UNIVERSITA' DEGLI STUDI DI ROMA
"TOR VERGATA"

DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

Corso di Laurea in Engineering Sciences

Carbon capture and storage technology: analysis of current situation and future scenarios

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Anno Accademico : 2016/2017

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Chapter 1

Introduction

Nowadays global climate changes, due to an increasing concentration of greenhouse gases in the atmosphere, bring most industrialized countries to adopt energy policies based on three different aspects:

- use of fossil fuels, with a remark for improving technologies able to reduce emissions;
- diffusion of energy saving plans in all sectors;
- increase of renewable sources.

The demand toward solutions, which limit environmental impacts, is born from the impossibility of completely substituting fossil fuels with alternative sources. This interests, in particular, carbon which is at the base of electrical energy production (30% of electricity in UE, 50% in USA, 75% in China, …).

Sustainable use of carbon, achieved through an improvement in energy efficiencies and development of carbon capture and sequestration technologies, is the main objective.

For what concerns strategies, there's a need to incorporate various concepts such as:

1. "clean" technologies, or those with low emissions of pollutants;
2. solutions which imply higher efficiency values;
3. CCS technologies (Carbon Capture and Storage) able to capture CO_2 and confine it definitively without introducing it in the atmosphere.

Today, these goals seem to be achievable thanks to the perspectives offered by research and development. CCS, now, represents a good option to withstand climate changes.

Even though electrical power plants are not the only carbon dioxide producers (as for example industrial applications related to metallurgy or transportation sector etc.), they contribute to about 1/3 of 30.000 million tons CO_2 globally produced every year.

At an international level, many initiatives want to enhance collaboration between different countries for the development of CCS technologies and for the definition of political agreements on limits regarding CO_2 emissions.

From a technological point of view, CCS consists of three parts: capture, transportation and storage.

Low carbon power plants are implemented with capture systems in post-combustion, or pre-combustion, depending on whether CO_2 capture occurs before or after fuel combustion.

Currently research is focused on finding solutions able to make this process more efficient, essential aspect for its marketing.

Transportation of CO_2 represents the least worrying part of the entire process, because of the great knowledge in hydrocarbon sector. Pipelines and ships are basic means of transportation of the fluid. As regards storage, various methods for geological sequestration of CO_2 can be adopted, and some of them, like EOR, contribute to dampen CCS cost.

Problems related to safety and procedures have made many projects not feasible and a difficulty is now represented by a poor local implementation of international projects. Even if CCS technologies demonstrate that they can give a significant contribution to emissions reduction, today, are not competitive for what concerns efficiency and costs.

Boundary Dam project is the first-ever, commercial scale, coal-fired power plant incorporating amine solvent absorption carbon capture. It began operation near Estevan, Saskatchewan, Canada on October 2, 2014. This was a global landmark event. Although carbon capture technologies had been pilot tested prior to this, a commercial scale power plant now exists and it has demonstrated that a number of high-risk technology and business issues have been overcome.

Regarding Europe, the state is completely different, indeed European commission has repeatedly encouraged the development of CCS. From 2009 on, several institutions have been set up with the task of evaluating the use of this technology in Europe.

Since then, various studies on feasibility and economic impact have been started.

From these studies, many projects have arisen in several European states, however none of them has ever reached a demonstration phase.

The world's largest market for low carbon technologies has also been set up, which aims to stimulate their use.

This market is based on a trading of emission certificates (ETS). The exchange of these certificates could lead to emit less or to spend more money by purchasing certificates up to an established maximum.

The ETS was also thought for those companies at risk of relocation if they were excessively eco-taxed. Nevertheless, CCS projects continue to have little follow up.

European perspectives on this technology are therefore subjected to what will be European policies in next years and state of maturity of future CCS plans. In order to be implemented it's necessary to rethink the contribution system.

Chapter 2

CCS TECHNOLOGIES AND GLOBAL CONTEXT

The following chapter is focused on the analysis of the aspects which refer to climate change, in particular greenhouse gases and the link between carbon dioxide and emission sources.

Subsequently some data on current and future levels of emissions, associated with energy sector, are illustrated.

In the end various prospects, aimed to contain an increase in greenhouse gases concentration in order to mitigate global warming, are exposed.

2.1 Current climate change

Currently, very lit up turns to be the debate, which involves scientific community as whole, on how much the climate context in which we live is in constant change, both for natural causes and for anthropic causes. In particular, the scientific community continues to research which relationships exist between increase in greenhouse gases, increase in the earth temperature, sea level rise caused by glacial melting and acidification of oceanic waters.

According to some scientists the growing global temperature, extrapolated from thermometers, sediments, corals and tree rings, is due to cycles, sometimes cooler, sometimes more tempered, which occur through millennia; however, this temperature increase is a phenomenon that has been configured in a relatively short period of time, around 100 years.

The speed with which the change took place suggests that it does not have a natural evolution: average rainfall and oceanic currents alter; average atmospheric temperature rises and extreme atmospheric events become more and more frequent.

As a consequence of temperature rise there's a proportional increase in precipitation and in water vapour, which is one of the leading greenhouse gas able to capture irradiated heat contributing to global warming; a decrease in the average pressure gradients of seas and a shift in wind currents (Creamer and Gao, 2015).

Other phenomena to consider are: modified biological scenarios, the occurrence frequency of El Niño, event in which the surface of the central Pacific Ocean manifests an increase in temperature of about 0.5 °C for a period of time less than 5 months.

2.2 Carbon dioxide and its role in climate change

Among the major causes of global warming, there are certainly greenhouse gases. This is why scientific community has focused, for a long time, on the study of how they worked.

Although they are already present in atmosphere, their excessive concentration is associated to man activities. The amount of gas that nature is able to emit and absorb without any consequences is not comparable with the quantity that man is able to produce (World Energy Outlook IEA, 2016).

CO_2, among all greenhouse gases, is the substance introduced in atmosphere in greater quantities and accounts for about 78% of total volume occupied by greenhouse gases.

What is now known is its steady increase, ranging from a value of 280 ppm in the pre-industrial age to a value of 389 ppm to the end of 2010 (IPCC Climate Change, 2014).

This trend seems to be consolidating in the absence of appropriate containment policies and such levels could soon affect the overall Earth's ecosystem.

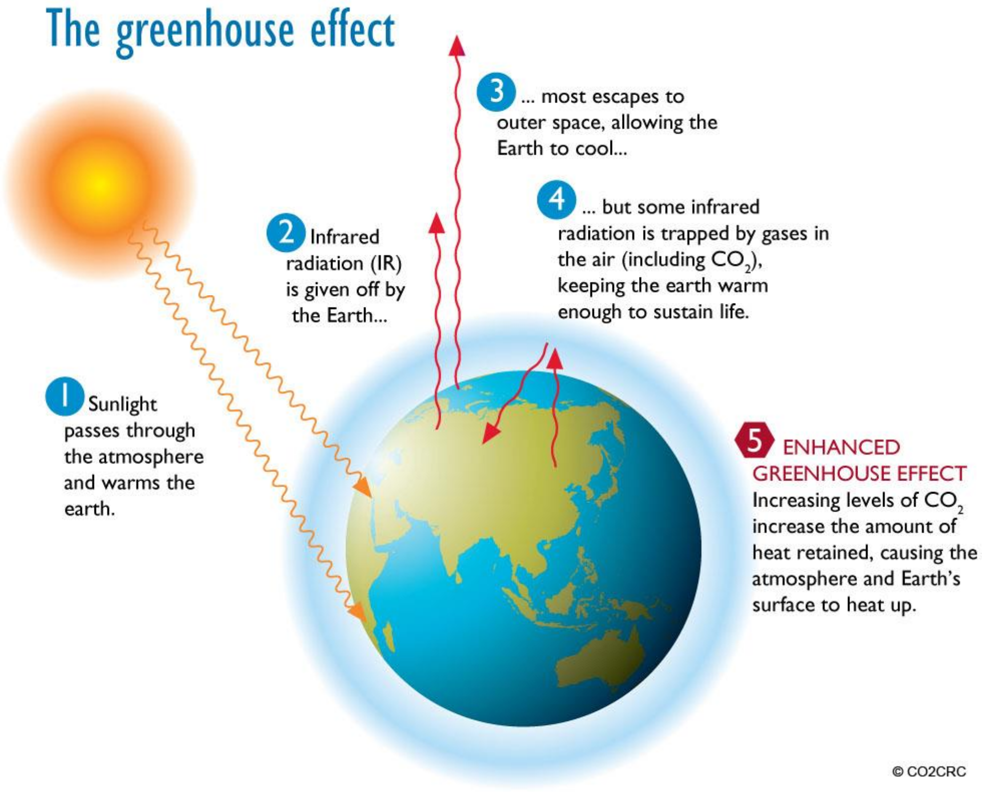

Figure 1.1: CO_2 as greenhouse gas (Source: CO2CRC, Cooperative Research Center for Greenhouse Gas Technologies)

In this regard, IPCC believes that CO_2 concentration increase results in an average global temperature increase between 0.2 and 0.6 ºC since the end of the 19th century and foresees that by 2100 the rise could reach up to 5.8 ºC. In addition, to prevent global overheating, limiting the temperature rise to below 2 ºC, CO_2 level should remain below 450 ppm, target recognized by Conference of the parties which took place in Paris in 2015, through quick actions.

It's necessary to decrease emitted CO_2, so that this goal can be reached (IEA Technology Roadmap, 2013).

In this framework, climate change is a key driver in the development of CCS technologies intended to reduce emissions on a large scale.

2.3 Global energy situation

IEA data show that, from 1973 to 2015 Total Primary Energy Supply has increased from about 6101 Mtoe to 13647 Mtoe (fig. 1.2).

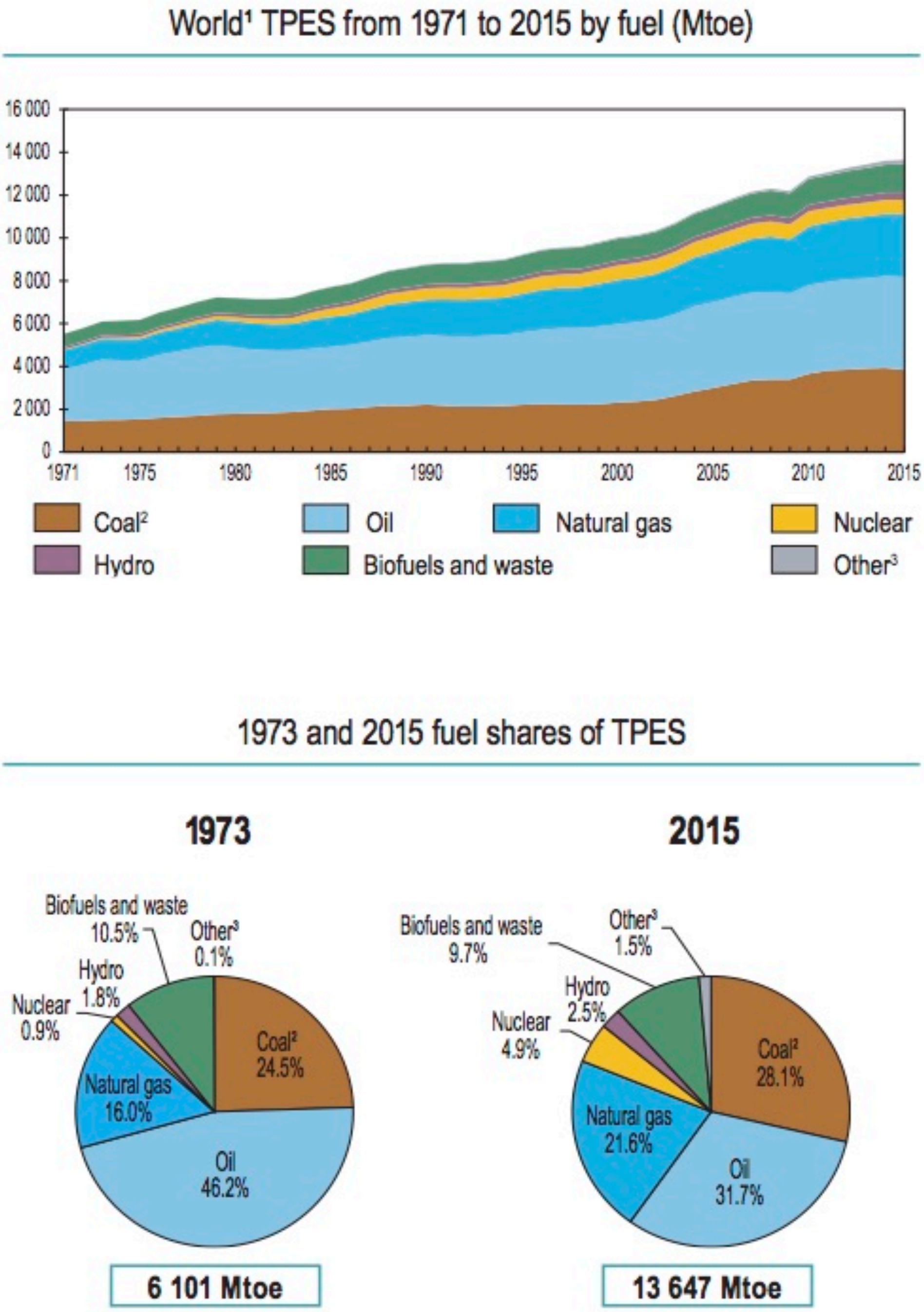

Figure 1.2: Trend of primary energy demand from 1973 to 2015. (Source: IEA 2016)

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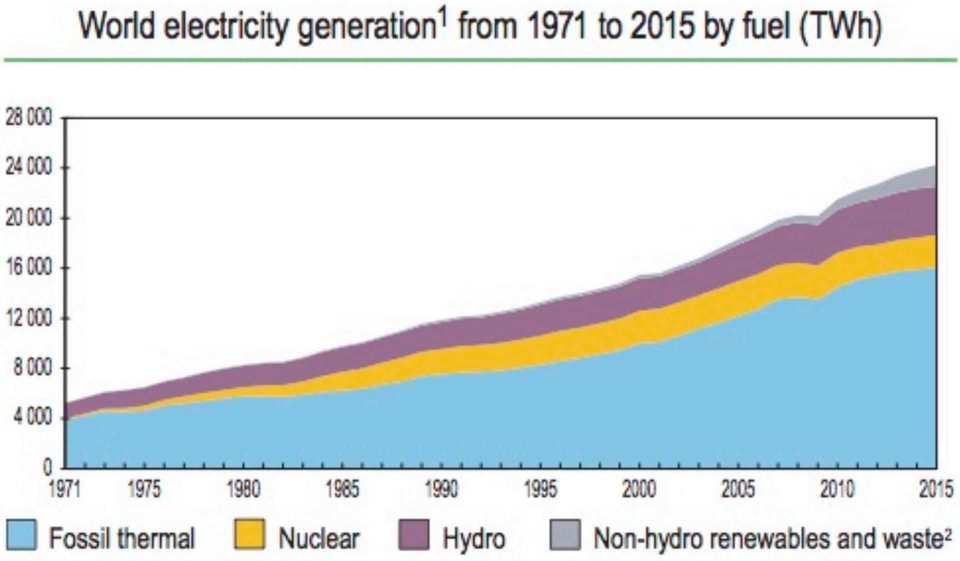
[1] The toe is a unit of energy defined as the amount of energy released during combustion of one ton of crude oil. It’s about 42 GJ or 11.63 MWh.

Much of the energy demand is now covered thanks to the use of fossil fuels: 28.6% carbon, 31.3% petroleum, 21.2% natural gas.
Analysing the electrical generation component, percentages vary; indeed, carbon produces 39.3%of electricity in the world, followed by natural gas 22.9% and hydroelectric 16.0% (fig. 1.3). Therefore, being the main source of sustainability of world electricity production, it’s unthinkable to replace them completely with renewable sources in the short term.



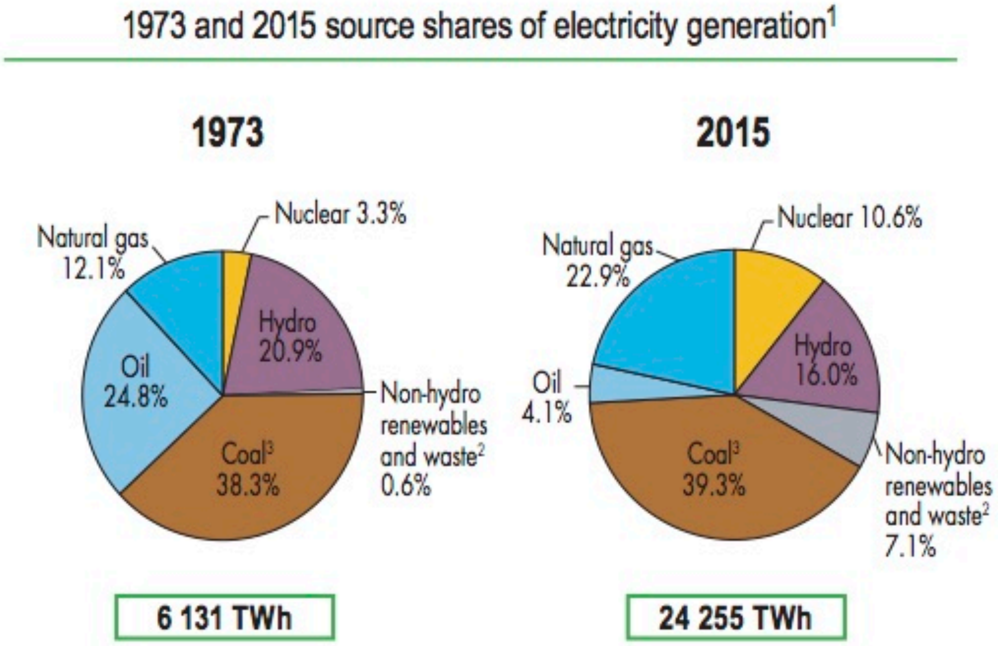


Figure 1.3: Electricity generation from 1973 to 2015. (Source: IEA, 2017)

As regards emissions, CO_2 has risen from 15458 Mt in 1973 to 32294 Mt[2] in 2015. These values are also a consequence of the fact that developing economies weighed 33.4% in 1973 while now weigh 63.4%. This, considering future economic growth of these countries, could produce adverse effects.

2.4 Future trends

The International Energy Agency estimates that generation of electricity will increase by two-thirds in 2040. World's primary energy demand is expected to grow from 13647 Mtoe to 17866 Mtoe in 2040, an increase of 30.6%.
Coal, in particular, is projected to cover 23.2% of primary demand in 2040 especially in Asian countries such as China and India, where it still represents the main source of energy.
Indeed, investments in fossil fuel power plants seem to remain fairly constant (1065 to 1112 billion dollars) mainly due to newly completed and under construction plants in non-OECD[3] countries (WEO, 2016).
Coal, as other non-renewable sources, remains important in world electricity production, even if Europe intends to reduce its use.

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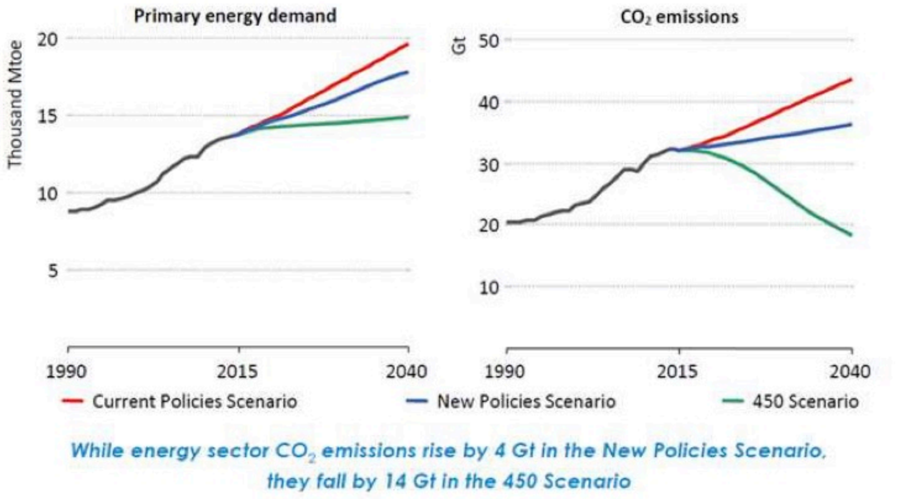
[2] Millions of tons of carbon dioxide emitted.

[3] Countries that are not part of the Organization for Economic Co-operation and Development

2.5 New Policies Scenario vs 450 Scenario

Despite many nations commit themselves in the containment of greenhouse gas emissions, the IEA thinks the goal of 2 ºC (COP21 Paris, 2015) is not yet reachable.
The analysis of emissions from the point of view of energy production and industrial production shows how they should be kept below 42 Gt CO_2-eq[4], of which 35 Gt coming from fossil fuels, in 2030.
However, despite the efforts of NDC[5] in COP21, emissions will be able to lead to an increase of 2.7 ºC by the end of 2100.



While energy sector CO_2 emissions rise by 4 Gt in the New Policies Scenario, they fall by 14 Gt in the 450 Scenario

Figure 1.4: Data provided by IEA on primary energy demand and CO_2 emissions (Source IEA, 2016).

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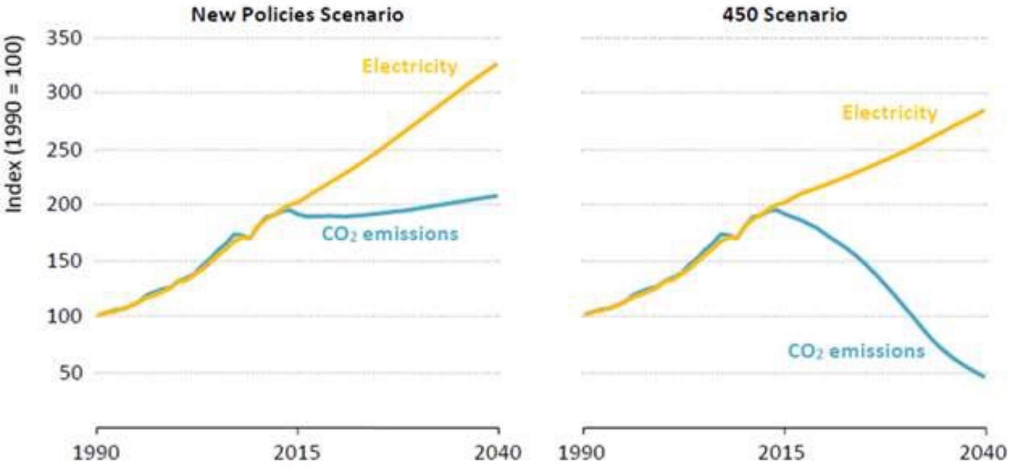
[4] Carbon dioxide equivalent is a measure used to describe how much global warming is caused by a specific type of greenhouse gas, in function of an equivalent CO_2.
[5] Nationally Determined Contributions (NDC) are those nations which signed Paris agreement (IEA WEO, 2016).

New Policies Scenario provides how data on global CO_2 emissions, with reference to 2040, are expected to increase by 4 Gt while their intensity is expected to decrease from 515 to 335 gCO_2/kWh[6].

In this context, fossil sources will reach about 74% of the entire energy system.

450 Scenario[7], on the contrary, shows how these will reach a peak in 2020 and then settle in 2040 at a value of 18 Gt while their intensity will approach 80 gCO_2/kWh. Fossil sources, in this case, will thus amount to 58%.

Figures below illustrate data previously presented. These results imply a widespread use of renewable energy sources in the electricity sector, the adoption of energy efficiency policies and also a crucial use of carbon capture and storage technologies in industrial and energy sectors (IEA, 2016).



Electricity generation and CO_2 emissions decouple in the New Policies Scenario, but more is needed to achieve climate goals

Figure 1.5: Electricity generation and CO_2 emissions in New Policies Scenario and 450 Scenario (Source: IEA, 2016).

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[6] Value of emissions with respect to kilowatt hour produced.

[7] *450 Scenario* proposes to limit global temperature increase to 2 °C, decreasing greenhouse gas concentration in the atmosphere to about 450 ppm of CO_2.

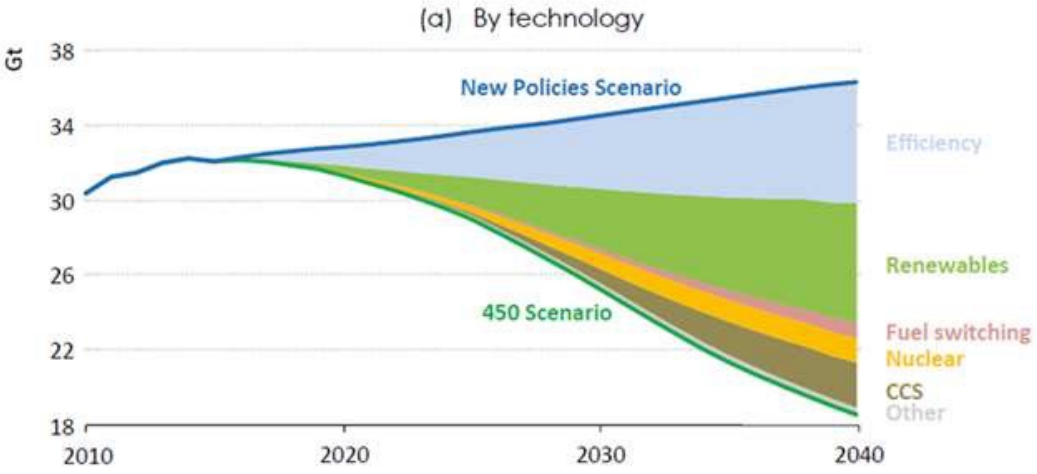

Figure 1.6: Possible technologies able to reduce emissions gap between the two scenarios (Source: IEA, 2016).

Chapter 3

CARBON DIOXIDE CAPTURE AND SEQUESTRATION TECHNOLOGIES

CCS is the acronym of Carbon Capture and Sequestration, which is a set of technologies that allow:

1. Capture of CO_2 where it's emitted, especially industrial plants also defined as *emission-intensive*[8];
2. Transport of the fluid produced in first phase, after compression;
3. Permanent storage in suitable sites.

The birth of the underlying technologies is not recent; however, they have never been applied completely on a commercial scale with the aim of reducing CO_2 emissions.
CCS can be applied mainly to processes that represent a localized source of significant amount of CO_2 emissions. Among them, production process of cement which exploits both fossil fuels and limestone and steel production process, which instead uses coke, limestone and fossil fuels.

3.1 CO_2 capture

The main purpose is to extract the CO_2 present in the gas mixture involved upstream or downstream in combustion processes.
The product of this first phase is a concentrated stream of high pressure carbon dioxide, which can, then, be transported to storage site. In the same way, an insufficiently concentrated stream can be transported but costs related to transfer make the whole operation impracticable. Furthermore, the operation of the system may be compromised by the presence of impurities. Ultimately, the stream must be pure and concentrated.

3.1.1 Capture technologies

There are different ways to capture carbon dioxide; each mode is associated with a specific technique for separating the gaseous fluid.
Let's focus on the analysis of a power plants based on fossil fuels.

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[8] Emission sources having a high average emission rate for a specific pollutant.

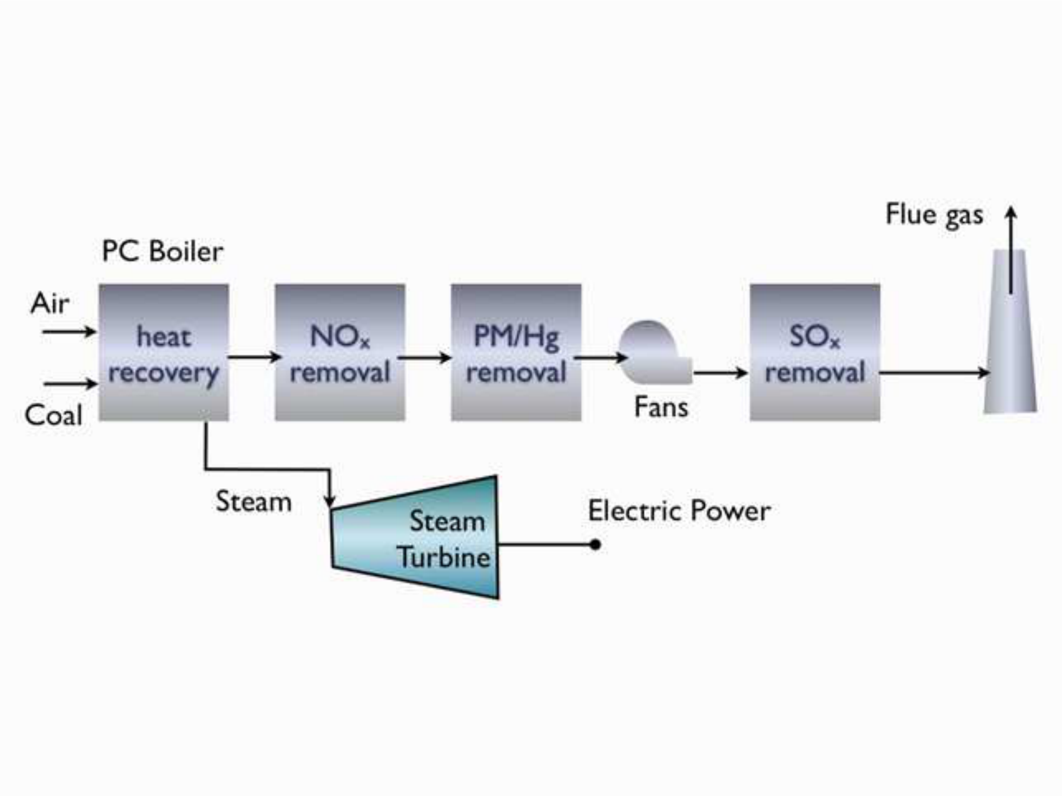

Figure 2.1: Schematic Illustration of a coal-fired plant.
(Source: Smith et al. 2014)

Steam generation occurs through mixture of fuel and air, which give rise to the combustion process.

The resulting heat is transferred to the fluid, which is then transformed into steam. The latter then is led to a turbine in which it evolves, lowering its enthalpy, producing mechanical work only which is converted into electricity.

Within the fuel, elements mainly involved in this process are carbon and hydrogen; however, there are other substances, such as nitrogen, sulphur and some metals, present in lower quantities. Resulting impurities must be removed before the gaseous fluid is released into the atmosphere, in accordance with current regulations. In particular, NO_x, SO_x and various heavy metals are removed in order to reduce the environmental impact of these pollutants.

The abatement of these substances is costly both from the economic and energetic point of view. In this context, capture of carbon dioxide takes on a primary role and is described below.

Post-combustion capture

The first technique, defined as post-combustion capture, occurs downstream to the process. Instead of being discharged directly into the atmosphere, the flue gas is passed through equipment which separates most of the CO_2 with the use of a liquid solvent. CO_2 is then fed to a storage reservoir and the remaining flue gas is discharged to the atmosphere. A chemical sorbent process would normally be used for CO_2 separation. Besides industrial applications, the main power plants where this technology is feasible are coal, oil and natural gas power plants, supercritical pulverized coal fired plants (PC or PF) and natural gas combined cycle power plants (NGCC), where in the last two cases an organic solvent such as monoethanolamine (MEA) is used.

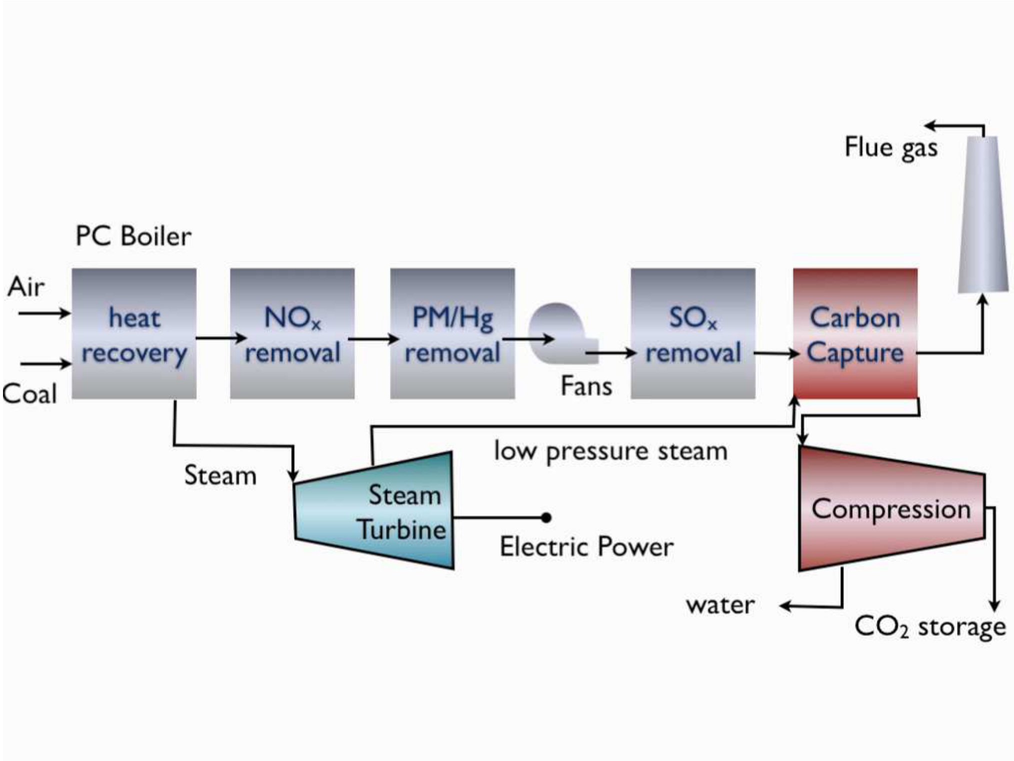

Figure 2.2: Post combustion capture in a thermoelectric power plant. (Source: Smith et al. 2014)

Post-combustion systems present also critical issues like large volumes of combustible gas to be treated, making difficult the application in case of retrofitting, CO_2 dilution in combustible gases (in steam systems 10-15% in volume for GT and 5-7% for NGCC, given the high excess of air), presence of impurities in fumes (PM, SO_2, NOx, etc.) resulting in loss of efficiency associated to separation process.

Pre-combustion capture

Pre-combustion capture occurs by decarbonising fossil fuel before combustion phase takes place. It involves reacting a fuel with oxygen or air and/or steam to give mainly a synthesis gas named also ‘syngas’, a fuel gas composed by hydrogen and carbon monoxide.

Carbon monoxide is then reacted with steam in a catalytic reactor called shift converter, to give CO_2 and more hydrogen. CO_2 is successively separated, usually by a physical or chemical absorption process, resulting in a fuel rich of hydrogen which can be used in different applications such as boilers, furnaces, gas turbines, engines and fuel cells. These systems are considered to be strategically important and power plants of reference today are 4 GW_e of both oil and coal based integrated gasification combined cycles (IGCC) which are around 0.1% of total installed capacity worldwide and require always an additional component for separating O_2 from air (IPCC, 2005). Regarding other reference systems are represented by natural gas, oil and coal based syngas/hydrogen production facilities.

Despite the process being more elaborated, there are two benefit factors such as the high concentration of CO_2 (from 15% to 60% in volume) in the flow generated by reactor and high pressures used. Therefore, the whole technology entails less costs related to capture and transportation of CO_2.

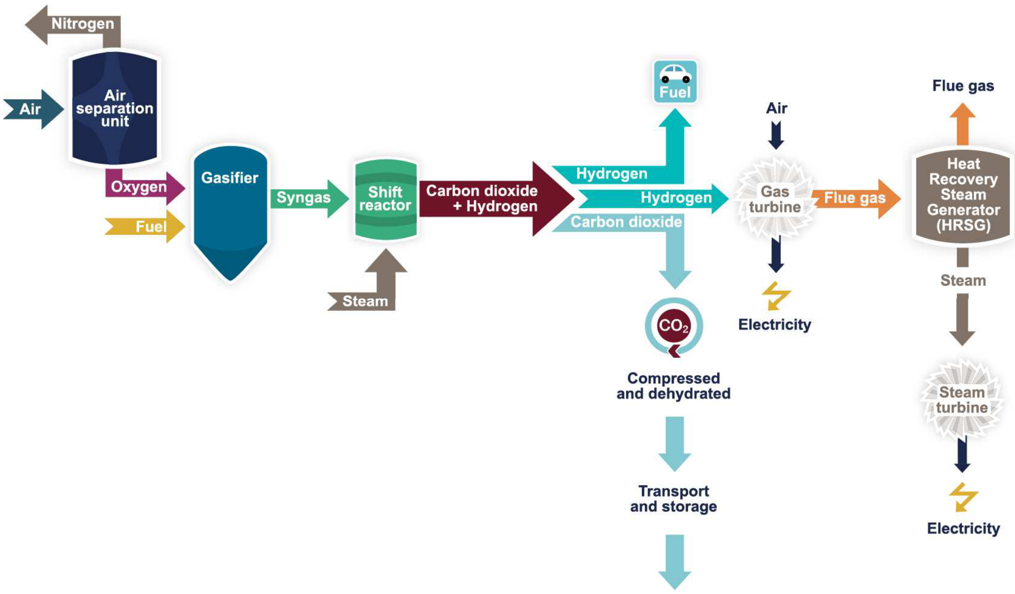

Figure 3.3: IGCC capture system (Source:www.zeroemissionsplatform.eu)

Other capture technologies include: oxy-fuel combustion and chemical looping.

Oxy-fuel combustion capture

In oxy-fuel combustion, nearly pure oxygen is used for combustion instead of air, resulting in a flue gas that is mainly CO_2 and H_2O. If fuel is burnt in pure oxygen, the flame temperature is excessively high, but CO_2 and/or H_2O rich flue gas can be recycled to the combustor to moderate this effect.

Oxygen is usually produced by low temperature (cryogenic) air separation in the Air Separating Unit (ASU) and novel techniques to supply oxygen to the fuel, such as membranes and chemical looping cycles are being developed.

Another problem in coal fired plants is the presence of a boiler that does not have a selective catalytic reactor[9] able to control NO_x emissions. Power plant systems of reference for oxy-fuel combustion capture systems are the same as those noted for post combustion capture systems. However, appealing to this technology is limited by the considerable energy consumption associated with cryogenic air separation section and lack of exercise experience.
Up to now, oxy-fuel combustion, for electric power purposes, has only been demonstrated on a scale of less than 10 MWe (Smit et al. 2014).

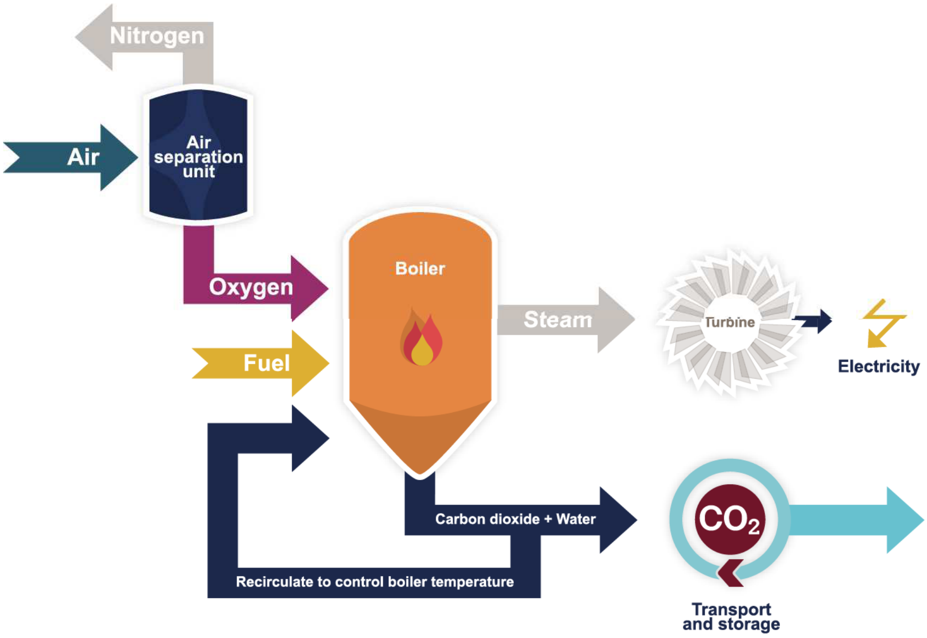

Figure 3.4: Oxy-fuel combustion capture system. (Source: www.zeroemissionsplatform.eu)

Chemical Looping

Chemical Looping is a novel technology that could provide the means to convert fossil fuels into electricity without significant efficiency or cost penalties. It consists of an air reactor and a fuel reactor. Usually these reactors consist of interconnected fluidized beds. An oxygen carrier is circulated between the two reactors. This oxygen carrier is made up of a metal that is easily oxidized such as Fe, Ni or Cu. In the air reactor Me (metal) is entrained in a fluidized bed with air as the fluidizing agent.

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[9] The selective catalytic reactor is a commonly used device for the removal of nitrogen oxides.

At an elevated temperature (around 700 to 900 ºC) Me reacts with oxygen in an exothermic reaction producing MeO.
MeO is then separated from N_2 and transported to the fuel reactor, where it reacts with a hydrocarbon fuel to produce CO_2 and H_2O while reducing MeO to Me. Then Me is transported back to the air reactor to repeat the process.

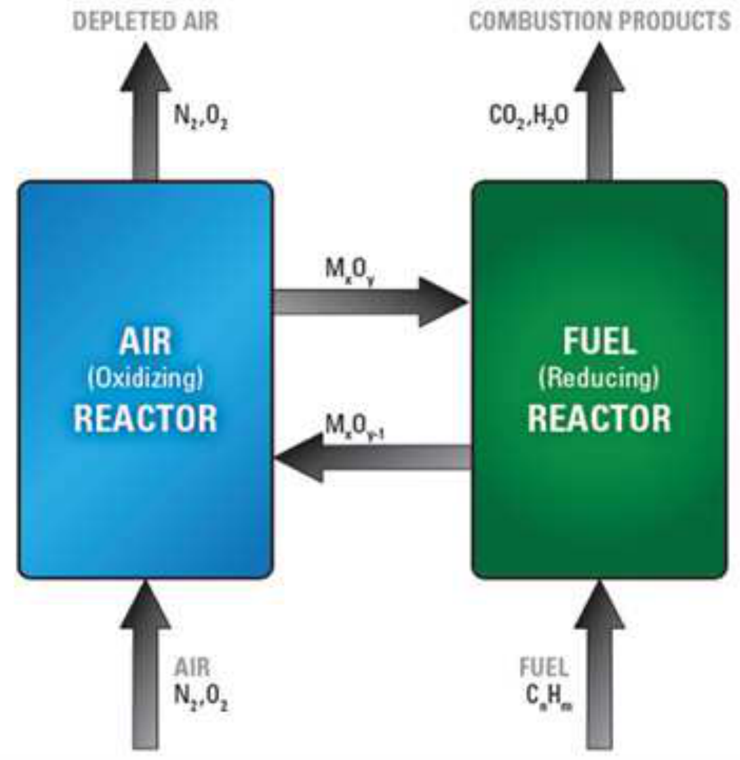

Figure 3.5: Chemical Looping capture system

3.2 Technologies for CO_2 separation

With exception for oxy-combustion processes, in which CO_2 is separated through simple condensation of vapour present in the exhaust, the other approaches considered imply separation of carbon dioxide from a gaseous stream.
Among them the most interesting ones are:

- Chemical or physical absorption;
- Membrane separation;
- Pressure swing adsorption, PSA;
- Cryogenic fractionation.

3.2.1 Chemical or physical absorption

Absorption technologies through liquid solvents of various nature are the most effective solution. The interaction between solvent and carbon dioxide refers to chemical or physical absorption processes. Choice is generally associated with partial pressure of CO_2. In fact, if this is low, chemical absorption is preferred, otherwise physical absorption performs better.

The first one is applied to fossil-fuel power plants where separation of carbon dioxide is carried out on combustion products, which are at atmospheric pressure and at temperatures above 90-100 °C, due to a treatment for removal of polluting compounds. Gases are sent to a blower to overcome load losses in the system and then cooled to process temperature, which is determined by the solvent used.

In the absorption column, carbon dioxide chemically binds to solvent through acid-base reactions. Most common solvent used is monoethanolamine. Temperature within the absorber could reach 40-60 °C. Other components of the gaseous stream leave the absorbent while CO_2 “rich” solvent is sent to the desorber, where CO_2 release occurs by thermal stripping, or breaking up of previously formed chemical bonds, at a temperature of about 120 °C. “Poor” solvent is instead sent back to the absorbent, passing through a heat exchanger which preheat the “rich” one. Process efficiency through amines, given by the ratio between energy used and energy produced, is very high and is equal to 85%-95%.

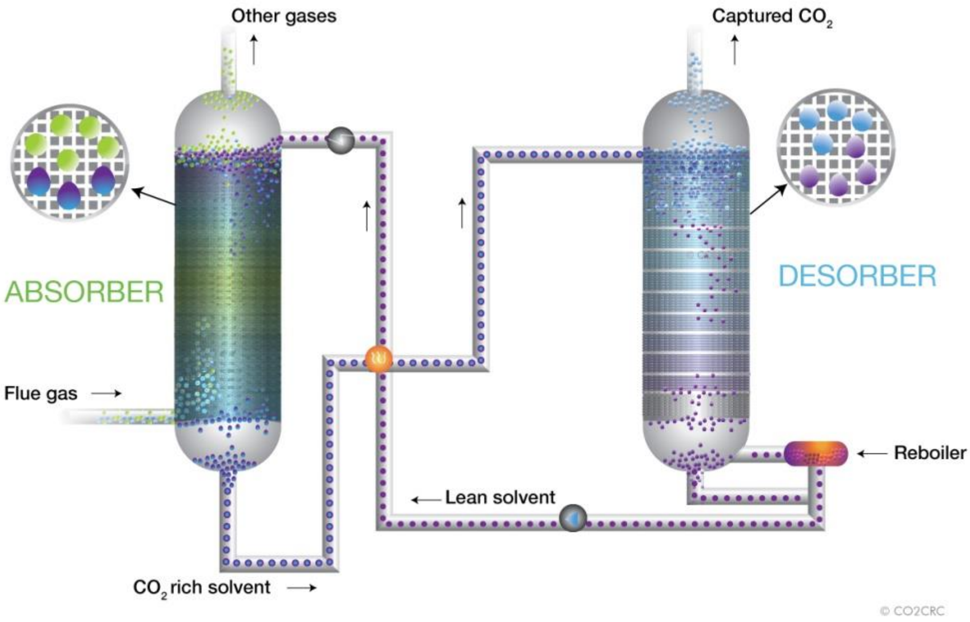

Figure 3.6: Chemical absorption system (Source: CO2RC)

CO_2 pre-combustion separation from syngas typically operates at high pressures. In such conditions, separation processes through physical absorption on liquid solvents are effective. CO_2 is separated by contacting the gas to be treated, at high pressure, with an absorbent solution generally formed by solvents such as methanol, dimethyl ether, polyethylene glycol and others.

Solvent regeneration occurs as a result of pressure reductions, with still a high energy consumption but lower than chemical processes.

Syngas enters the absorbing column and flows in counter current with the solvent. From column purified gas comes while rich solution is extracted and sent into a series of decompression chambers where CO_2 separates. Increasing pressure and decreasing temperature, solubility of CO_2 in the solvent increases. From last chamber, operating at a pressure close to atmospheric one, the solution is returned to the absorption column by means of a pressurization pump. Physical absorption process achieves efficiencies up to 90% or even higher.

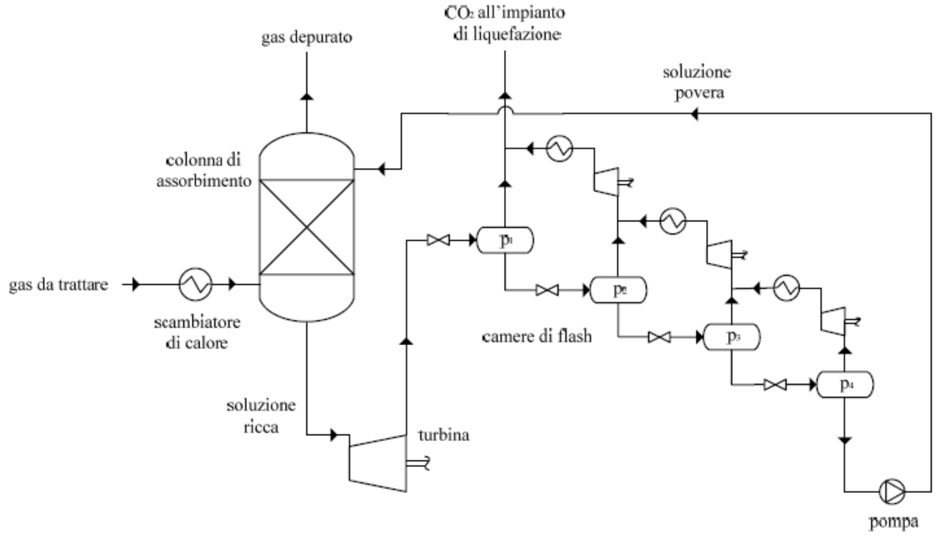

Figure 3.7: Physical absorption system (Source: CO2RC)

3.2.2 Membrane separation

Membrane separation process is particularly simple and does not involve significant energy input. This technology is based on the use of materials which allow retention of a gas through a permeable surface by means of pressure difference on the two sides of the membrane itself. Currently, treatment of gas currents with membranes is already used at industrial level in various processes, including air separation, hydrogen separation.

For what concerns thermoelectric power plants, different types of membranes, such as polymeric or ceramic ones, are in development. These can be used for CO_2 separation from a gaseous stream both upstream and downstream of combustion. One of the main difficulties is the need to identify structures and materials that are sufficiently resistant from the mechanical and chemical point of view.

Two distinct approaches characterize this technology: membrane gas absorption and gas separation membrane.

In the first one, the membrane separates gaseous mixture from a liquid solvent, CO_2, if modest, filters through its pores, is absorbed by solvent and then is removed.

In the second one, the membrane acts as a semi-permeable barrier therefore selective with respect to CO_2. The advantage, in this case, lies in smaller dimensions of equipment involved and absence of solvents.

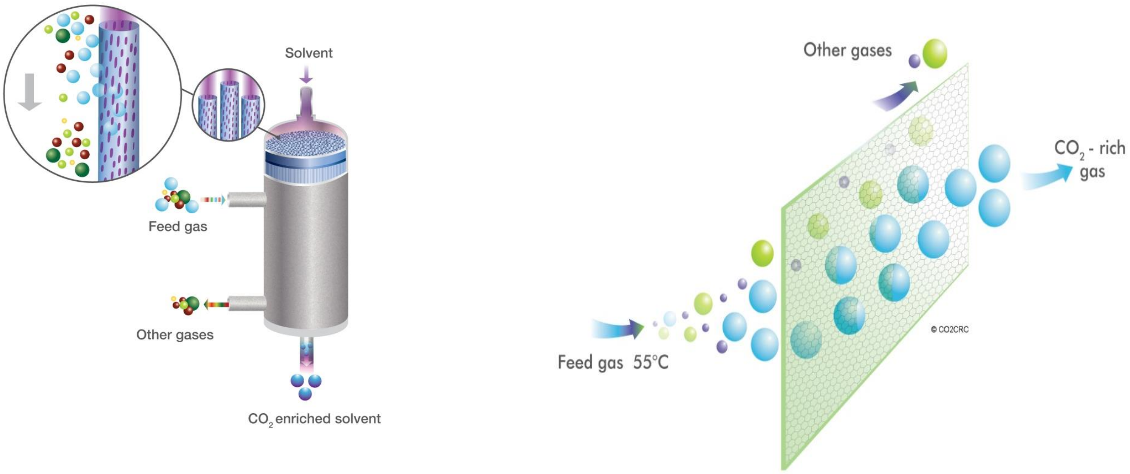

Figure 3.8: Membrane gas absorption and gas separation membrane approaches (Source: CO2RC)

3.2.3 Pressure swing adsorption

Adsorption is the name of a spontaneous attraction phenomenon that a fluid-phase molecule experiences when it is near the surface of a solid. This technology is potentially the most effective one as it is less energy-intensive, cheaper and involves less environmental impact. Adsorbents are normally solid or zeolite[10] materials, which can adsorb CO_2 on their surface. CO_2 can be subsequently released by pressure or temperature variations. Pressure swing adsorption is the most developed technology; in this case, carbon dioxide is released by pressure drop. Materials involved, operate at elevated temperatures up to 250 ºC and this results in a reduction in costs, eliminating the need for cooling of the syngas in separation by fuel decarbonisation.

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[10] Zeolites are minerals with a regular crystalline structure and microporous characterized by a huge amount of empty volumes inside the crystals, which acts as a "molecular sieve".

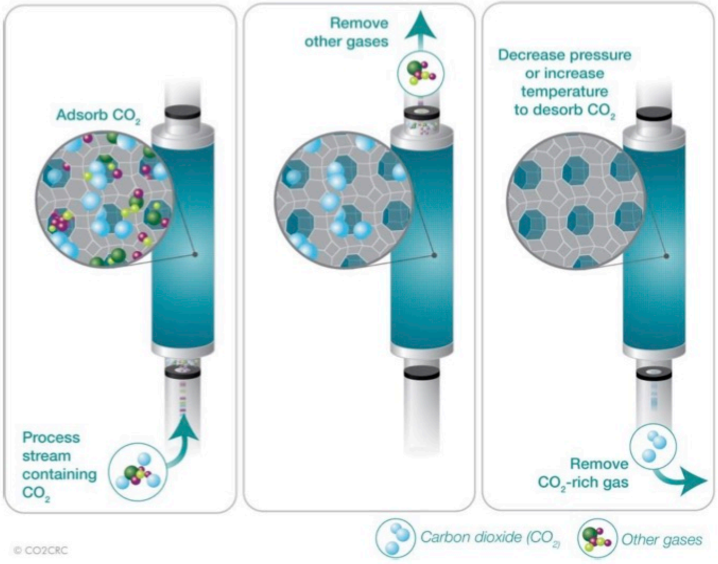


Figure 3.9: Pressure swing adsorption (Source: CO2RC)

3.2.4 Cryogenic fractionation

The very large quantities of oxygen required for CO_2 capture can only be economically produced, at present, by using the established process of oxygen separation from air by distillation at cryogenic temperatures. In a typical cryogenic air separation plant, air is compressed to a pressure of 0.5 to 0.6 MPa and purified to remove water, CO_2, N_2O and hydrocarbons.

Two or more switching fixed bed adsorbers are used, which can be regenerated by either pressure swing or temperature, using a low pressure waste nitrogen stream. The air is cooled against returning products in a battery of aluminium plate-fin heat exchangers and separated into pure oxygen and nitrogen fractions in a double distillation column. Oxygen can be pumped as liquid and delivered as a high pressure gas at up to 10 MPa. In a pumped cycle, a high pressure air booster compressor provides a means of efficiently vaporizing and heating the liquid oxygen stream to ambient temperature. Typical power consumption for the delivery of 95% O_2 at low pressure is 200 to 240 kWh/tO2. Numerous process cycle variations particularly for the production of oxygen at less than 97.5% purity have been developed to reduce power and capital cost (CASTLE, 2002).

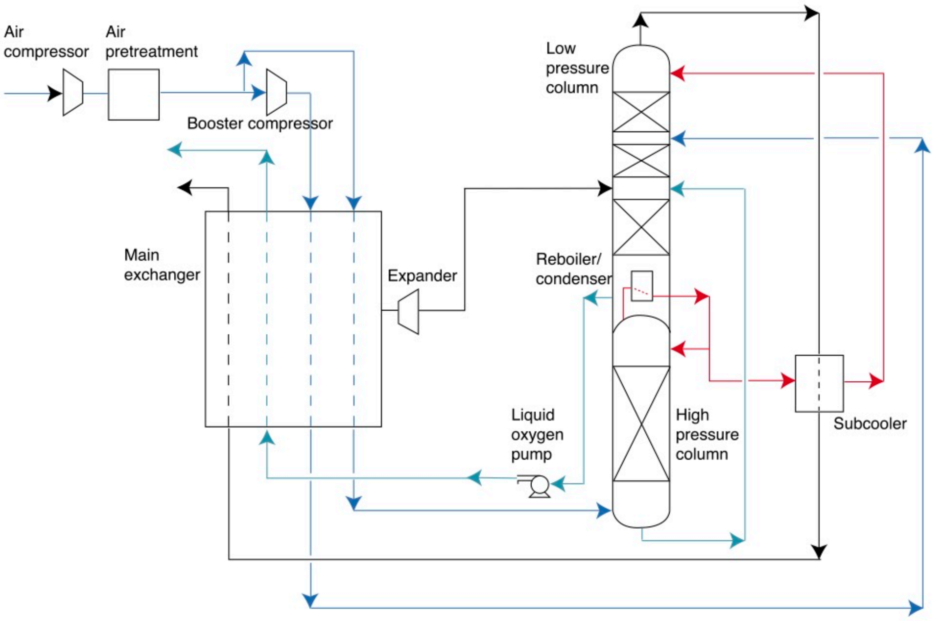


Figure 3.10: Cryogenic oxygen production

3.3 Compression

Geological confinement of CO_2 always requires a compressed (possibly liquefied) and dehydrated stream, in order to reduce its volume. Moreover, in almost all cases, carbon dioxide confinement site does not correspond to the production area, where the power plant is located. Carbon dioxide, separated from syngas or combustion fumes, must be generally liquefied to facilitate transport and subsequent confinement, and dehydrated, in order to avoid the formation of weak acids.

Liquefaction and dehydration are obtained through a compression in several stages. End compression pressure is typically higher than 8 MPa. To reduce energy demand, the entire compression phase is divided into several stages, each followed by an inter-cooler which returns gas temperature to values close to the ambient (typically about 35 °C in early stages up to 20 °C in final stages).

Upstream of the penultimate compression stage a complete dehydration is carried out to prevent corrosion in transport ducts. It is important to emphasize that compression of CO_2 involves a high absorption of electricity, which contributes to a reduction in the overall performance of the plant.

3.4 Transport of CO_2

CO_2 is transported in three states: gas, liquid and solid. Commercial scale transport uses tanks, pipelines and ships for gaseous and liquid carbon dioxide.

Gas transported at close to atmospheric pressure occupies such a large volume that very large facilities are needed. Gas occupies less volume if it's compressed, and compressed gas is transported by pipeline. Volume can be further reduced by liquefaction, solidification or hydration. Liquefaction is an established technology for gas transport by ships as LPG (liquefied petroleum gas) and LNG (liquefied natural gas). This existing technology can be transferred to liquid CO_2 transport. Solidification needs much more energy compared with other options, and is inferior from a cost and energy viewpoint. In pipeline transportation, the volume is reduced by transporting at a high pressure, which is between 10 and 80 MPa.

A transportation infrastructure that carries carbon dioxide in large enough quantities to make a significant contribution to climate change mitigation will require a large network of pipelines. The most economical carbon dioxide capture systems appear to favour CO_2 capture, first, from pure stream sources such as hydrogen reformers and chemical plants, and then from centralized power plants. A regulatory framework will need to emerge for the low-greenhouse-gas-emissions power industry of the future to guide investment decisions. Future power plant owners may find carbon dioxide transport component one of the leading issues in their decision making.

3.4.1 Pipeline transportation systems

CO_2 pipelines connect a variety of sinks and sources with each other. The most common CO_2 sources are gas processing plants, fossil fuelled power stations and natural sources of CO_2. Common sinks are oil fields for EOR, but also depleted oil and gas fields are used. Purity of CO_2 stream depends on CO_2 source and CO_2 capture technology. The physical characteristics of CO_2 pipelines vary greatly, in fact, the range in length lies between 1.9 and 808 km. The longest pipelines are located in north America and the average length is longer than Europe. Another interesting point is a correlation between length and capacity of pipelines; longer pipelines have to transport larger volumes of CO_2 to be economically viable.

CO_2 pipelines are comparable to natural gas pipelines but there are key differences:

1) Properties of CO_2 lead to different design parameters;
2) Do not transport a product that people see as beneficial;
3) Risks associated with geological storage.

In contrast to natural gas, high pressure CO_2 pipelines are not self-arresting in terms of longitudinal failure and thus require installation of crack arrestors which are joints of pipe with greater wall thickness and improved hoop-stress properties.

Re- purposing a pipeline for CO_2 use can drastically reduce overall CCS project costs. As long as the initial design can support the pressures, volumes, compositions and design operating parameters required in CO_2 service, there is every reason to re-use the line.

Two areas where existing pipeline are commonly reused are offshore where pipeline costs are high and in onshore acid gas re-injection (a mixture of CO_2 and H_2S is injected into an aquifer or into a depleted gas reservoir). Most CO_2 pipelines are buried under the ground, so they need both internal and external corrosion protection. To prevent external corrosion most commonly used method is cathodic protection, sometimes in combination with coating. For internal corrosion water is the main risk factor and pipeline operator aims to keep water content as low as possible. A dehydration system is used to control water content in the CO_2 stream.

3.4.2 Ships for CO_2 transportation

Carbon dioxide is continuously captured at the plant on land, but the cycle of ship transport is discrete, and so a marine transportation system includes temporary storage on land and a loading facility. The capacity, service speed, number of ships and shipping schedule will be planned, taking into consideration the capture of CO_2, transport distance and social and technical restrictions. This issue is, of course, not specific to the case of CO_2 transport; CO_2 transportation by ship has a number of similarities to liquefied petroleum gas (LPG) transportation by ship.

What happens at the delivery point depends on the CO_2 storage system. If the delivery point is onshore, carbon dioxide is unloaded from the ships into temporary storage tanks. If the delivery point is offshore, as in the ocean storage option, ships might unload to a platform, to a floating storage facility (similar to a floating production and storage facility routinely applied to offshore petroleum production), to a single-buoy mooring or directly to a storage system. Naval units, having small dimensions, do not allow large amounts of carbon dioxide to be transported easily. This makes difficult system implementation.

3.5 Storage mechanisms

It represents the third and final stage of Carbon Capture and Sequestration chain (CCS). This phase consists of carbon dioxide injection into underground geological formations. The options identified to permanently confine CO_2 are:

1. Geological storage (ex. Depleted oil, gas or coal deposits, high depth salt formations, etc.);
2. Mineral carbonation;
3. Storage in ocean depths;
4. Use in industrial processes.

These mechanisms are carefully monitored from the very beginning of the site selection to the closure of injection well.

3.5.1 Geological storage

Geological storage involves injection of CO_2 at underground depths over 800m, where it is in supercritical conditions (31.1 ºC and 7.38 MPa) and has a density 500-600 times greater than that at the surface (it can reach densities greater than 700 kg/m^3). In fact, pressure increases by about 0.1 bar/m deep, and if we consider injecting CO_2 at 3 km depth, we would expect 300 kg/m^3 density, at 200 bars and 60 ºC.

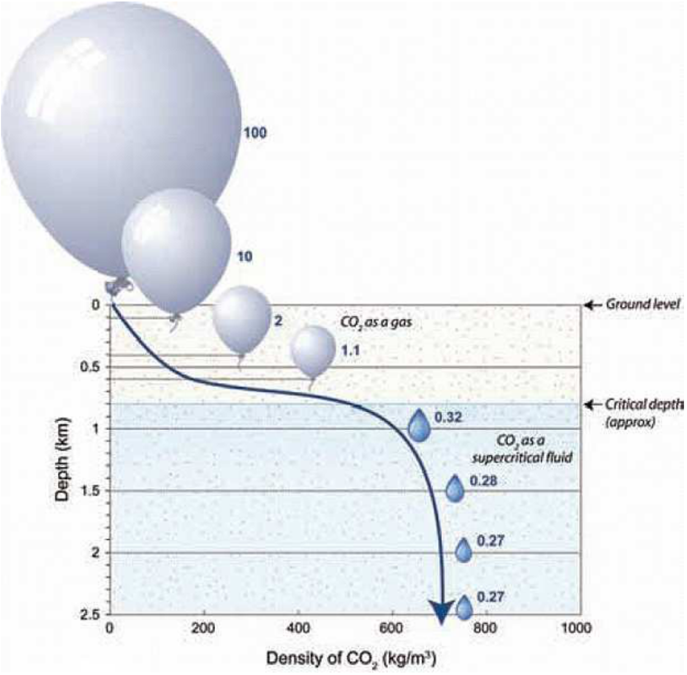


Figure 3.11: Density of CO_2 as depth increases

Injection of fluids into deep geological formations is achieved by pumping fluids down into a well. The part of the well in the storage zone is either perforated or covered with a permeable screen to enable CO_2 to enter the formation. The perforated or screened interval is usually on the order of 10-100 m thick, depending on the permeability and thickness of the formation.

Injection increases pressure near the well, allowing CO_2 to enter the pore spaces initially occupied by the *in situ* formation fluids. Even this operation, like previous ones, requires energy expenditure, but costs are unreasonable.

A geological storage site should have adequate capacity, good isolation from surrounding environment, and a geological condition which guarantees its integrity over time. Different types of sites can be identified.

Porous rock formations (both onshore and offshore), which hold fluid, are potential candidates. Unprofitable coal mines, with sufficient permeability, offer a further confinement opportunity, even though they are still under experimentation. In the case of oil or gas, most of the volume occupied by in situ fluid can be replaced by CO_2, while in the case of salt formations the potentially available volume is less than 30% of total volume. Carbon dioxide actually confined to the long term depends on a number of a physical and geochemical mechanisms.

Abandoned oil and gas fields

Depleted oil and gas reservoirs are prime candidates for CO_2 storage for several reasons. First, the oil and gas which originally accumulated in traps (structural and stratigraphic) did not escape (in some cases for many millions of years), demonstrating their integrity and safety. Second, the geological structure and physical properties of most oil and gas fields have been extensively studied and characterized. Third, computer models have been developed in the oil and gas industry to predict the movement, displacement behaviour and trapping hydrocarbons. Finally, some of the infrastructure and wells already in place, may be used for handling CO_2 storage operations. The capacity of a reservoir will be limited by the need to avoid overpressures that damage the caprock.

Enhanced Oil Recovery

Oil production is separated into three phases: primary, secondary and tertiary, which is also known as enhanced oil recovery (EOR). Primary oil recovery is limited to hydrocarbons that naturally rise to the surface, or with artificial devices such as pump jacks. Secondary recovery employs water and gas injection, displacing oil and driving it to the surface. According to the US Department of Energy, utilizing these two methods of production can leave up to 75% of the oil in the well. The way to further increase oil production is through tertiary recovery method or EOR. Used in fields which exhibit heavy oil, poor permeability and irregular fault lines, EOR entails changing actual properties of hydrocarbons. While waterflooding and gas injection, during the secondary recovery method, are used to push the oil through the well, EOR applies steam or gas to change the makeup of the reservoir, restoring formation pressure and enhancing oil displacement. There are three main types of EOR, including chemical flooding, gas injection and thermal recovery. Chemical flooding helps to free trapped oil within the reservoir. This method introduces long-chained molecules called polymers to increase efficiency of waterflooding or to boost the effectiveness of surfactants which are cleansers that help lower surface tension to inhibit flow of oil through reservoir.

Gas injection involves injecting natural gas, nitrogen or carbon dioxide into the reservoir. Gases can either expand and push gases through reservoir or mix with or dissolve within the oil, decreasing viscosity and increasing flow.

Thermal recovery introduces heat into reservoir to reduce viscosity of the oil. Many times, steam is applied to the reservoir in order to thin the oil and enhance its ability to flow. It accounts now for more than 50% of applied EOR in the US.

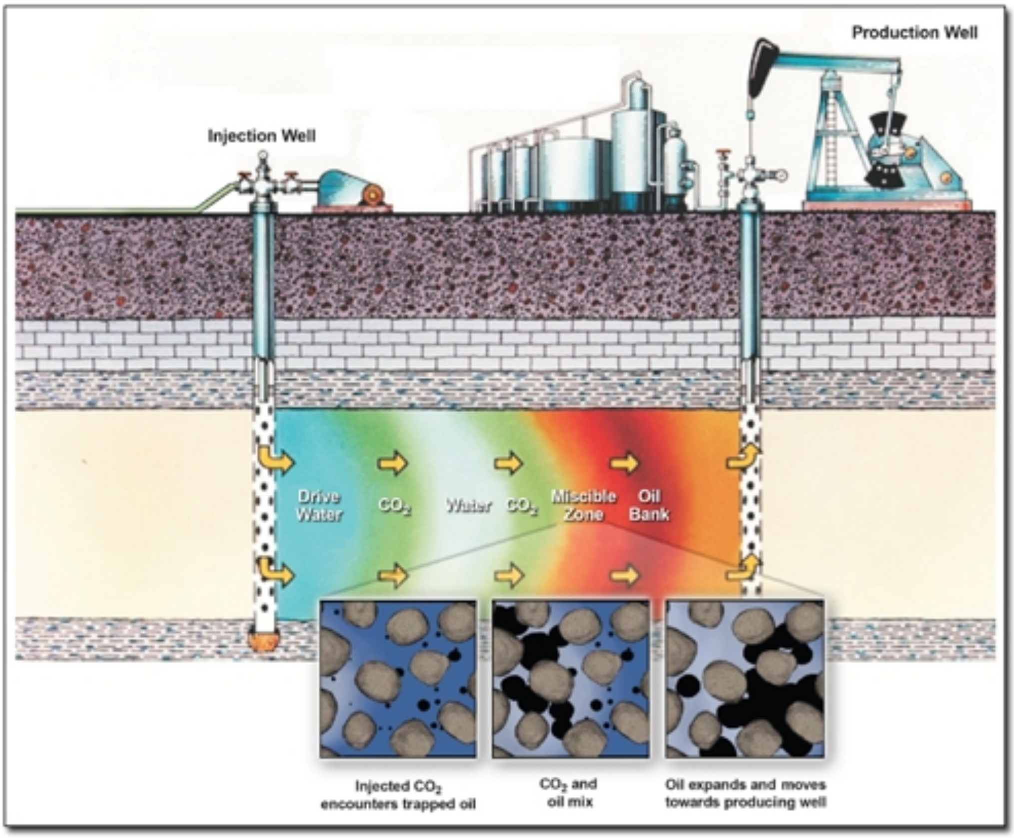


Figure 3.12: Enhanced oil recovery

Enhanced Gas Recovery

As well as EOR, EGR consists in the injection of CO_2 into natural gas reservoirs with the aim of increasing its production by pressurizing the site. The main difference lies in the fact that depleted gas field has a higher storage capacity due to larger sizes and a higher recovery factor (between 25-65%, sometimes even greater than 80%) against a value lower than 5% in case of oil. CO_2 flows through the wells, thanks to the existing pressure gradient, expand and being thicker tends to flow down by shifting methane already present in the formation.

Enhanced Coal Bed Methane

Enhanced Coal Bed Methane consists of the geological confinement of CO_2 in untreated coal beds, resulting in the release of methane present in the mineral structure itself. Methane, present in coal deposits, naturally liberates by simply depressurizing the carbon vein through extraction of water present therein. In this way recovery is represented by a percentage of methane typically ranging from 20% to 60%.

This technique is based on the injection of CO_2 into deep carbon layers and allow to extract methane, with the advantage of achieving carbon sink confinement in layers difficult to exploit. ECBM technique has clear advantages over those relying on the use of other storage environments (mainly petroleum and natural gas) since coal deposits are present on every continent and affect about two thirds of the planet. Experience, gained so far, has allowed us to define a set of criteria for selecting the ideal site for ECBM application. In particular, the features of ideal site can be summarized as follows:

- homogeneity and isolation, the coal reservoir should be laterally continuous and stratigraphically isolated in order to contain injected CO_2 and obtain an efficient gas distribution;
- confinement, coal beds must be contained between layers of waterproof rocks;
- simple structure, coal veins should have minimum number of creases and folds;
- coal geometry;
- GIP (gas in place) saturation conditions for better performance in extracting CH_4;
- Adequate primary permeability (inside coal) and secondary (clamps and microdiscontinuities) to obtain an effective ECBM production.

3.5.2 Mineral carbonation

Mineral carbonation is based on the reaction of CO_2 with metal oxide bearing materials to form insoluble carbonates, with calcium and magnesium being the most attractive metals. In nature such reaction is called silicate weathering and takes place on a geological time scale. It involves naturally occurring silicates as the source of alkaline and alkaline-earth metals, MgO or CaO, and consumes atmospheric CO_2. Suitable materials may be abundant silicate rocks, serpentine and olivine minerals. In the case of silicate rocks, carbonation can be carried out either ex-situ in a chemical processing plant after mining and pretreating the silicates, or in-situ, by injecting CO_2 in silicate-rich geological formations or in alkaline aquifers.

This kind of confinement is essentially permanent, with substantially zero risks. This is a very costly process from an energy point of view and with a strong environmental impact; an increase of 60% to 180% of primary energy requires in a thermoelectric power plant was estimated.

Saline formations

Saline formations are deep sedimentary rocks saturated with formation waters or bines containing high concentrations of dissolved salts. These formations are widespread and contain enormous quantities of water, but are unsuitable for agriculture or human consumption. Saline brines are used locally by the chemical industry and formation waters of varying salinity are used in health spas and for producing low enthalpy geothermal energy. It has been suggested that combined geological storage and geothermal energy may be feasible, but regions with good geothermal energy potential are generally less favourable for CO_2 geological storage because of the high degree of faulting and fracturing and the sharp increase of temperature with depth.

3.5.3 Storage in ocean depths

Water storage requires injection of CO_2 directly into depths over 1000 m, where it can be confined for hundreds of years. Possible environmental risks associated with this practice include harmful effects on marine organisms, pH variations. In fact, in the case of 3000 m injection of a quantity CO_2 equal to 10% of the amount needed to confine and stabilize its concentration in the atmosphere at 550 ppmv, models show that acidity would increase of 0.4 to 1% of total volume.

3.5.4 Use in industrial processes

Industrial uses of CO_2 include chemical and biological processes where CO_2 is a reactant, such as those used in urea and methanol production, as well as various technological applications that use CO_2 directly, for example in the horticulture industry, refrigeration, food packaging, welding, beverages and fire extinguishers. Currently, CO_2 is used at a rate of approximately 120 $MtCO_2$ per year worldwide.

Most is used to produce urea, which is used in the manufacture of fertilizers and other products. Some of CO_2 is extracted from natural wells, and some originates from industrial sources, mainly high concentration sources such as ammonia and hydrogen production plants, that capture CO_2 as part of the production process. Industrial uses of carbon dioxide can contribute to keep CO_2 out of the atmosphere by storing it in the "carbon chemical pool" (stock of carbon bearing manufactured products). Typical lifetime of most CO_2 currently used by industrial processes has storage times of only days to months. The stored carbon is then degraded to CO_2 and again emitted to the atmosphere. Such short time scales do not contribute meaningfully to climate change mitigation. Another important question is whether industrial uses of CO_2 can result in an overall net reduction of CO_2 emissions. This can be evaluated correctly only by considering proper system boundaries for the energy and material balances of the CO_2 utilization processes, and by carrying out a detailed life-cycle analysis of the proposed use of CO_2. However, it can be concluded that the contribution of industrial uses of captured CO_2 to climate change mitigation is expected to be small.

3.6 Trapping mechanisms

The effectiveness of geological storage depends on a combination of physical and geochemical trapping mechanisms. The most effective storage sites are those where CO_2 is immobile because it is trapped permanently under a thick, low permeability seal or is converted to solid minerals or is adsorbed on the surfaces of coal micropores or through a combination of physical and chemical trapping mechanisms.

3.6.1 Physical trapping: stratigraphic and structural

Initially, physical trapping of CO_2 below low permeability seals (caprocks), such as very low permeability shale or salt beds, is the principal means to store CO_2 in geological formations. Sedimentary basins have much closed, physically bound traps or structures, which are occupied mainly by saline water, oil and gas. Structural traps include those formed by folded or fractured rocks. Faults can act as permeability barriers in some circumstances and as preferential pathways for fluid flow in other circumstances.

Stratigraphic traps are formed by changes in rock type caused by variation in the setting where the rocks were deposited. Both of these types of traps are suitable for CO_2 storage, although, care must be taken not to exceed the allowable overpressure to avoid fracturing the caprock or re-activating faults.

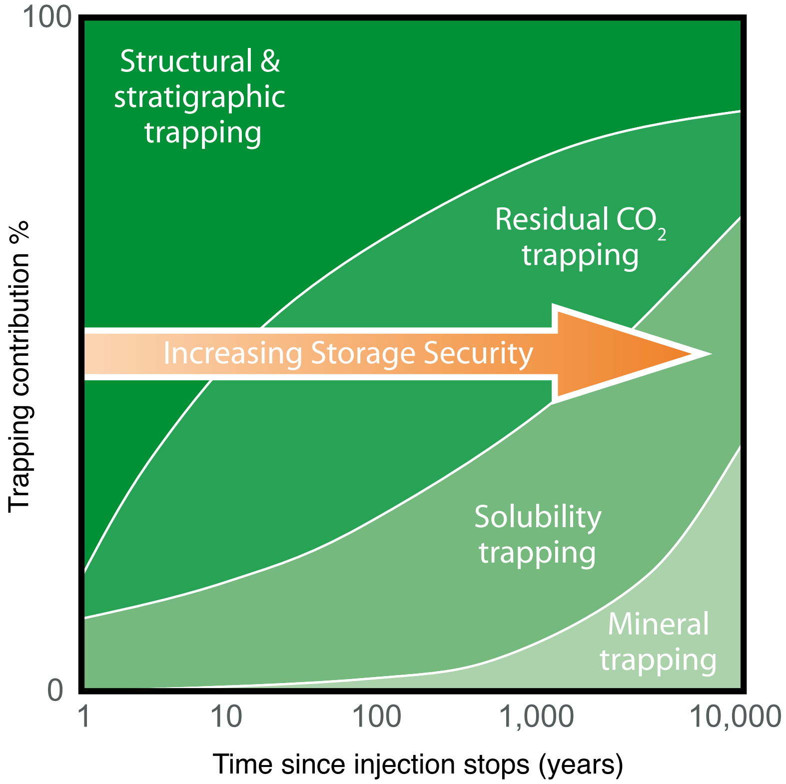


Figure 3.13: Trapping mechanisms over years

3.6.2 Physical trapping: hydrodynamic

Hydrodynamic trapping can occur in saline formations that do not have a closed trap, but where fluids migrate very slowly over long distances. When CO_2 is injected into a formation, it displaces saline formation water and then migrates buoyantly upwards, because it is less dense than water. When it reaches the top of the formation, it continues to migrate as a separate phase until it is trapped as residual CO_2 saturation or in local structural or stratigraphic traps within the sealing formation. In the longer term, significant quantities of CO_2 dissolve in the formation water and then migrate with the groundwater.

Where the distance from the deep injection site to the end of the overlying impermeable formation is hundreds of kilometres, the time scale for fluid to reach the surface from the deep basin can be millions of years.

3.6.3 Geochemical trapping

Carbon dioxide in the subsurface can undergo a sequence of geochemical interactions with the rock and formation water which will further increase storage capacity and effectiveness. First, when CO_2 dissolves in formation water, a process commonly called solubility trapping occurs. Primary benefit of solubility trapping is that once CO_2 is dissolved, it no longer exists as a separate phase, thereby eliminating the buoyant forces that drive it upwards. Next, it will form ionic species as the rock dissolves, accompanied by a rise in pH. Finally, some fraction may be converted to stable carbonate minerals (mineral trapping), the most permanent form of geological storage. Mineral trapping is believed to be comparatively slow, potentially taking a thousand years or longer. Nevertheless, the permanence of mineral storage, combined with the potentially large storage capacity present in some geological settings, makes this a desirable feature of long-term storage. Dissolution of CO_2 in formation waters can be represented by the chemical reaction:

$$CO\ (g) + H\ O \leftrightarrow \ H\ CO \leftrightarrow \ HCO^{\,-} + H^{+} \leftrightarrow \ CO^{\,2-} + 2H^{+}$$

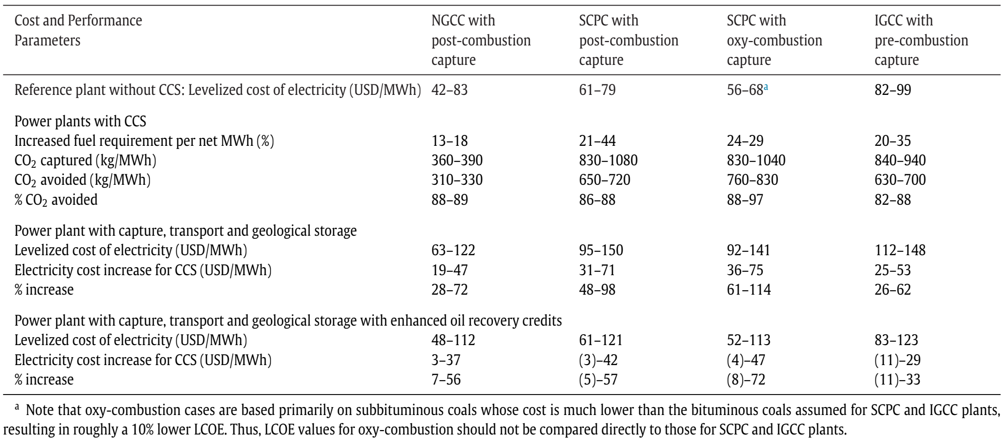
CO_2 solubility in formation water decreases as temperature and salinity increase. Dissolution is rapid when formation water and CO_2 share the same pore space, but once the formation fluid is saturated with CO_2, the rate slows and is controlled by diffusion and convection rates. CO_2 dissolved in water produces a weak acid, which reacts with the sodium and potassium basic silicate or calcium, magnesium and iron carbonate or silicate minerals in the reservoir or formation to form bicarbonate ions. Reaction of dissolved CO_2 with minerals can be rapid (days) in the case of some carbonate minerals, but slow (hundreds to thousands of years) in the case of silicate minerals.

3.7 Costs and economic potential

The stringency of future requirements for the control of greenhouse gas emissions and the expected costs of CCS systems will determine, to a large extent, the future deployment of CCS technologies relative to other greenhouse gas mitigation options. “Costs” refer only to market prices but do not include external costs such as environmental damages and broader societal costs. While some CCS components are already deployed in mature markets for certain industrial applications, it has still not been used in large-scale power plants. Literature reports a fairly wide range of costs for CCS components. The range is due primarily to the variability of site specific factors, especially the design, operating and financing characteristics of power plants or industrial facilities in which CCS is involved; type and costs of fuel used; required distances, terrains and quantities involved in CO_2 transport; type and characteristics of CO_2 storage. Uncertainty still remains about the performance and cost of current and future CCS technology components and integrated systems. In most CCS systems, the cost of capture, including compression, is the largest cost component. Costs of electricity and fuel vary considerably from country to country, and these factors influence economic viability of CCS options. In table T.1, components are combined to show total costs of CCS and electricity generation for four power systems with pipeline transport and two geological storage options. For the plants with geological storage and no EOR credit, the cost of CCS ranges from 0.02–0.05 US$/kWh for PC plants and 0.01–0.03 US$/kWh for NGCC plants (both employing post-combustion capture). For IGCC plants (using pre-combustion capture), the CCS cost ranges from

0.01–0.03 US$/kWh relative to a similar plant without CCS. For all electricity systems, the cost of CCS can be reduced by about 0.01–0.02 US$/kWh when using EOR with CO_2 storage because the EOR revenues partly compensate for the CCS costs (IPCC, 2006).

The largest cost reductions are seen for coal based plants, which capture the largest amounts of CO_2. When we analyze energy expenditure for CCS technology, we must be aware that energy output, associated with the plant, will be reduced by the amount needed to accomplish this task. To increase energy output, an increase in fuel is required, resulting in a rise in pollutant emissions. Along with energy costs, unit construction costs are also significant, accounting for about 50% of total cost.



Cost and Performance Parameters	NGCC with post-combustion capture	SCPC with post-combustion capture	SCPC with oxy-combustion capture	IGCC with pre-combustion capture
Reference plant without CCS: Levelized cost of electricity (USD/MWh)	42–83	61–79	56–68[a]	82–99
Power plants with CCS				
Increased fuel requirement per net MWh (%)	13–18	21–44	24–29	20–35
CO_2 captured (kg/MWh)	360–390	830–1080	830–1040	840–940
CO_2 avoided (kg/MWh)	310–330	650–720	760–830	630–700
% CO_2 avoided	88–89	86–88	88–97	82–88
Power plant with capture, transport and geological storage				
Levelized cost of electricity (USD/MWh)	63–122	95–150	92–141	112–148
Electricity cost increase for CCS (USD/MWh)	19–47	31–71	36–75	25–53
% increase	28–72	48–98	61–114	26–62
Power plant with capture, transport and geological storage with enhanced oil recovery credits				
Levelized cost of electricity (USD/MWh)	48–112	61–121	52–113	83–123
Electricity cost increase for CCS (USD/MWh)	3–37	(3)–42	(4)–47	(11)–29
% increase	7–56	(5)–57	(8)–72	(11)–33

[a] Note that oxy-combustion cases are based primarily on subbituminous coals whose cost is much lower than the bituminous coals assumed for SCPC and IGCC plants, resulting in roughly a 10% lower LCOE. Thus, LCOE values for oxy-combustion should not be compared directly to those for SCPC and IGCC plants.

Table T.1: Power plants performance and costs associated to different parameters (Source: International Journal of Greenhouse Gas Control, 2015)

Assessments of the economic potential of CCS are based on energy and economic models that study future CCS deployment and costs in the context of scenarios that achieve economically efficient, least cost paths to the stabilization of atmospheric CO_2 concentrations. Energy and economic models indicate that CCS systems are unlikely to contribute significantly to the mitigation of climate change unless deployed in the power sector. For this to happen, the price of carbon dioxide reductions would have to exceed 25-30 US$/kWh, or an equivalent limit on CO_2 emissions would have to be mandated.

	Net power output	**CO_2 captured**	**CO_2 emissions**	**Efficiency**		**Efficiency penalty for capture (LHV)**
				HHV	**LHV**	
	MW	kg/MWh	kg/MWh	%	%	% points
Pulverised coal						
No capture (reference plant)	1030	-	746	42.2	44.1	
Post combustion capture	822	840	93	33.6	35.2	8.9
Oxy-combustion	833	823	92	34.1	35.7	8.4
IGCC						
Shell, oxygen-blown	804	837	93	33.9	35.5	8.6
GE, oxygen-blown	874	844	94	33.3	34.9	9.2
MHI, air-blown	863	842	104	33.2	34.8	9.3

Table T.2: Power plants performance: an outline of efficiency and net power output for emitted CO_2 (Source: Davison et al., 2014)

Table T.2 gives an outline of efficiency and net power output for different power plants according to emitted CO_2. Capturing CO_2 requires energy and thus reduces the thermal efficiency of the plants. There are a number of factors which contribute to efficiency reductions for CO_2 capture, and they vary depending on the fuel and technology used for combustion. Considering post-combustion capture, the major source of energy reduction is the use of low pressure steam to regenerate the solvent. The oxy-combustion plant loses efficiency because of the electricity used by the oxygen production unit. For what concerns pre-combustion capture, instead, the loss is much smaller but the impact of the components for the production of the syngas is significant: in this case it is essential to optimize energy integration of the gasification island with the island of power. The efficiencies and CO_2 emissions of the plants with capture are all broadly similar and the difference between the highest and lowest efficiency is less than 1 percentage point. Future technology improvements, such as development of improved CO_2 capture solvents, gas turbines and air separation units, could change the relative efficiencies of the processes.

Chapter 4

BOUNDARY DAM CARBON CAPTURE PROJECT

The world's first commercial scale post-combustion coal fired carbon capture and storage project was started in September of 2014 at the SaskPower Boundary Dam Power Station in Estevan, Saskatchewan, Canada (IEAGHG, 2015). SaskPower is leading the way to make a viable technical, environmental and economic case for the continued use of coal. The $1.24 billion government industry partnership between the Government of Canada, Government of Saskatchewan, SaskPower and private industry saw the full integration of a rebuilt coal-fired generation unit with carbon capture technology into the operation of a commercial power station, resulting in low-emission electricity and carbon dioxide (CO_2) for enhanced oil recovery operations or storage in deep saline aquifers. This leading-edge project determined the technical, economic and environmental performance of carbon capture, utilization and storage (CCUS) technology. Saskatchewan has an estimated 300 years supply of coal. Lignite coal currently provides more than 50 per cent of provincial electricity. It is essential that SaskPower has these base load generators in the supply mix. However, doing so in today's operating environment requires meeting new standards to address emerging regulatory requirements, while satisfying environmental and economic demands.

4.1 About the power plant

Boundary Dam power station was built in stages starting in 1955. The plant contains a total of 6 coal fired units, two of which are retired; the remaining four produces approximately seven hundred and fifty megawatts. It's SaskPower largest generating plant.

The station is positioned around boundary reservoir and uses its water as coolant; that's why the reservoir is the only Saskatchewan embody of water that does not freeze in winter and why it's recognized as one of the best vision spot in Canada. Three hundred employees operate and maintain the station three hundred and sixty-five days a year. Unit 3 alone consumes over 800.000 tonnes of coal annually. Canadian federal regulations limit amount of carbon dioxide that can be released from a coal fired unit that is reaching the end of its useful life or fifty years of age. Unit 3 has been retrofitted with carbon capture technology and the turbine has been replaced; this will prolong its useful life by decades allowing to capture up to 90% of all pollutants which come from this unit. Just in terms of carbon dioxide, it is the equivalent of taking 250,000 vehicles off road every year. That's how SaskPower can continue to produce affordable electricity from coal but in a way that minimizes its impact on the environment. Rebuilding Unit 3 also meant

upgrading its controls to operate CCS equipped unit 3. SaskPower concept can be applicable on the majority of coal fired power stations around the world; that's a positive step in making coal sustainable for the future.
Ducting attached to unit 3 is what connects refurnished power plant to the newly build carbon capture facility: this sends flue gas off to have carbon dioxide and sulphur dioxide removed and repurposed.

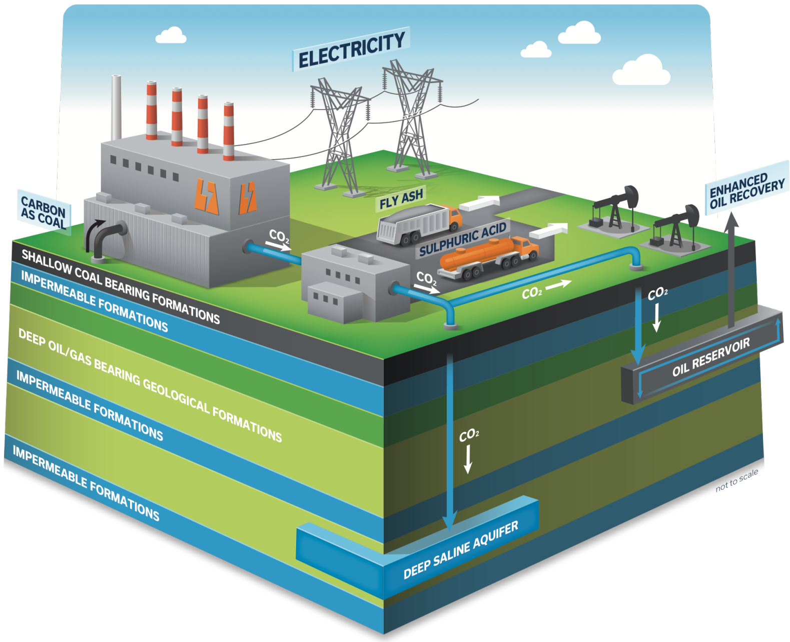


Figure 4.1: Boundary Dam Power Station
(Source: www.ieaghg.org)

4.2 CCS facility

Construction of the carbon capture facility began in 2011 after extensive feasibility studies. It came operative in 2014; in total, it took more than 1700 workers and more than 4.5 million hours of work to complete first discussed project. Operators are trained in a high-tech simulator on site which allows them to be fully ready to safely operate this first of its kind.

4.2.1 Carbon dioxide process and sulphur dioxide process

Following the absorption of carbon dioxide and sulphur dioxide from flue gas with two different amine solutions, the one with carbon dioxide is sent to the mass of CO_2 stripper, this is where CO_2 is released from amine and gas is formed. The absorber towers allow flue gas to enter and react with amine solvent; when the flue gas makes contact with amine, sulphur dioxide is first absorbed and flue gas continues to flow to the second carbon dioxide absorber where a different amine absorbs CO_2. From the exterior, you will see two absorber towers connected side by side. To ensure the concrete walls, 70,000 ceramic tiles are used inside the absorber. Ceramic tiles are also used on spatial to protect vessels from burning upon re-entering into the atmosphere. From there heat exchangers are used within the facility to heat up the amine before it's sent to the strippers. In this facility, the walls largest available plate type heat exchangers were installed to assist with the large amount of flue gas. The carbon dioxide stripper is a cylinder with large surface area where amine has further heat added and CO_2 is completely separated from it. CO_2 is then released and delivered through pipes to a smaller building next door for compression. With CO_2 removed, amine is sent to a complex filtration system that removes contaminants and recycles liquid solution. Amine can then go back for another round. Gas, which is poor of carbon dioxide, must now be prepared for transportation so that it does not enter the atmosphere.

CO_2 is sent to a compression system which takes it from a gas state and brings it to a pressure level at 250 pounds per square inch or 1.723 Mpa, about seventy times higher with respect to the pressure of a car tyre.

This compresses carbon dioxide into a liquid like state which is perfect for transportation through pipeline. Carbon dioxide pipeline leaves the CCS facility and goes deep underground in one of two ways: 1) stored in aquifers offsite 2) sold in the oil industry.

Oil industry uses CO_2 in a process called Enhanced Oil Recovery which helps increasing productivity in oil wells but also keeps carbon dioxide underground once operation is finished in a specific oil field. It can also be sent to SaskPower Carbon Storage and Research Center which stores it into deep rock formations permanently and safely 3.4 km underground. Injection well and underground storage are continually monitored as are all parts of the CO_2 pipeline coming out of Boundary Dam CCS facility.

Once the fuel gas from power plant is cooled, amine solution absorbs sulphur dioxide molecules from the gas and brings them to the SO_2 stripper. Stripper removes sulphur dioxide from amine solution and amine is then sent to a complex filtration system so it can be reused in the process once again. After the stripper separates sulphur dioxide gas, it's sent to an acid plant housed within the CCS facility. Sulphuric acid plant is the first of its kind to be installed in a carbon capture facility and its job is to transform sulphur dioxide gas into commercial grade sulphuric acid that is roughly 94% pure.

The acid plant produces approximately sixteen thousand litres of liquid sulphuric acid every day.

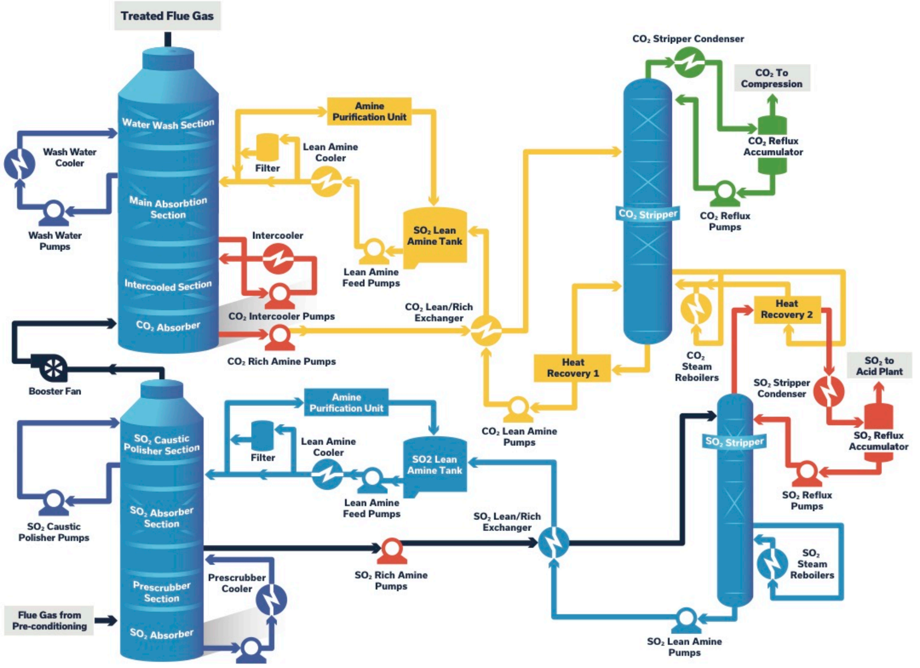


Figure 4.2: Shell Cansolv's combined SO_2 and CO_2 capture process.
(Source: IEAGHG, 2015)

4.3 Project costs

The total cost of the project was $ 1.3 billion. Of these, 800 million used to carry out CCS process, the remaining 500 million for retrofit of the existing plant. Based on this first realization, SaskPower believes that it will be possible to reduce costs by 20-30% for the subsequent CCS unit. Boundary Dam project received $ 240 million from the federal government, plus other funding from the provincial government. In addition to the electricity generated, revenues also come from the sale of CO_2, sulfuric acid and fly ashes. The projected, highly competitive market for by-products is expected to span the useful operating life of the retrofitted plant (i.e. 30-35 years), thereby offsetting a major part of the capture plant investment cost.

The Government of Canada announced funding to support the government of Saskatchewan's efforts in its pursuit of commercialization of carbon capture and storage. That federal funding was the catalyst for converting SaskPower's clean power concept into a fully engineered design. The economic evaluation of the BD3 design assumed that the capture plant would be operated at 85% capacity, and would produce 1 Mt per year of supercritical, high purity CO_2 or approximately 3250 tonnes per day. This economic scenario could be characterized as the yield of a zero net present value for the Integrated Carbon Capture and Storage Project at BD3.

In addition, well before the first delivery of carbon dioxide by SaskPower in October 2014, the entire volume of CO_2 was sold to Cenovus under a ten year contract.

Cenovus planned to use the CO_2 for its EOR operation at the Weyburn oil field. It seems entirely likely that should the value of CO_2 rise over time due to increased demand by the local industry, SaskPower would actually realize an unplanned financial gain from the BD3 retrofit that couldn’t be predicted when the capital expenditure was approved in 2011.

Chapter 5

CCS IN EUROPE

The European Commission has adopted a target of limiting anthropogenic global climate change to well below 2°C above pre-industrial levels, according to what was established at the conference of the parties or COP21. The main objective is a reduction of 80-95% of emissions by 2050 compared to the level reached in 1990. Regarding the electricity sector, any forthcoming policy, based on the recent EU Energy Roadmap communication, suggests a 93 to 99% reduction in CO_2 emissions relative to 1990 levels by the year 2050. This obviously calls for new power plant technology which must have more or less zero CO_2 emissions. Since there will be a continued need for base load over the foreseeable future as well as there exists large resources of fossil fuels both within EU (e.g. lignite) and globally, the choice is to either apply CCS technologies or soon to stop exploiting the fossil fuel resources if the above emission targets should be met. The European Union, as expressed in the Energy Roadmap 2050, bases its energy on the use of fossil fuels. At present, the European system is based on fossil fuel power plants with regard to electricity production, reaching almost 56% of total electricity demand, followed by nuclear energy with 31% and renewable energy with 13%.

In the European Union, combined cycle plans with natural gas have 19% share in electricity production while those with coal have a 29% share. In the medium and long term, fossil fuels are the primary source based on current energy forecasts , maintaining a high level of production of around 40-50% up to 2030. Making the environmental target set in COP21 more stringent strengthens the case for a need of deep-cut technologies such as carbon capture and storage, as deep reductions are needed not only in the power sector, but also for the industry, where decarbonisation options are limited. The aim is therefore to bring CCS plants from 7% to 32% of gross energy consumption, producing around 190 GWe in the EU for 2030.

5.1 Project costs

The investment necessary for this technology to develop is around 100 billion dollars a year for the next fifty years. With regard to the first commercial model of the plant including CCS, the expenditure is a few billion euros with 30-70% higher share compared to standard plants. From the point of view of plant operations, the cost exceeds 25 to 75% of the value of coal plants not equipped with CCS, mainly due to efficiency losses and CO_2 capture and transport costs. However, a substantial investment is required since energy production through the use of CCS is developed on a large scale, a commitment that the industry is not able to tackle on its own. The economic obstacles are the first reason why this technology struggles to see a planning horizon and therefore will take some time to be overcome. Although demonstration projects and research have predicted cost reductions in the future, fixed and variable costs will increase sharply in CCS implementation unlike CCS free energy production. In this regard, the prices of CO_2 emissions are not lower than 35 euro/t of CO_2.

5.2 ETS system

The European Union, from the Kyoto Protocol onwards, adopts the ETS system or emission trading scheme with the aim of reducing greenhouse gas emissions in energy sectors. This system is based on cap&trade mechanism, according to the directive 2003/87/CE, regarding the sectors of production of electrical and thermal energy. The ETS is defined as a cap&trade system because it sets a maximum threshold also called “cap” for total level of emissions allowed to all the restricted parties, but at the same time allows participants to sell and buy or “trade” on the market rights to emit carbon dioxide according to their needs within a set limit. According to the ETS directive, from January 1st,2005, plants with high emissions volumes cannot operate without an authorization for the emission of greenhouse gases. In this regard, each plant must monitor its emissions every year and offset them with European emission allowances that can be sold and bought on the market. Who manages these plants is able to choose between investing to reduce their emissions through low carbon technologies and energy efficiency measures or buy quotas. There are some benchmarks in relation to which a portion of allowances are managed free of charge and assigned to manufacturing plants, in particular those that risk delocalization due to the costs of carbon or carbon leakage. These benchmarks are agreed at European level and expressed in terms of CO_2eq emissions per unit of product. The total quantity of allowances in circulation within the system is based on criteria stablished at European level according to the EU targets for 2020, ie -20% of emissions compared to 1990 levels. Maximum threshold for 2017 amounts to about 1,931 billion units and, in the 2013-2020 range, it is reduced by a factor of 1.74% of the total annual average quantity of allowances issued by the member states in the period 2008-2012, and equivalent to over 38 million shares. However, this factor is destined to decrease further reaching a value equal to 2.2% per year from 2021, in accordance with the July 2015 reform proposal. This is associated with a consequent reduction in the shares of around 55 million per year, thus respecting the established objective, aimed at reducing greenhouse gas emissions of 40% by 2030.

5.3 Projects under study or canceled

In 2009 the European Commission established the European CCS Demonstration Project Network in order to accelerate the deployment of safe, commercially viable large scale CCS projects across Europe by creating a forum for exchange and dissemination of new knowledge. Although initially the bootable demonstration projects were more, only 12 of these should have been completed by the end of 2015. Such projects were underway, partly thanks to early initiatives in several European countries, the EU's European Energy Programme for Recovery (EEPR) and through the NER 300. Currently the network is operational with 6 projects, for which a contribution of about 1 billion has been allocated. Among them we list:

- Belchatow, Poland: post combustion capture technology verified on a new 260 MW supercritical unit, with onshore storage;
- Compostilla, Spain: capture technology using oxy-combustion and circulating bed-fluid technology based on a new 30 MW coal pilot plant, which will be upgraded to 323 MW, with onshore storage;
- Don Valley,UK: integrated gasification combined cycle (IGCC) technology verified on a capacity of 900 mw, with offshore storage in saline aquifers;
- Jaenschwalde, Germany: capturing technologies by oxy-combustion and post-combustion tested on a 300 MW demonstration plant, with onshore storage;
- Porto Tolle, Italy: post-combustion capture technology verified on a 250 MW co-combustion plant, with offshore storage;
- ROAD Rotterdam, The Netherlands: post-combustion capture technology measured on a combustion gas flow equivalent to 250 MW, for a 1.070 MW coal fired power plant with offshore storage;

Three of the previous projects have not been implemented. As far as Janschwalde is concerned, although it was scheduled to be operational in 2016, it was abandoned due to opposition based on environmental fears and lack of legal framework in 2011. In the case of Porto Tolle, the project has been cancelled because Italian energy needs have changed, which make the management costs of power plants too high. Finally, the Belchatow project ended in April 2013 as the PGE company was unable to secure the necessary financing for the project and due to a lack of necessary requirements to manage the storage phase. From the point of view of the projects that are being developed, those that fall within the CCS Joint Programme, launched in November 2010 at the SET-Plan conference in Bruxelles under the European Energy Research Alliance (EERA).

5.4 Projects under development

In Europe there are currently 4 projects under study, two of which are in execution. In particular, we refer to the Sleipner and Snøhvit projects, two plants that treat natural gas and operate on a small scale producing 1 Mtpa and 0.7 Mtpa respectively. As far as industrial separation processes are concerned, both use amines and store carbon dioxide in saline aquifers in the North Sea. among the projects under development we can list the following:

- Rotterdam Opslag en Afvang Demonstratieproject: post-combustion capture plant capable of storing 1.1 Mtpa of CO_2 in a depleted gas reservoir, operational from 2020;

- Norway Full Chain CCS: an advanced development for the possible capture of approximately 1.3 Mtpa of CO_2 by 2022.

- Teesside Collective: a cluster of energy intensive companies that are examining the opportunity to build one of Europe's first CCS equipped industrial zone in Tees Valley, UK. It may begin operations in the mid-2020s, with an initial CO_2 capture capacity of 0.8 Mtpa. The captured carbon dioxide is then transported via pipeline to an offshore site.

- Caledonia Clean Energy: pre-combustion plant of around 3 Mtpa; the start of operations is scheduled for 2020.

However, of all these projects, only last two are still in the early stages of evaluation.

5.5 Future perspectives

As far as the future prospects are concerned, a single model seems to encourage the gradual development of CCS technology and this is the ETS system. In spite of this, price associated to emission quotas is, today, very low and this prevent CCS projects from being funded. At the same time, those who use their own resources in the development of solar and wind energy have an advantage because these sources are not based exclusively on the shares exchanged in the ETS. Added to this, there is a growth in the production of electricity, which has resulted in a depression in the electricity market, a reduction in its price and a fall in investments in CCS technologies. So that projects can take place on a large scale, they need support from the ETS system, other financial incentives and possibly also by appropriate framework regulations. However, a lack of clarity on the incentives to the market and on the regulatory requirements to be implemented disincentive also further investments in the sector. In spite of the support that, from an economic point of view, the European Union is able to provide to projects through ETS, some points need to be addressed from the point of view of research and development. In fact, in all phases of the CCS chain there are technological improvements which, if applied, would be able to reduce costs and therefore allow a further growth in the use of the same.

5.5.1 Storage limitations

Reliability associated with CCS technology is still minimal since it is still in the initial phase of development. It is not possible, today, to provide reliable estimates regarding the storage capacity of a given site. Moreover, a fundamental aspect of CCS is represented by the permanence of carbon dioxide storage capacity, since any global loss, even if small, is able to make this technology a risky choice. In this regard the complete emission into the atmosphere of the stored CO_2 would have disastrous effects on the environment. Currently, several evaluation and monitoring techniques are being researched, particularly with regard to long term geological storage.

5.5.2 Implant technique

Sometimes, the addition of CCS technology inside already established plants could make the installation complex as well as the general operation of the plant itself. In fact, modern systems, in particular those with high efficiencies and low emissions of SO_x and NO_x, are difficult to treat. Also the phase of carbon dioxide transport to the storage site turns out to be complicated because the difficulty lies in the different storage options, in the current position of the site and in the pipeline network used. Another aspect to consider is certainly partial pressure that CO_2 has in post combustion, very often low and therefore difficult to capture. Analyzing the volume percentages of captures CO_2 it can be noted that these are higher in the case of coal-fired power plants and equal about 12-14%, while they are reduced considerably in the case of natural gas power plants to a value of 3-4%, highlighting a clear penalization in the capture phase.

5.5.3 Environmental aspects

The use of CCS in energy systems is attributable to negative aspects especially with regard to environmental risks. In fact, the injection of CO_2 into tanks can have biological impacts as well as ocean storage increase acidity of oceans. In the same way, it should not be underestimated, in the capture phase, how solvents such as monoethanolamine have a negative impact on the environment and therefore need careful monitoring. Another significant aspect is also represented by the fact that this technology involves conspicuous consumption of water.

5.6 R&D in capture technologies

To enable quantitative, more precise cost and performance assessments of emerging capture technologies, it is important that these reach a sufficiently credible pilot scale testing at TRL. Capture technologies, which have already achieved high TRL under certain boundary conditions, e.g. for power applications, cannot necessarily be classified with the same TRL for other industrial applications. However, it should be possible to build on existing pilot infrastructures experience and quickly adapt them to new, modified boundary conditions of different industrial sectors. Regarding solvent based capture processes, they are commercially available but there is a substantial scope to reduce their relatively high cost and efficiency penalty. An open R&D challenge is the continuous development of new functional materials such as solvents, sorbents, membranes, ect, which possess the following characteristics:

- Less sensitive towards the most abundant impurities in flue or process gases, in order to prolong lifetime of a given plant;
- Fast adsorption/absorption kinetics to reduce residence time, allowing for more compact capture equipment.

There is a need to intensify and support fast up-scaling of promising lab-scale capture technologies in order to speed up its development and avoid stagnation. For example, many new materials synthesized in labs lack a commercial supply chain which makes their up-scaling costly. Therefore, specific R&D challenges closely linked to large demonstration projects will remain an important R&D priority.

5.7 R&D in transport technologies

In contrast to capture technologies, transport and storage technologies rely to a high degree on commercially available equipment used in the oil and gas industry. Future development of transport and storage technology will mostly be of incremental nature, leading to improved performance and/or lowered costs of existing technology. There are some exceptions, which relate to transport by ship and storage in basalts which are both at low TRL levels today and can be considered as emerging technologies. In transport networks, the management of the quality of CO_2 becomes an issue, when mixing of streams of different quality could affect the performance of the system. The required knowledge about the relation between CO_2 quality and the behavior of the CO_2 in the system has advanced considerably in recent years, allowing accurate estimates of the flow through pipelines. Transport by ship is a well-established practice but for large-scale CCS ship transport need to be scaled up and the potential implications of transporting impure CO2 need to be considered. Larger ships will be required; the same can be said about loading and unloading facilities at ports. Offloading offshore, near the injection location, requires some technology development and demonstration, such as flexible hoses and mooring systems. This typology may lead to batch-wise injection, leading to intermittent injections. Therefore, it is important to study the effects that intermittent injections can produce con injection wells. An on-site buffer storage could remove some of the intermittency, however, the design remains to be optimized and the optimization relates to the location of and power source for facilities to condition the CO2 prior to injection.

5.8 R&D in storage technologies

The required operational flexibility holds for the whole CCS chain including CO_2 injection and storage. Research including full-scale demonstration is required on expanding the operational envelope of injection wells and subsea equipment under repetitive cycles of pressure and temperature changes. Furthermore, sufficient storage capacity must be assured before investors can decide on financing CCS. There is a need to assess site conformance, the level at which the site behaves as expected, on a quantitative level. A methodology should be available to support operators and regulators in their assessment of the performance of the storage site: during storage operations, when unexpected events occur, and when preparing site handover to the competent authorities.

Chapter 6

Conclusions

What the data show, today, is the growing need to put into practice policies aimed at limiting unpleasant consequences due to a poorly man made management of the ecosystem, and this can be seen from this document. In the last century man has over exploited natural resources in his possession by virtue of an over the top lifestyle and a well-being that this planet does not seem able to sustain for years to come. Although the technology outlined here, namely CCS technology, is an important tool through which reduce significantly emissions due to greenhouse gases and therefore global warming, it is currently a transition phase and as such its temporal horizon is limited. At the same time, many others are being developed and are only waiting to be implemented. For a real climate change to occur, it is essential that energy savings exist. Science, in this context, reserves a very important role in the development of CCS and its improvement, as well as demonstrating the many good prospects from an engineering point of view. An extremely efficient and logistically manageable capture process would contribute to the rapid dissemination of technology. An improvement from this point of view could amortize the initial investment and decrease operating costs accordingly. As far as the transport phase is concerned, it is still difficult to imagine a possible reduction in terms of costs as for some types of offshore storage, planning, maintenance and management still constitute an important part. In addition to this, we must add the fact that transport by ship also has a cost in terms of carbon dioxide emitted, due to marine propulsion. As far as storage is concerned, the most economic practice is that of placing CO_2 inside sites aimed at recovering hydrocarbons. This is in fact an interesting solution as it allows to have an income, allows an amortization of the initial investment and in the same way to not resort to the development of studies regarding morphology of the site concerned. This particular phase presents various problems, above all related to public opinion and to the procedures adopted. However, one aspect that should not be underestimated is security issues. In fact, to date, plume escape events can be rare but not impossible and they are configured as a risk whose consequences may even be catastrophic. In the recent past, this is demonstrated by events related to nuclear energy and the legacy that these have brought with them. The expansion of CCS technology suffers from negative influences and fatigue to take hold especially in Europe. The margins within which certain sectors operate are increasingly reduced and this contrasts to make the context more competitive. On the other hand, emerging economies impose a progressive reduction of their profits to the developed countries.

The imposition of a zero emission regime could produce the so - called risk of relocation. The implementation of the CCS itself is a considerable economic expenditure and without substantial contributions it has no way of being put into practice. Continuing to carry out large-scale demonstration projects is certainly the priority today. Only from that moment on, we can talk about a commercial development of technology. Estimates on costs and future developments will be accessible. In the current world a greater incentive is directed toward renewable resources with regard to low-carbon production.

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