6: Production cost (construction, fuel, Operation and Maintenance) of the different systems with and without CO2 capture relative to PC [Adapted from ref 15]

6.5. Avoided CO_2 and Cost of Avoided CO_2

As seen previously (Graph 4) introducing post-combustion capturing technologies as a high impact on the overall power plant efficiency, in other words, this means that if we want to produce the same amount of electricity and use PCC technology more fuel needs to be consumed and therefore more CO_2 emitted.

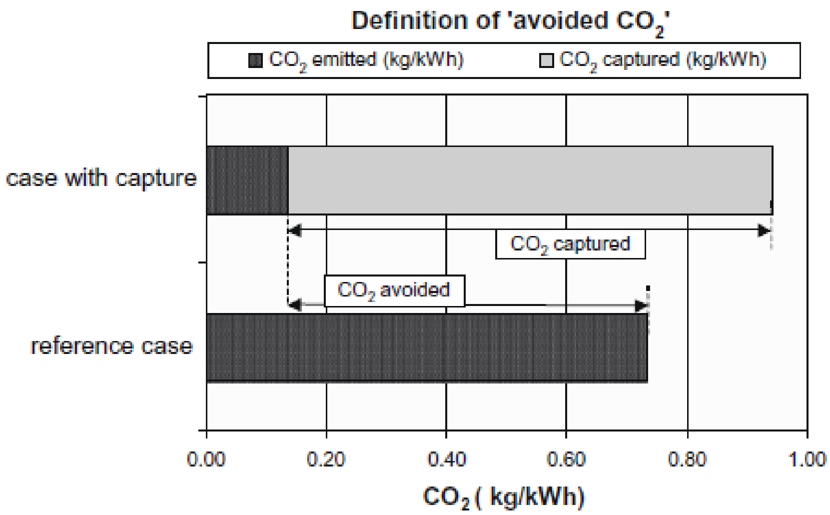
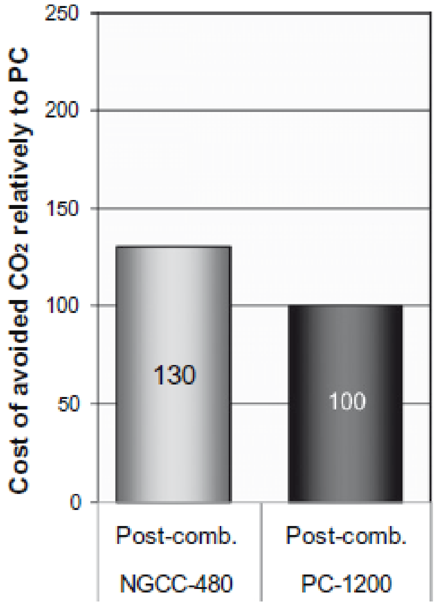


Figure 10 : Avoided CO_2 [15]

The avoided CO_2, on Figure 10, is the difference between the CO_2 produced without using PCC technology and the CO_2 that didn't got capture in the case of a power plant with PCC technology (which produces more CO_2 than without PCC technology but captures 85 to 90% of it). This difference is the amount of CO_2 we avoided sending to the atmosphere by using capturing technology.



Graph 7: Cost of avoided CO2 relatively to PC (11% interest rate) [Adapted from ref 15]

The cost of Avoided CO_2 (Graph 7) is higher in NGCCC by 30% in relation to PC with PCC technology.

6.6. Summary

By comparison of the application of post-combustion capture process in PC and NGCC we can say that it is a better choice for NGCC based on is better efficiency, investment cost and cost of production due to the combustion cycle of the power plant being simpler than in PC . However this factors are only part to determine which kind of fossil fuel power plant does better with PCC technology, factors like logistics and price of fuel may change the result.

We can conclude that the implementation of CO_2 post-combustion capturing technologies have a high impact on the efficiency and total cost relative to a power plant without it showing that there is many developments that can be done to make CCS more appealing.

7. Plant size economic impact on Natural Gas Combined Cycle with and without post-combustion capture technologies [16]

Introducing PCC technologies in a power plant influences its overall production and efficiency, we also analyzed that in the case of NGCC the PCC technologies applied better, having a reduction in efficiency of 10%. Now we will see how changing the size of the power plant and therefore its power output influences the results derived from post-combustion CO_2 capturing.

Table 4: Impact of Plant size in NGCC and NGCCC [16]

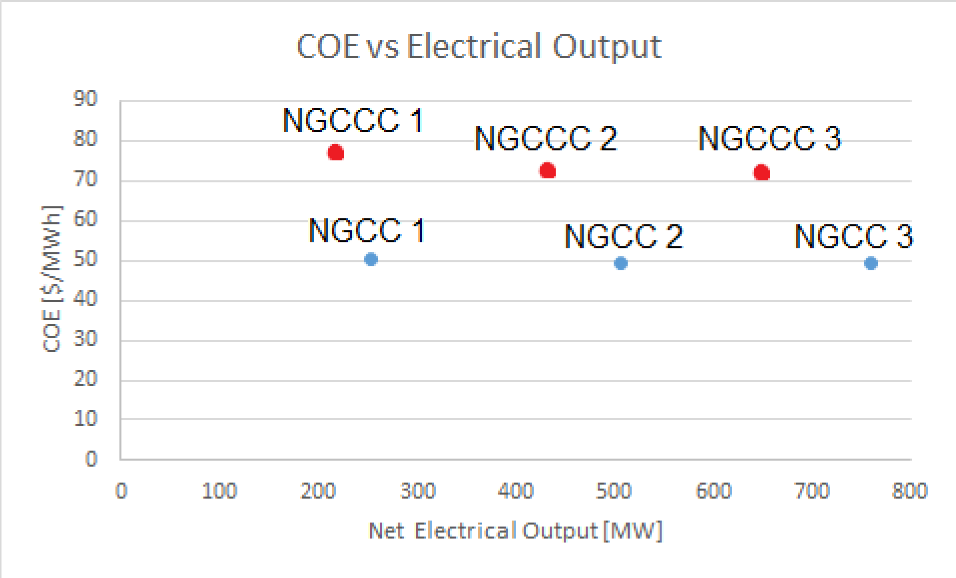
Cases	Net Electrical Output [MW]	Net Plant Efficiency – HHV [%]	CO2 emissions [t/h]	Fixed O&M [M$/year]	Variable O&M [M$/year]	Capital required [$/kW.net]	COE [$/MWh]
NGCC 1 turbine	253.3	50.15	102.6	4.620	53.91	668.9	50.21
NGCC 2 turbines	506.5	50.15	205.1	7.087	107.8	665.2	49.48
NGCC 3 turbines	759.8	50.15	307.7	9.548	161.7	663.3	49.22
NGCCC 1 turbine	216.1	42.80	10.26	7.451	64.80	1174	77.27
NGCCC 2 turbines	432.3	42.80	20.51	11.080	124.8	1085	72.23
NGCCC 3 turbines	648.4	42.80	30.77	15.470	184.4	1103	71.71

The analyses is done with Natural Gas Combined Cycle with and without use of post-combustion capture and with different number of turbines, from one to three (Table 4).

7.1. COE vs Electrical Output

The Cost of Electricity in the NGCC is close to the same, even when increasing the number of turbines having a variation of 0.78 $/MWh from 1 to 2 turbines and 0.26 $/MWh from 2 to 3 turbines, the electrical output increases at the same ratio as turbines are added having no major variations, as shown in Graph 8.

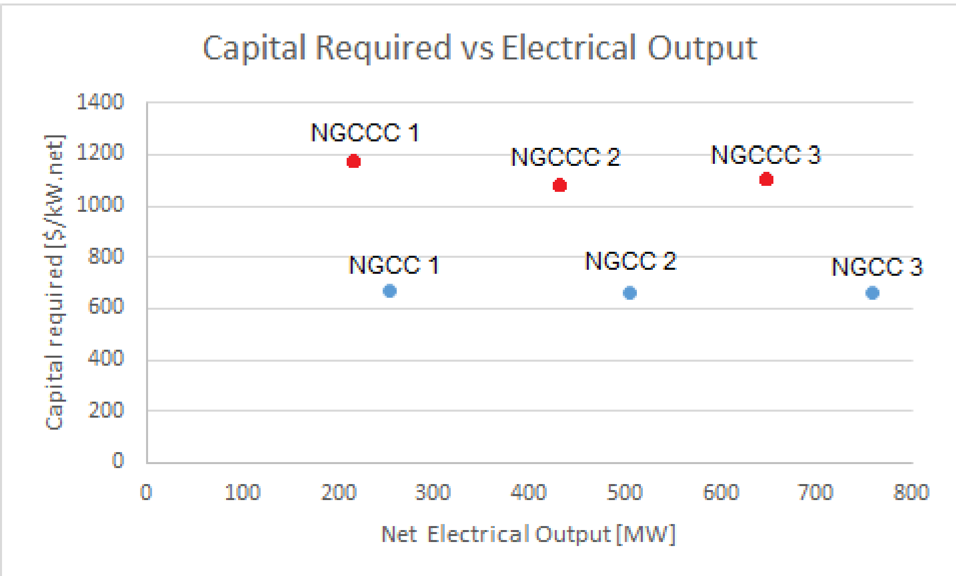
In the case of NGCCC the electrical output also increases steadily (in relation to the number of turbines) but being lower than in the case of NGCC because the post-combustion process uses a lot of energy (Graph 4). What we can see from this study is that having post-combustion integrated in the NGCC lowers COE considerable from one to multiple turbines (5.56-5.04 $/MWh) making more suitable to be used in the case of a larger NGCCC.



Graph 8: Cost of Electricity versus Electrical Output [16]

7.2. Capital Required vs Electrical Output

Analysing Graph 9 we can see that the cost of NGCCC 1 is 1.75 times more expensive that in the case of NGCC 1 and having a electrical output 0.15 times lower. This ratios get better with the increase number of turbines on both power plants making NGCCC 2, 1.63 times more expensive than NGCC 2, and NGCCC 3, times, the electricity output ratio remains 0.15 times lower.

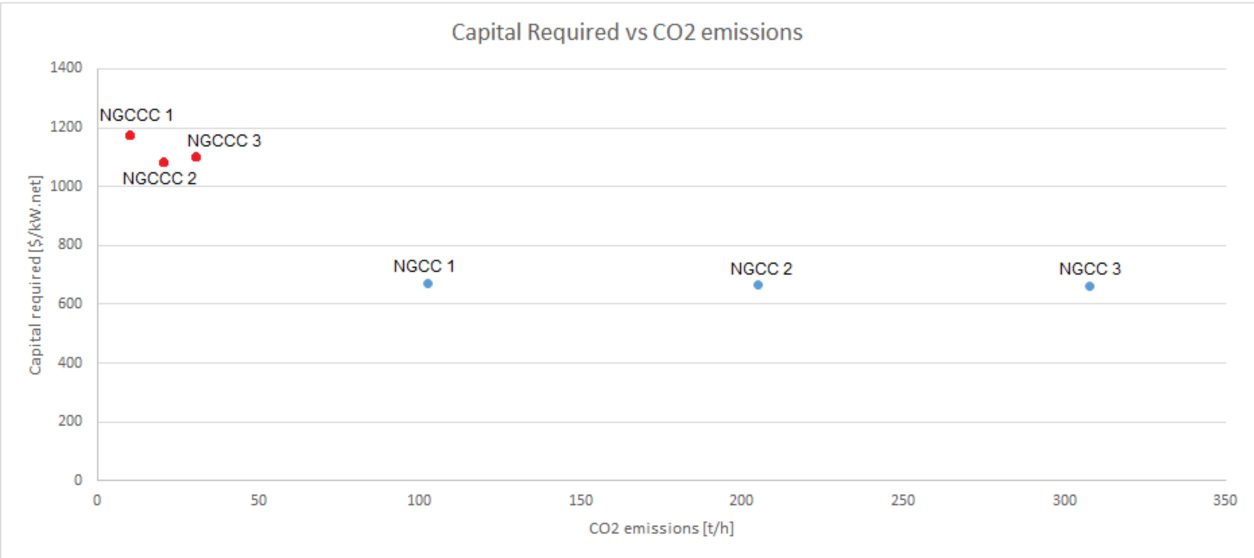


Graph 9: Capital Required versus Electrical Output [16]

The investment cost is much higher in the case of NGCCC in comparison to NGCC because of the cost of the post-combustion capture technology, however the capital required decreases from NGCCC 1 to NGCCC 2 and increases a little bit from 2 to 3, showing that is better to have a larger size plant with PCC (more than 1 turbine) but due to Operation and Maintenance costs, having multiple turbines gets more expensive.

7.3. Capital Required vs CO_2 Emissions

Analyzing Graph 10 we can see that in the case of NGCC the investment cost and the CO_2 emissions go up at the same ratio when more turbines are added. In the case of NGCCC the more turbines are added doesn't change the CO_2 emission levels, which are really low, and increase according with the number of turbines. What is to notice is that the capital required gets lower significantly if the power plant has more than 1 turbine and that the capital required for NGCCC with 1 turbine is almost double of the capital required for NGCC.



Graph 10: Capital Required versus CO2 Emissions [16]

After analyzing all the data and checking the comparison on the graphs above, we can say that although the net plant efficiency doesn't change, in both NGCC and NGCCC, a larger size plant with post-combustion capture technology gets cheaper in relation to when it has a lower electrical output. We can also observe that the O&M increase with the size of the plant, making it possible that those costs get too high, making it more expensive than if it only had 2 turbines.

8. Techno-economic Impact of PCC technology integration into fossil power plants in Europe [22, 23]

Different studies in Europe by different organizations on the Organization for Economic Co-operation and Development (OEOD) region can give a general and more accurate idea of the economic and performance state of Post-combustion Capture Technologies. This data in Table 5 uses different types of power plants and fuels for an overall comparison, all using amine based solvent capture.

Table 5: Post-Combustion Capture in Europe in OEOD Region [23]

Year of Publication	2007	2007	2009	2007	2009	2009
Organization	GHG IA	GHG IA	GHG IA	GHG IA	CCP	CCP
Fuel type	Bit Coal	Bit Coal	90% Bit Coal 10% Biomass	Natural Gas	Natural Gas	Natural Gas
Power plant	USCPC	USCPC	SCPC	NGCC	NGCC	NGCC
Net power output w/o capture (MW)	758	758	519	776	395	395
Net power output w capture (MW)	666	676	399	662	367	360
Net efficiency w/o capture – LHV (%)	44.0	44	44.8	55.6	58.0	58
Net efficiency w/ capture – LHV (%)	34.8	35.3	34.5	47.4	49.3	49.7
CO_2 emissions w/o capture (Kg/MWh)	743	743	754	379	370	370
CO_2 emissions w/ capture (Kg/MWh)	117	92	73	66	60	60
Investment cost w/o capture (USD/kW)	1408	1408	1710	499	1245	1245
Investment cost w/ capture (USD/kW)	1979	2043	2790	869	1741	1786
Relative decrease in net efficiency (%)	21	20	23	15	15	14
CO2 capture cost (USD/tCO2)	42	42	59	69	75	76
EU ETS carbon price (USD/tCO2)*	24*	24*	12*	24*	12*	12*

*The data was subtracted from Figure 11.

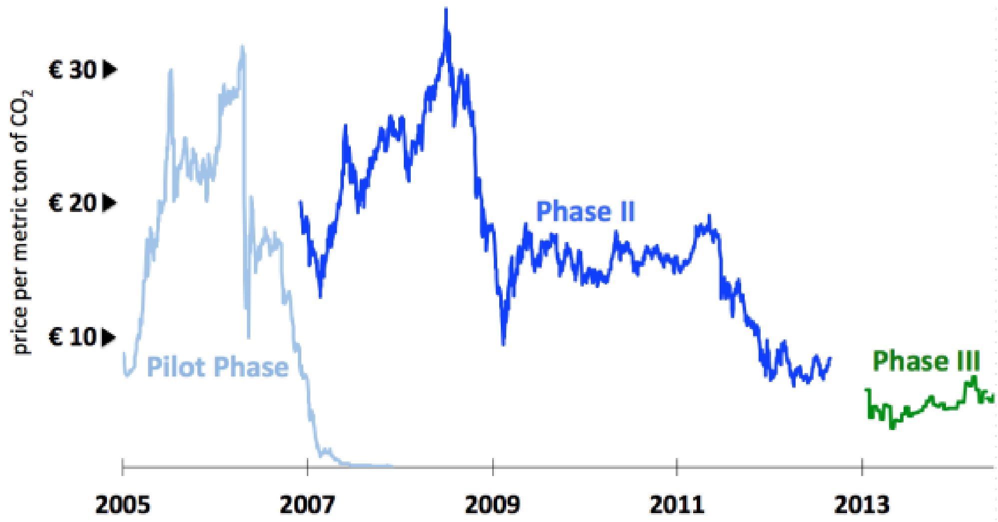
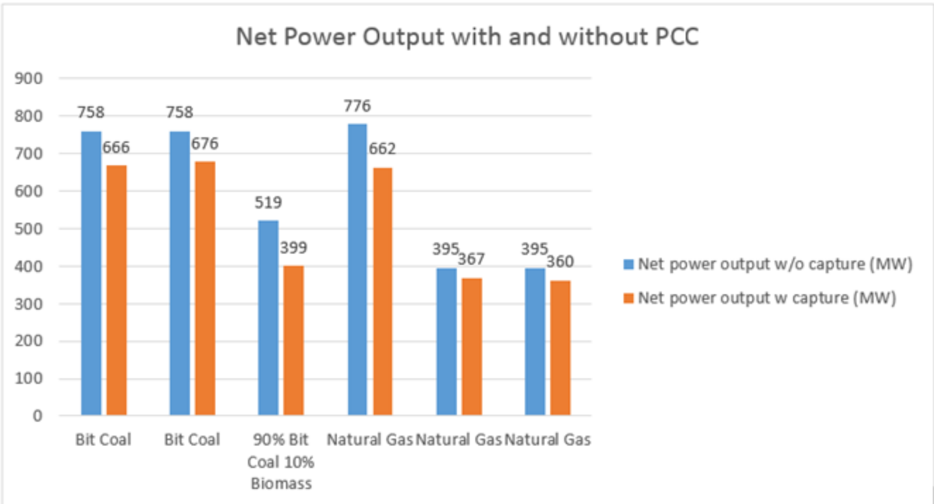


Figure 11: EU carbon prices by 2005-2013 [26]

Both Ultra-Supercritical Pulverized Coal Power Plants (USCPC) and the Supercritical Pulverized Coal Power Plant (SCPC) use bituminous coal (Bit Coal) and in the case of SCPC 10% is Biomass. On the NGCC the fuel is natural gas.

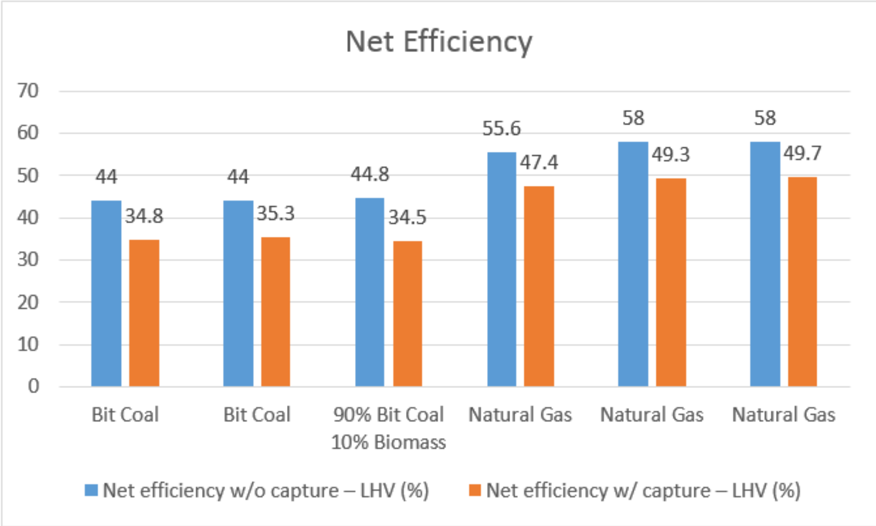
8.1. Net Power Output and Net Efficiency

We can observe, as shown in Graph 11, that the net power output drops when using PCC. For USCPC with Bit Coal use the Net Power Output drops 92MW in on case and 82MW in the second case. The power drop in the case of SCPC is higher than in the case of the USCPC (in the order of 122MW) due to its lower efficiency and use of 10% Biomass.



Graph 11: Net Power Output with and without PCC

In the case of NGCCC with 776 MW Power Output the drop when using PCC is close to the cases for Bit Coal power plants, at 114MW, however in the cases when the Net Power Output is 395 MW the application of PCC reduces it to 28 MW and 35 MW.



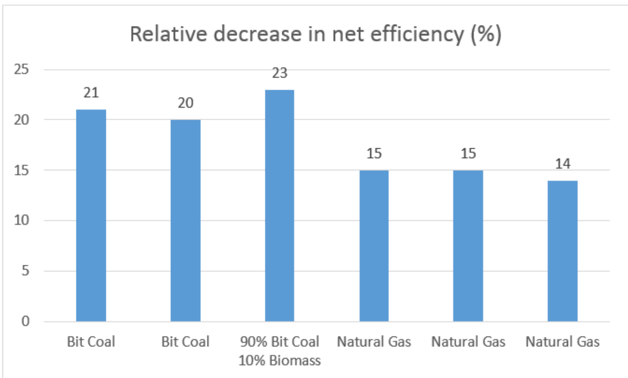
Graph 12: Net Efficiency with and without PCC

The Net Efficiency with capture shows us (Graph 12) a variation of 8.7% and 9.2% for the cases of Bit Coal and 10.3% variation in the case of Bit Coal with 10% Biomass. For Natural Gas, in the three study cases, the variation is from 8.2% to 8.7% which is lower than in the case of PC. This difference in net efficiency would be more noticeable if HHV was used instead of LHV because its values depend on the fuel – LHV is around 4% less than HHV in case of Bit coal and about 10% less than HHV for natural gas.

8.2. Relative Decrease in Net Efficiency

The Relative Net efficiency is related to a reference power plant without CCS for calculations (IPCC, 2005). [22]

PC, that uses just Bit Coal, have similar results, which show that the studies have high precision. An interesting result is by comparing the USCPC, that uses Bit Coal as a fuel, and SCPC which uses 90% Bit Coal and 10% Biomass (in Graph 13).



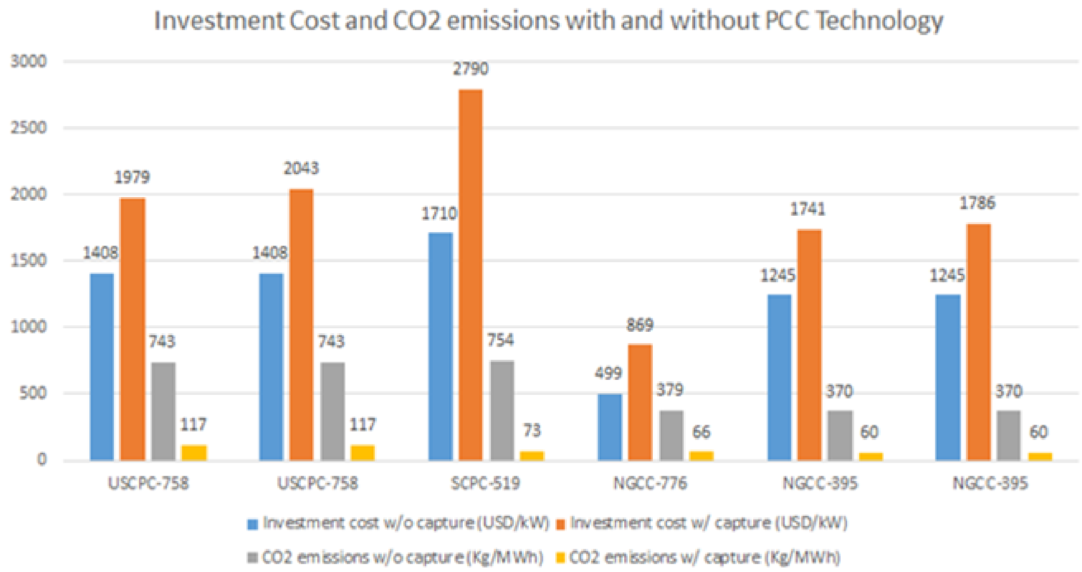
Graph 13: Relative decrease in net efficiency (%)

The SCPC uses 10% of Biomass and the difference in the net efficiency to USCPC, that uses 100% Bit Coal, is in the order of 2 to 3 percent, although they have different outputs but there are not many studies on PC which also use Biomass.

In the case of NGCCC the efficiency reductions of 14-15% is lower than in the case of PC with PCC technology showing a better adaption to the PCC Technology.

8.3. Investment Cost and CO_2 Emission Levels

Has shown in Graph 14 the reduction of CO_2 emissions in USCPC with capture is of 84.2% relative to USCPC without capture (from 743 Kg/MWh to 117 Kg/MWh in both cases) and in the case of SCPC the reduction is of 90.3%, from 754 Kg/MWh to 73 Kg/MWh. The investment cost however increases 63.1% in the case of SCPC (90% Bit Coal and 10% Biomass) from 1710 USD/kW to 2790 USD/kW and in the case of USCPC, that uses only Bit Coal, the increase is of 40.55% from 1408 USD/kW to 1979 USD/kW and of 45.09 % from 1408 USD/kW to 2043 USD/kW.



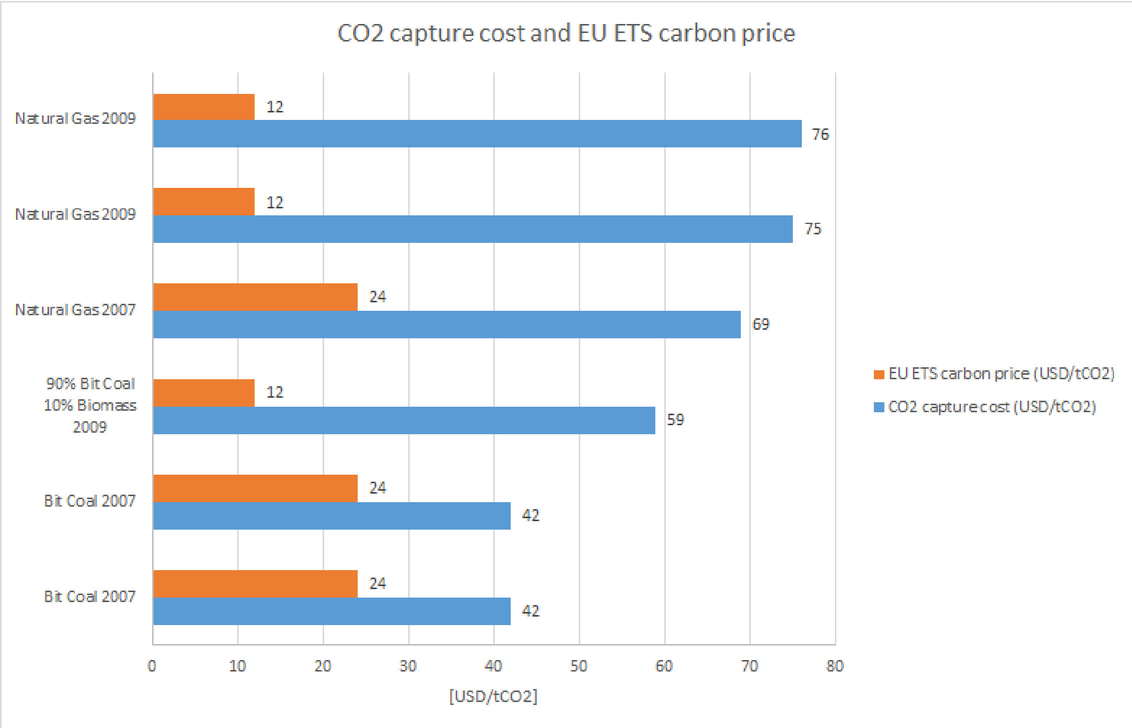
Graph 14: Investment Cost and CO2 emissions with and without PCC

The NGCC-776 investment cost (as in USD per kW), with or without PCC, is lower than in the cases of the NGCC-395 as we also verify previously in Graph10. In NGCC-776 there is an increase of 74.1% in cost when PCC is implemented (from 499 USD/kW to 869 USD/kW) reducing the CO_2 emissions from 379 Kg/MWh to 66 Kg/MWh and in the cases of NGCC-395 an increase of 39.8% in cost (from 1245 USD/kW to 1741 USD/kW) and of 43.45% (from 1245 USD/kW to 1786 USD/kW) with both cases showing a reduction of the CO_2 emissions from 370 Kg/MWh to 60 Kg/MWh.

PC with PCC technology has a higher investment cost than NGCCC because the flue gas needs to be clean from particles, SO_x and NO_x before the CO_2 capture and Natural Gas is a cleaner fuel compared with Bit Coal.

8.4. CO2 capture cost and EU ETS carbon price

The relation between CO_2 capture cost and the EU ETS carbon price in Graph 15 show a huge difference in values. The analyzed study cases are from 2007 when EU ETS carbon price was at 24 USD/tCO_2 and 2009 when EU ETS carbon price was at 12 USD/tCO_2, on the other hand the CO_2 capture cost was in the case of Bit Coal power plant in 2007, 42 USD/tCO_2 and in the case of Natural Gas 69 USD/tCO_2.



Graph 15: CO2 capture cost and EU ETS carbon price for analyses cases

For the year 2009 the CO_2 capture cost was 75 and 76 USD/tCO_2 Natural Gas and 59 USD/tCO_2 for 90% Bit Coal and 10% Biomass.

This big difference in values between EU ETS carbon price and CO_2 capture cost is related to the big variance in the carbon market shown in the shown in Figure 11, making a big variation in each year.

9. Future PCC projects in Europe [19]

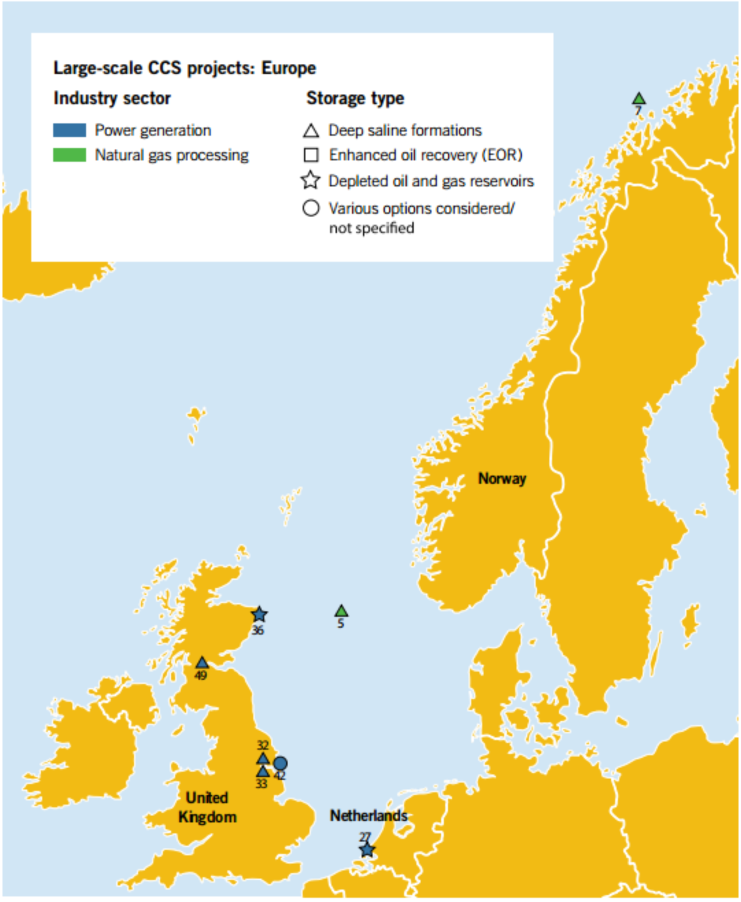


Figure 12: Large-scale CCS projects in Europe [19]

Many projects have been coming up for large-scale CCS in Europe, mainly in Norway, see in Figure 12, United Kingdom and Netherlands. Some projects are still in a evaluating stage and others did not proceeded went thought due to lack of financial support, such projects were the Industrikraft Møre AS Norway Project and the Full Scale CO_2 Capture Mongstad Project (in Norway), the Teesside Low Carbon Project (UK) and the Getica CCS Demonstration Project (Romania).

Table 6: Projects for Large-scale CSS in Define stage in Europe [Adapted from 19]

PROJECT NAME	STAGE	MASS OF CO_2 (MTPA)	PORTFOLIO BENEFIT
Peterhead CCS Project	Define	1.0	Power sector, post-combustion, natural gas feedstock, dedicated geologic storage - offshore depleted gas reservoir
ROAD	Define	1.1	Power sector, post-combustion, coal feedstock (plus biomass), dedicated geologic storage - offshore depleted gas reservoir

As for Projects on a define stage (Picture)we got the ROAD Project in the Netherlands and the Peterhead CCS Project in Scotland, both implementing Post-Combusting capturing technologies into already existing power plants.

9.1. ROAD Project [21]

The ROAD Project (Rotterdam Storage and Capture Demonstration Project) is a project located on the Netherlands for a new coal and biomass-based power plant within the Maasvlakte section of the Rotterdam industrial zone to collect CO_2 emission using post-combustion capture by method of absorption chemical solvent based process (amine), with CO_2 capture capacity volume of 1.1 million tonnes per year.

Initially the financial support was going to be in December of 2010, however due to problems with permits and commercial negotiations it was delayed until September of 2014 when the European Union together with the Government of the Netherlands gave financial support to start and will be fully operating in the end of this current year (2015).

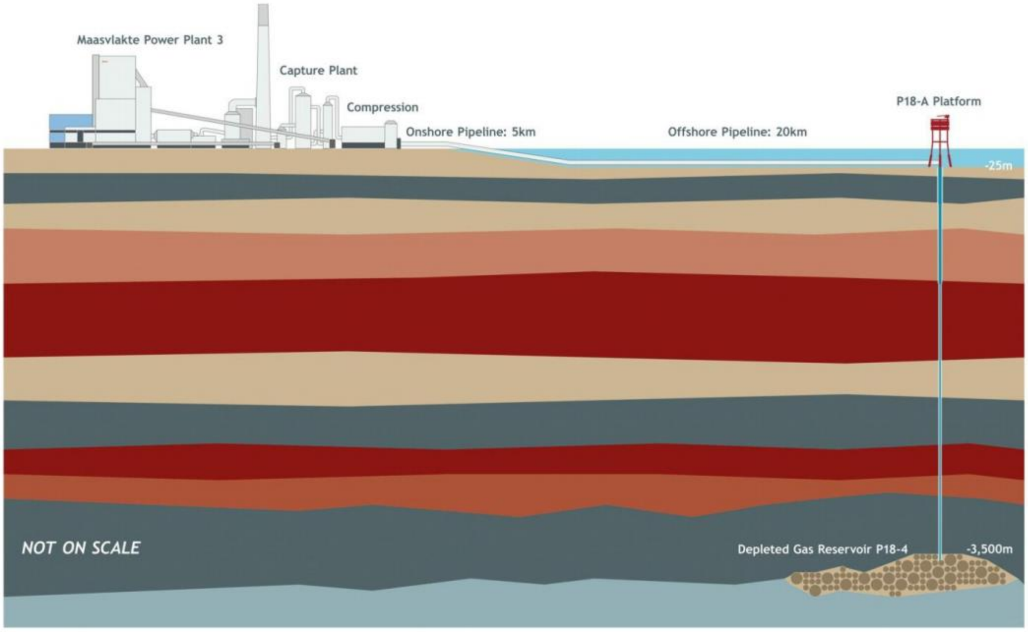


Figure 13: Scheme of ROAD Project CCS Methods [21]

The ROAD post-combustion capture plant, will have a capacity of more than 250 MWe and its main goal is to show that it is viable to use CCS technologies in large scale industrial projects and well adapted to coal-fired power (Maasvlakte Power Plant 3) .The captured CO_2 will be transported for storage in an offshore gas field by a 25 km pipeline from the PCC plant.

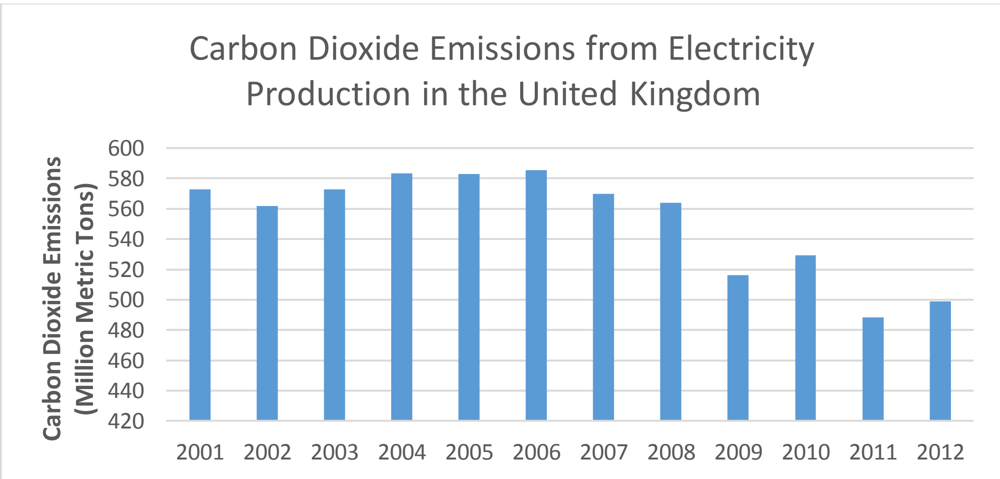
9.2. Peterhead CCS Project

The Peterhead CCS Project, located in Aberdeenshire - Scotland, is a project for a post-combustion capture facility that will be introduce to one of the three existing Natural Gas Combined Cycles of the Peterhead Power Station which have 385MW. It uses amine capture technology (absorption process) and with CO_2 capture capacity volume of 1.0 million tons per year.

After the captured, CO_2 is than dehydrated, compressed and transported, by pipeline, to storage at Goldeneye gas reservoir located 100 kilometers away from the coast and 2.5 kilometers deep.

Figure 14: Peterhead Power Station on the left, Goldeneye gas platform on the right [25]

It got funded by the United Kingdom Government and by the Department of Energy and Climate Change in April of 2012 and the project is schedule to be operational in the end of 2020. We can see on Graph 15 how the constant investment on CO_2 emission reduction by the UK government has a big impact in the 10 year before 2012.



Graph 16: Carbon Dioxide Emissions from Electricity Production in the United Kingdom[13]

10. Assessment of the applicability of PCC technologies in fossil fuels power plants in Europe [7,16,17]

10.1.Type of PCC Technology

Has seen during this thesis the Post-combustion capturing technologies use a lot of energy from the power plant mainly to regenerate the solvent or sorbent, to clean the flue gas before regeneration (in the case of PC) and to prepare the capture CO_2 for transporting (dehydration and compression).

Table 7 (based on a study by Global Carbon Capture and Storage Institute) shows that operations in both Absorbent processes and Adsorbent processes are reliable but that in case of Membranes it is still doubtable, which is understandable since it is not a technology as evolved as absorption or adsorption of CO2 emissions.

Table 7: PCC Technologies Development [7]

Post-Combustion CO_2 Capture Development

	Absorbent	Adsorbent	Membrane
Operational Confidence	High	High, but complex	Low to moderate
Primary Source of Energy Penalty	Solvent Regeneration (thermal)	Sorbent Regeneration (thermal/vacuum)	Compression on feed and/or vacuum on permeate
Development Trends	New chemistry, thermal integration	New chemistry, process configuration	New membrane, process configuration

Steps forward for the development of PCC should come from lowering the energy necessary for regeneration of the absorbent or of the adsorbent by creating new technological design that have a better thermodynamic efficiency or creating new chemical absorbent or adsorbent that makes heat transfers less electrical consuming.

In the case of membranes, the development of them with new materials is being test and new configurations for that process so it can become more reliable and with a better permeability.

The development of technology design, chemistry of the processes and power saving the more is in collaboration with each other the faster progression will be made.

10.2. Type of Fossil Fuel

Has we seen during this thesis the integration of PCC technologies as a great impact in the technical and economic parameters of PC and NGCC (Chapter 8). NGCC adapts better to PCC technologies because natural gas is a cleaner flue than coal and therefore needs less technologies to clean the gas before the CO_2 capture. This next Tables show how fuel data (two types of Bit Coal and Natural Gas) compares with each other and how it influences in the technologies need it:

Table 8: Bituminous Coal Components [16]

Components [wt%]	Appalachian medium sulfur	Illinois # 6
Carbon [wt%]	73.81	61.2
Hydrogen [wt%]	4.880	4.2
Oxygen [wt%]	5.41	6.02
Nitrogen [wt%]	1.42	1.16
Sulfur [wt%]	2.13	3.25
Ash [wt%]	7.24	11
Moisture [wt%]	5.05	13
Others [wt%]	0.06	0.17

Natural Gas varies in composition depending on the location, Table 9 shows the range of its components:

Table 9: Components of Natural Gas [17]

NG components	Range of Components [mole%]
Methane	87 - 97
Ethane	1.5 - 7
Propane	0.1 – 1.5
Nitrogen	0.2 – 5.5
CO_2	0.1 - 1
Oxygen	0.01 - 1
Hydrogen	~0 – 0.02
Others	0.01 – 0.08

The fact that Natural Gas is cleaner than Coal makes the application of PCC Technologies more viable than in PC, although it is a great CO_2 capture technology for both of them. There is a bigger drop in efficiency in the case of PC due to the fact that needs more technologies to clean the flue gas, such as an electrostatic precipitator for removal of particulates, a flue gas desulphurization technology for SO_x and NO_x control technologies (e.g. Selective Catalytic Reduction).

10.3. Efficiency Losses

A big factor for reducing the efficiency is the regeneration process of the solvent. In Table 10 we see the impact in NGCCC and PC with PCC technologies using Absorption process with amine base system in this case mono-ethanol amine (MEA).

In the case of NGCCC with amine base absorbent the flue gas goes to the Absorber Vessel at temperature between 40ºC to 60ºC for the CO_2 to be capture, than the rich sorbent is pumped to the Regenerator Vessel where it is heated to temperatures between 100ºC to 140ºC for the solvent to be regenerated, the heat necessary of 5422 kJ/kg CO_2 so that lower the CO_2 concentration gets the higher energy is needed.

The MEA absorption is an exothermic process, meaning, that if the temperatures are lower the efficiency of CO_2 capture is higher, NGCCC uses lower temperatures than PC with PCC technology making it more efficient. [16]

Table 10 : PCC data using absorption process with amine base [16]

Components	PC with PCC	NGCCC
Absorbent used	MEA	MEA
Absorbent cost	1425 [USD/tonne]	1425 [USD/tonne]
Absorbent Losses	1.5 [kg/tonne CO_2]	1.5 [kg/tonne CO_2]
Regeneration Heat Requirement	4000 [kJ/kg CO_2]	5422 [kJ/kg CO_2]
Temperature for Absorption	45 – 50 [ºC]	40 – 60 [ºC]
Temperature for Regeneration	100 - 140 [ºC]	100 – 140 [ºC]
CO_2 Capture Compression Pressure	13.79 [MPa]	13.79 [MPa]
Energy Consumption for CO_2 Compression	117.9 [kWh/tonne CO_2]	117.9 [kWh/tonne CO_2]

For PC with PCC technologies with amine base absorbent the heat required for the absorbent regeneration is of 4000 kJ/kg CO_2 [16]

The absorbent cost in both PC with PCC and NGCCC are the same making and having in account the losses it has the expense of 2.1375 USD per tonne of CO_2. Finally the compression of the captured CO_2 is made at 13.79 MPA and has a cost of 117.9 kWh/tonne CO_2 making it a really expensive process.

11. Conclusion

In Europe levels of CO_2 from power production emission are decreasing since 2005, the year that EU ETS was implemented along with greenhouse gases legislation.

After analyzing different studies from following year that those laws were implemented in Europe on the application of PCC technologies on fossil fuels power plants, namely PC and NGCC, we can say that they have a great impact on them. In the case of NGCC the relative net efficiency dropped around 15% with the investment cost increase, in case of NGCC-776, of 78% relative to the same power plant without PCC and NGCC-395 a raise of 39.8%. On PC the drop was in the order of 21-20% in relative net efficiency (23% when using 10% of Biomass as fuel and 90% Bit Coal), the investment cost increases 84.2% for USCPC and 90.3% for SCPC.

On both types of power plants the CO_2 emissions decreased considerably, showing high effectiveness of CO_2 capture in the order of 83% to 90.4%. All of these studies use amine absorption because it is an already well tested mature technology widely used. Adsorption is a more complex process and membranes are still being developed (although they have a promising future).

Both systems have the same losses in the compression of CO_2 to be ready for transport and storage, consuming 117 kWh/tonne CO_2, making it a really expensive process.

We conclude that the reduction in efficiency in PC is bigger than in NGCC using post-combustion capture because natural gas is a cleaner fuel then coal. The flue gas from coal combustion needs to be clean before the CO_2 capture by eliminating particulates, SO_x and NO_x. Also NGCCC can operate the absorbent process in slightly lower temperatures than in PC with PCC Technology and because MEA (amine absorbent used) absorption is an exothermic process, meaning the efficiency is higher at lower temperatures.

PCC is however really easy to integrate to an already operating power plants with large CO_2 emissions, opposite to pre-combustion and oxy-fuel which need to be planned from the start of operations.

REFERENCES

[1] Global Carbon Capture and Storage Institute. “Fact sheet What is CCS?”. 07 May 2015 < http://www.globalccsinstitute.com/publications/what-ccs>

[2] Energy.gov “Adding “Utilization” to Carbon Capture and Storage” 01 May 2012 <http://www.energy.gov/articles/adding-utilization-carbon-capture-and-storage>

[3] Intergovernmental Panel on Climate Change. “Special Report on Carbon Dioxide Capture and Storage”, 2005, <https://www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf>

[4] Global Carbon Capture and Storage Institute. “Fact sheet CAPTURING CO_2”. 05 May 2015 < http://www.globalccsinstitute.com/publications/capturing-co2>

[5] Carbon Capture and Storage Association. “Capture” < http://www.ccsassociation.org/what-is-ccs/capture/>

[6] The Bellona Foundation. “WHY CCS NOW”. 05 December 2009 <http://bellona.org/assets/sites/6/Why_CCS_now.pdf>

[7] Global Carbon Capture and Storage Institute. “CO_2 CAPTURE TECHNOLOGIES POST COMBUSTION CAPTURE (PCC)” January 2012

[8] Global Carbon Capture and Storage Institute. “CO_2 CAPTURE TECHNOLOGIES PRE COMBUSTION CAPTURE (PCC)” January 2012

[9] Ligang Zheng, Yewen Tan. “Overview of Oxy-fuel Combustion Technology” <http://cornerstonemag.net/overview-of-oxy-fuel-combustion-technology-for-co2-capture/>

[10] Shuangzhen Wang, Xiaochun Han. “Application of Polymeric Membrane in CO_2 Capture from Post Combustion”. 8 June 2012

[11] Anne Andersen, Swapnil Divekar, Soumen Dasgupta, Aarti, Anshu Nanoti, Aud Spjelkavik, Amar N. Goswami, M.O. Garg, Richard Blom. “On the development of Vacuum Swing adsorption (VSA) technology for post-combustion CO_2 capture”. 05 August 2013

[12] M.T. Ho, G.W. Allinson, D.E. Wiley. “Reducing the cost of CO_2 capture from flue gases using pressure swing adsorption.Ind”. Eng. Chem. Res., 47 (2008), pp. 4883–4890

[13] Independent Statistics and Analysis Energy Information Administration. Data base on CO_2 emissions from Electrical Production. 1980-2012 <http://www.eia.gov/>

[14] European Commission. “The EU Emissions Trading System (EU ETS)” < http://ec.europa.eu/clima/policies/ets/index_en.htm >

[15] Mohamed Kanniche, René Gros-Bonnivard, Philippe Jaud, Jose Valle-Marcos , Jean-Marc Amann, Chakib Bouallou. “Pre-combustion, post-combustion and oxy-combustion in thermal power plant for CO2 capture” 08 May 2009

[16] Yasaman Mirfendererreski “Techno-Economic Assessment of Carbon Capture and Sequestration Technologies in the Fossil Fuel-based power Sector of the Global Energy-Economy System” Technische Universitat Berlin. May 2008

[17] Union Gas “Chemical Composition of Natural Gas” <https://www.uniongas.com/about-us/about-natural-gas/chemical-composition-of-natural-gas>

[18] Cheng-Hsiu Yu, Chih-Hung Huang, Chung-Sung Tan. “A Review of CO_2 Capture by Absorption and Adsorption”. National Tsing Hua University in Taiwan< http://aaqr.org/vol12_no5_october2012/7_aaqr-12-05-ir-0132_745-769.pdf>

[19] Global Carbon Capture and Storage Institute. “THE GLOBAL STATUS OF CCS 2014” 2014 <http://hub.globalccsinstitute.com/sites/default/files/publications/180923/global-status-ccs-2014.pdf>

[20] Global Carbon Capture and Storage Institute. “THE GLOBAL STATUS OF CCS: 2011” October 2011 <http://decarboni.se/sites/default/files/publications/22562/global-status-ccs-2011.pdf>

[21] Andy Reada , Onno Tillemaa , Menno Rosa , Tom Jonkera , Hette Hylkemab.” Update on the ROAD Project and Lessons Learnt” 2014 < http://www.sciencedirect.com/science/article/pii/S1876610214024552>

[22] Matthias Finkenrath. “Cost and Performance of Carbon Dioxide Capture from Power Generation” International Energy Agency. 2011

[23] International Energy Agency (IEA). “CO_2 EMISSIONS FROM FUEL COMBUSTION HIGHLIGHTS” 2013

<http://www.iea.org/publications/freepublications/publication/co2emissionsfromfuelcombustionhighlights2013.pdf>

[24] “Oxyfuel Combustion for Coal-Fired Power Generation with CO_2 Capture – Opportunities and Challenges,” Kristin Jordal et al, 7th International Conference on Greenhouse Gas Control Technologies, University of Regina, September 5-9, 2004, <http://uregina.ca/ghgt7/PDF/papers/peer/054.pdf>

[25] SSE and Shell “THE PETERHEAD CARBON CAPTURE AND STORAGE PROJECT” <https://s06.static-shell.com/content/dam/shell-new/local/country/gbr/downloads/pdf/peterhead-ccs-brochure.pdf>

[26] <http://daily.sightline.org/2014/07/02/four-carbon-pricing-pitfalls-to-avoid/>

ABBREVIATIONS

Bit Coal	Bituminous Coal
CCP	CO_2 Capture Project – CCP (Melien, 2009)
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilization and Storage
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COE	Cost of Electricity
ETS	Emission Trading System
EU	European Union
GHG IA	Greenhouse-Gas Implementing Agreement
H_2	Molecular Hydrogen
H_2O	Water Molecule
HHV	Higher Heat Value
IEA	International Energy Agency
LHV	Lower Heat Value
MEA	Mono-ethanol Amine
MMT	Million Metric Tons
NCCC	National Carbon Capture Central
NGCC	Natural Gas Combined Cycle
NGCC 1	NGCC with 1 turbine
NGCC 2	NGCC with 2 turbine
NGCC 3	NGCC with 3 turbine
NGCC-395	NGCC with 395 MWe gross power output
NGCC-480	NGCC with 480 MWe gross power output
NGCC-776	NGCC with 776 MWe gross power output
NGCCC	NGCC with post-combustion CCS
NGCCC 1	NGCC with 1 turbine and with post-combustion CCS
NGCCC 2	NGCC with 2 turbine and with post-combustion CCS
NGCCC 3	NGCC with 3 turbine and with post-combustion CCS

NO_x	Nitrogen Oxides
O&M	Operating and Maintenance Costs
OEOD	Organization for Economic Co-operation and Development
PC	Pulverized Coal Power Plant
PC-1200	PC with 1200 WMe gross power output
PCC	Post-combustion Capture
ROAD	Rotterdam Storage and Capture Demonstration
SCPC	Supercritical Pulverized Coal Power Plant
SCPC-519	SCPC with 519 WMe gross power output
SO_X	Sulphur Oxides
Syngas	Synthetic gas produced by the gasification
TRL	Technology Readiness Level
USCPC	Ultra-Supercritical Pulverized Coal Power Plant
USCPC-758	USCPC with 758 WMe gross power output
VSA	Vacuum Swing Adsorption

LIST OF FIGURES

Figure 1: Carbon Capture and Store Technology [11] 8
Figure 2: Carbon dioxide capture methods [3]..9
Figure 3: Pre-combustion Carbon Dioxide Capture [4] 10
Figure 4: Oxy-fuel Carbon Dioxide Capture [5]...11
Figure 5: Post-combustion Carbon Dioxide Capture [5]...12
Figure 6: PCC Absorption Technology [7] 14
Figure 7: PCC Adsorption Technology [7] 16
Figure 8: PCC Membrane Technology [11] 17
Figure 9: The European Union Emission Trading System [14] 21
Figure 10: Avoided CO_2 [15]..26
Figure 11: EU carbon prices by 2005-2013 [26] 32
Figure 12: Large-scale CCS projects in Europe [19]...36
Figure 13: Scheme of ROAD Project CCS Methods [21] 37
Figure 14: Peterhead Power Station on the left, Goldeneye gas platform on the right [25]...38

LIST OF GRAPHS

Graph 1:Total Carbon Dioxide Emission from Electrical Production in Europe in 2012..19

Graph 2: Total Carbon Dioxide Emission from Electrical Production in Europe from 1980 to 2012 20

Graph 3: Total CO_2 Emission from Electrical Production in Largest Emitters in Europe from 1980 to 2012 21

Graph 4: Efficiency without and with CO2 post-combustion capture [Adapted from ref. 15]....................24

Graph 5: Investment cost without and with capture of CO2 relatively to PC without CO2 capture (11% discount rate) [Adapted from ref. 15] 25

Graph 6: Production cost (construction, fuel, Operation and Maintenance) of the different systems with and without CO2 capture relative to PC [Adapted from ref. 15].26

Graph 7: Cost of avoided CO2 relatively to PC (11% interest rate) [Adapted from ref. 15]....................27

Graph 8: Cost of Electricity versus Electrical Output [16]....................29

Graph 9: Capital Required versus Electrical Output [16]....................29

Graph 10: Capital Required versus CO2 Emissions [16] 30

Graph 11: Net Power Output with and without PCC 32

Graph 12: Net Efficiency with and without PCC....................32

Graph 13: Relative decrease in net efficiency (%) 33

Graph 14: Investment Cost and CO2 emissions with and without PCC 33

Graph 15: CO2 capture cost and EU ETS carbon price for analyses cases 35

Graph 16: Carbon Dioxide Emissions from Electricity Production in the United Kingdom....................38

LIST OF TABLES

Table 1: Technology Readiness Level scale meaning 18
Table 2: Evaluation of development state of emerging PCC Technologies 18
Table 3: PC and NGCC parameters 23
Table 4: Impact of Plant size in NGCC and NGCCC [16] 28
Table 5: Post-Combustion Capture in Europe in OEOD Region [23] 31
Table 6: Projects for Large-scale CSS in Define stage in Europe [19] 36
Table 7: PCC Technologies Development [7] 39
Table 8: Bituminous Coal Components [16] 40
Table 9: Components of Natural Gas [17] 40
Table 10: PCC data using absorption process with amine base [16] 41

APPENDIX A

Total Carbon Dioxide Emissions from the Consumption of Energy (Million Metric Tons)

	2008	2009	2010	2011	2012
Europe	4581.15	4279.517	4386.991	4348.063	4263.257
Albania	4.37229	2.81575	3.79862	4.07652	3.96221
Austria	69.99211	65.26445	70.03595	69.33971	66.67506
Belgium	153.5328	134.7122	143.2184	140.1255	139.1389
Bosnia and Herzegovina	21.06355	21.57786	23.00197	27.50758	25.99681
Bulgaria	50.61403	44.73865	46.02672	52.56494	48.84771
Croatia	21.74174	20.04659	18.96968	17.83133	20.17905
Cyprus	9.8226	9.22531	8.91436	8.7309	8.8014
Czech Republic	99.10063	92.09819	95.58812	94.35327	91.15491
Denmark	51.90644	48.83244	49.58838	45.30879	40.51219
Faroe Islands	0.6997	0.72467	0.73226	0.77233	0.75336
Finland	53.61809	50.93984	57.28586	51.60939	46.80946
France	421.5602	386.3724	385.5897	374.3236	364.5382
Germany	812.6063	758.1783	796.9563	784.3775	788.321
Gibraltar	4.55158	4.86385	8.88013	4.75354	3.94625
Greece	106.0414	99.82669	93.54463	92.08394	87.55789
Hungary	56.01399	51.90245	52.50846	52.17165	47.90274
Iceland	3.71576	3.31827	3.80893	3.5902	3.50465
Ireland	44.86961	38.9215	39.57119	36.20716	35.48918
Italy	449.7486	407.6301	419.8112	411.5623	385.8128
Kosovo	6.28906	7.23411	9.3391	7.55743	7.57555
Luxembourg	11.96111	11.43675	12.1032	11.62882	11.68678
Macedonia	8.98171	8.41201	8.00855	8.68723	8.08411
Malta	3.17696	6.68233	8.03025	7.52033	6.56426
Montenegro	2.15773	1.54992	2.75156	16.90526	19.71808
Netherlands	229.5266	222.9308	234.31	239.7392	239.605
Norway	40.02858	44.71699	43.57717	41.65102	41.0579
Poland	294.6997	286.4704	304.6076	308.1041	289.4548
Portugal	56.13857	57.10018	53.22172	53.16434	51.19574
Romania	93.87531	81.16977	78.10375	89.48119	86.05824
Serbia	51.56919	49.73258	49.28028	43.87622	41.37553
Slovakia	38.30476	35.17909	36.95972	35.04475	32.08004
Slovenia	17.42004	16.11383	16.21085	15.99411	15.87215
Spain	354.6998	327.8008	312.588	318.232	312.442
Sweden	54.71347	51.83961	56.45176	54.0432	51.07729
Switzerland	45.26299	43.90447	45.61776	41.92415	42.96573
Turkey	272.9004	269.0631	268.5475	294.9092	296.9319
United Kingdom	563.8723	516.191	529.451	488.3102	498.8771

Independent Statistics and Analysis: Energy Information Administration