

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

185,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Carbon Capture and Storage – Technologies and Risk Management

Victor Esteves and Cláudia Morgado
*Federal University of Rio de Janeiro
Brazil*

1. Introduction

1.1 The greenhouse effect and climate changes

The greenhouse effect (GHE) that allowed the emergence and expansion of life on earth has been growing due to made-man greenhouse gases (GHG) emissions. The increasing use of fossil fuels since the beginning of the industrial revolution has been increasing the GHE and consequently gradually raising the earth’s temperature, affecting the conditions for species survival.

GHGs can be subdivided into two groups: those present in the atmosphere since before the industrial revolution and those that are chemical compounds created and produced by humans. The first group includes carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O), whose concentrations in the atmosphere have been rising as a consequence of intensification of human activity. The second group includes perfluorocarbons (PFCs), chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), hydrofluorchlorocarbons (HCFCs) and sulfur hexafluoride (SF₆). Each of these gases has a different potential to absorb infrared radiation.

Table 1 shows the global warming potential (GWP) over a 100-year horizon of some of the main GHGs (IPCC, 1996). The GWP represents the capacity of a gas present in the atmosphere to absorb energy from infrared radiation.

Gas	GWP
CO ₂	1
CH ₄	21
N ₂ O	310
CFC-113	4.800
HFC-23	11.700
CF ₄	6.500
C ₂ F ₆	9.200
SF ₆	23.900

Table 1. Global Warming Potentials (GWP) (100-Year Time Horizon) - Source: IPCC, 1996

The GWP of each gas is the relative warming potential of that gas in relation to CO₂, which has a normalized value of one. For example, N₂O has a GWP of 310, meaning its warming

effect is 310 times that of CO₂. Although the GWP indicates in exaggerated form the importance of each GHG over the short term in the atmosphere, particularly for methane, it is the standard defined by the IPCC in its Second Assessment Report (SAR) in 1996 and is utilized by the majority of emissions inventories.

Therefore, although nitrous oxide (N₂O) and methane (CH₄) are present in the atmosphere in much lower concentrations than carbon dioxide and their annual emission levels are far below that of CO₂, their molecules have much greater capacity to absorb infrared energy and hence contribute to increase the earth’s temperature on the same order of magnitude as CO₂.

Table 2 shows the anthropic emissions of GHGs of the United States (US EPA, 2011a) in 2008, the 27 countries of the European Union (EEA, 2010) in 2008 and of Brazil (MCT BRASIL, 2010) in 2005. The emissions of all the gases except for CO₂ are expressed by their GWP rather than in absolute mass values. By determination of the United Nations Convention on Climate Change, CFCs and HCFCs are not included in these inventories because they are controlled by the Montreal Protocol, which regulates emissions of gases that destroy the ozone layer. In the case of the United States and European Union (columns 2 to 5 in Table 2), the total emissions are expressed net of the emissions related to changing land use and forestry, which generate negative emissions in these countries. Therefore, changing land use and forestry in these countries cause an increase in the biological capture of CO₂, thus acting as carbon sinks. Just to have an idea of the order of magnitude, changing land use and forestry in the United States in 2008 accounted for negative emission of 1,140.5 MtCO₂, representing 16% of the total of 6,961.9 MtCO₂. In the European Union this negative emission was 256 MtCO₂, representing about 8% of the total of 3318 MtCO₂.

	USA 2008		EU 2008		Brazil 2005	
	Mt CO ₂ eq.		Mt CO ₂ eq.		Mt CO ₂ eq.	
CO ₂	5.921,400	83,9%	3.062,000	82,3%	1.637,905	74,70%
CH ₄	676,700	9,6%	302,000	8,1%	380,241	17,34%
N ₂ O	310,800	4,4%	282,000	7,6%	169,259	7,72%
FCs e HFCs	136,000	1,9%	66,000	1,8%	4,593	0,21%
SF ₆	16,100	0,2%	9,000	0,2%	0,602	0,03%
Total	7.061,000	100%	3.721,000	100%	2.192,600	100%

Sources: US EPA (2011a), EEA (2010) and MCT BRASIL (2010)

Table 2. GHG Emissions – USA and EU – Year: 2008 and Brazil – Year: 2005 (using GWP)

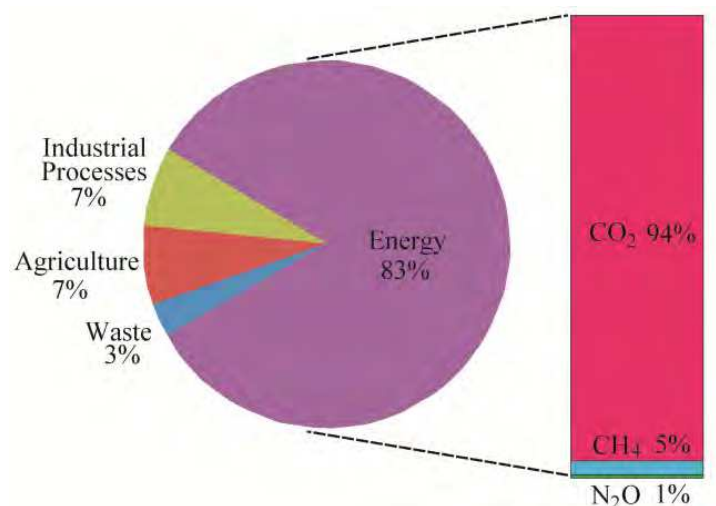
The second emissions inventory carried out in Brazil (MCT BRASIL, 2010) presents the emissions for 1990, 1994, 2000 and 2005. Columns 6 and 7 of Table 2 show the GHG emissions of Brazil in 2005. Unlike columns 2 to 5, the figures in columns 6 and 7 include emissions because of changing land use and forestry. The variation in the percentage shares of CO₂ and methane in comparison with those in the United States and European Union is the result of the less intensive industrial activity in Brazil. Besides this, the GWP methodology overstates methane emissions, which have a relatively high value in Brazil due to the importance of farming and stock breeding in comparison with industrial activity.

Until the industrial revolution, natural causes, such as large forest fires caused by lightening and volcanic eruptions, were the main sources of CO₂ release. But since the industrial revolution and the expansion of farming and animal husbandry, human activity has become

increasingly relevant. Among the main human activities that contribute to growing CO₂ emissions are the following:

- Thermoelectric plants that burn fossil or other fuels;
- Extraction of fossil fuels;
- Industrial processes that use any type of combustion;
- Land, waterborne and aerial vehicles that used combustion engines;
- Burning to clear land to plant crops or create pastures for animals.

According to the report “CO₂ Emissions from Fuel Combustion”, published by the International Energy Agency (IEA), in developed countries the use of energy is by far the human activity that produces the most GHG emissions. Figure 1 depicts the distribution of made-man GHG emissions from developed countries (Annex I of the Kyoto Protocol), excluding those generated by changing land use and forestry, which as mentioned before are negative in these countries. The emissions resulting from production, transformation, manipulation and consumption of all types of energy commodities in Annex I countries account for 83% of all GHG emissions (IEA,2010a).



Source: IEA (2010a)

Fig. 1. Shares of made-man GHG emissions in developed countries. Year: 2008.

Figure 2 presents the evolution of the total primary energy supply (TPES) in the world. It can be seen that this doubled between 1971 and 2008. The fact that the share of non-fossil fuels rose from 14% to 19% is due to the increased use of energy from “clean” sources, such as hydroelectric, nuclear and from renewable fuels. Nevertheless, the generation of energy from fossil fuels grew in absolute terms of some 5 gigatonnes of oil equivalent (IEA, 2010a).

The increasing energy demand from the growing consumer markets in emerging economies, of which China and Brazil are leading examples, can only be satisfied over the short term by the use of fossil fuels. In this respect, China is stepping up its use of coal to generate electricity, while Brazil has the option in the medium term of using its immense reserves of natural gas, largely untapped so far.

The use of renewable fuels, such as ethanol from sugarcane, theoretically has the advantage of not adding new carbon to the atmosphere, since the carbon generated by burning it is

captured from the atmosphere by the plants from which it is produced. However, it is necessary to perform a complete life cycle analysis of the production of renewable fuels such as ethanol. Practices such as burning off litter in cane fields to facilitate harvesting and the use of farm machinery and trucks that burn fossil fuels diminish the comparative advantage, not to mention social questions. Besides this, the use of renewable energy from biofuels in general competes with land use to produce food, to meet the exploding global demand caused by the inclusion in the consumer market of lower classes from densely populated emerging countries like China and India.

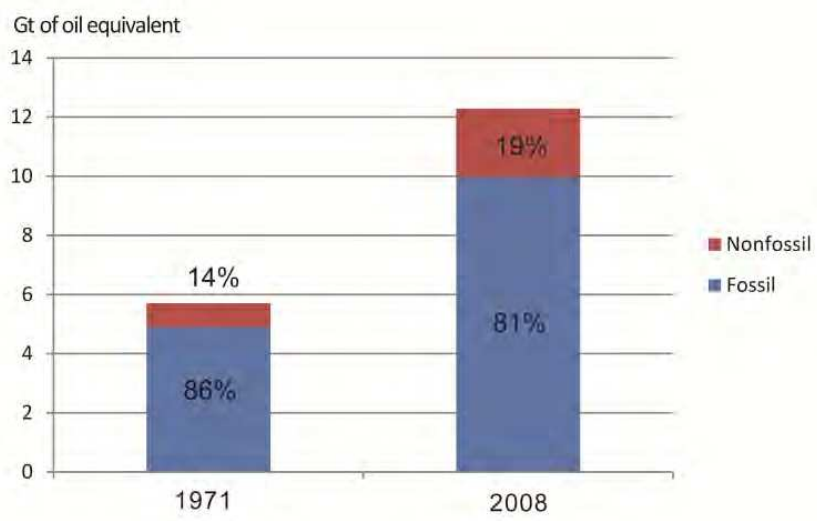


Fig. 2. World Primary Energy Supply (TEPS) - Source: IEA (2010a)

1.2 Carbon capture and storage (CCS) – A way to mitigate climate change

Carbon capture and storage (CCS), also known as carbon capture and geological storage (CCGS), is a process to mitigate climate change by which the CO₂ generated by concentrated industrial activities, such as thermoelectric plants, fossil fuel extraction and refining facilities and other industrial processes that rely on combustion, is captured and stored in geological formations.

One may question the importance of using CCGS to reduce CO₂ emissions since nowadays vehicles are the main contributors to the greenhouse effect. Nevertheless, vehicles are becoming cleaner through better efficiency and the shift to different engines and fuels, such as electric cars. While the electricity used by these cars may be generated by a power plant burning coal, considered a “dirty” source, the CO₂ emitted in concentrated form at this plant can be sequestered while the capture of that emitted in dispersed form by thousands of vehicles with internal combustion engines is economically unfeasible.

The study by the International Energy Agency (IEA, 2010b) shows that the reduction of GHG emissions can only be attained by adopting a series of technological measures. As seen in Figure 3, by the lines traced out to 2050, the IEA believes that if we continue emitting GHGs indiscriminately, global emissions can reach 57 GtCO₂ a year over that horizon. But with an intense effort to reduce emissions, through a mixture of CCGS, carbon sequestration by biomass, increased use of renewable energies such as nuclear and enhanced energy efficiency, the world can reduce its emissions to 14 GtCO₂ a year.

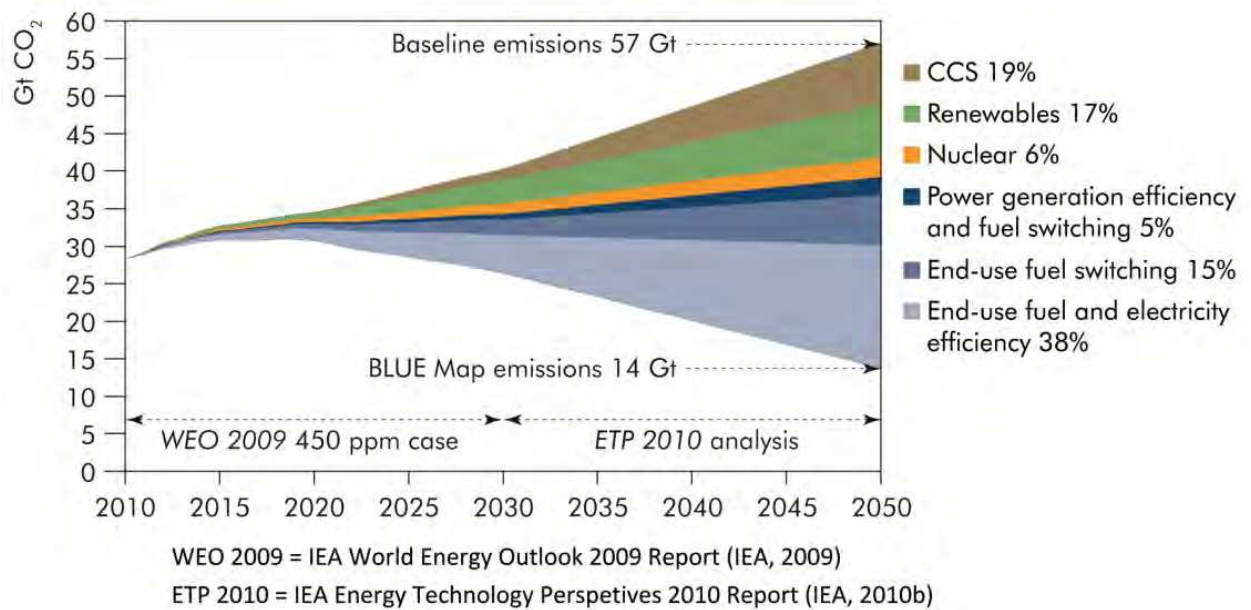


Fig. 3. Technologies for reducing CO₂ emissions - Source: IEA (2010b)

The IEA together with the CSLF (Carbon Sequestration Leadership Forum) prepared a report called “Carbon Capture and Storage – Progress and Next Steps” (IEA & CSLF, 2010) for the G8 summit meeting held in Muskoka, Canada, on June 25-26, 2010. This report lists 80 CCGS projects that fit under a series of criteria, among them the capture of over 500 MtCO₂ per year and being in operation between 2015 and 2020. Of these 80 projects, 9 are already in operation and the remaining 71 are in one of the four phases (identification, assessment, definition or execution) that precede operation. Among these 80 projects, 73 are located in developed countries, 4 are in China, 2 in the Middle East and 1 in Africa.

In a graph, shown in Figure 4, the report predicts growth to as many as 3,400 projects in 2050, of which 65% will be located in countries not belonging to the Organization for Economic Cooperation and Development (OECD). These 3,400 projects will be responsible for capturing some 10 GtCO₂ annually, representing a yearly average of 3 MtCO₂ per project.

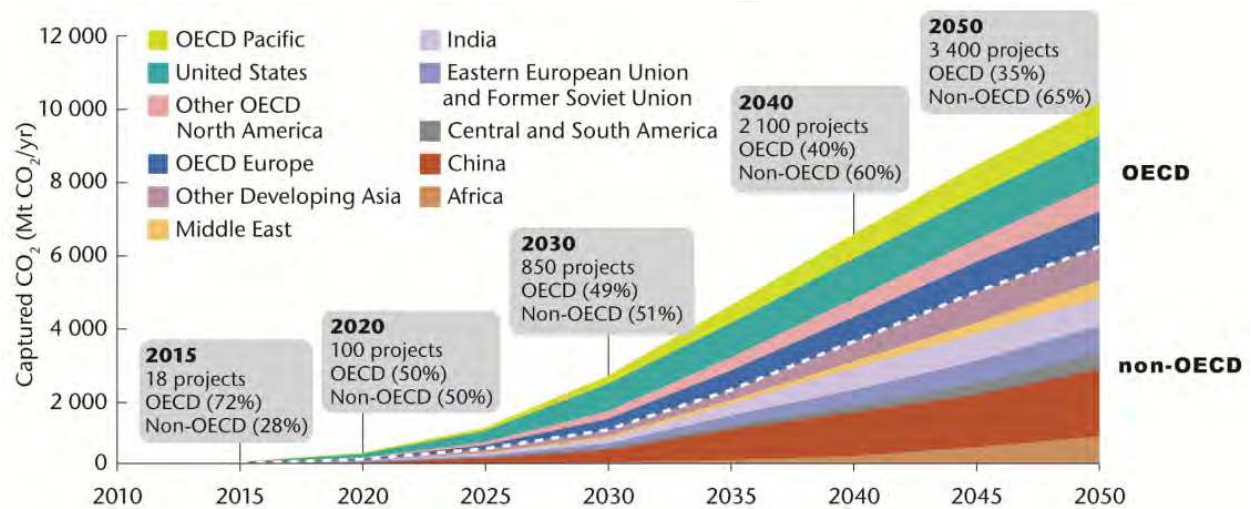


Fig. 4. Global deployment of CCGS 2010-2050 by region - Source: IEA & CSLF (2010)

2. CCS steps – Involved technologies

The CCS process can be divided into six basic steps:

- Separation
- Dehydration;
- Compression
- Transport;
- Injection;
- Storage and monitoring.

2.1 Separation

At present there are basically four cases where the concentration of CO₂ emissions makes its separation for geological sequestration technically and commercially viable. The first is related to the processes of extraction of natural gas, which depending on where and how it is extracted brings with it a varying percentage of CO₂ along with a series of other gases and impurities. The second case the process of gasification of coal, which generates large amounts of CO₂. The third is the generation of hydrogen, in which CO₂ is generated as a byproduct. And the fourth situation, which contributes most to emissions, is the generation of CO₂ from industrial processes involving combustion. Figure 5 presents, as an example of this fourth case, a coal-fired power plant. The coal is burned to heat a boiler to generate steam, which drives the turbines coupled to the generators. The exhaust gases, composed of roughly 15% CO₂, 85% N₂ and under 1% of other compounds such as sulfur oxides (SO_x) and nitrogen oxides (NO_x), pass through a desulfurization system for removal of most of the sulfur-based compounds. The exhaust gases then go to the capture unit, where the CO₂ is separated from the other constituents, which are discharged into the atmosphere. The part discharged is mainly composed of nitrogen (N₂).

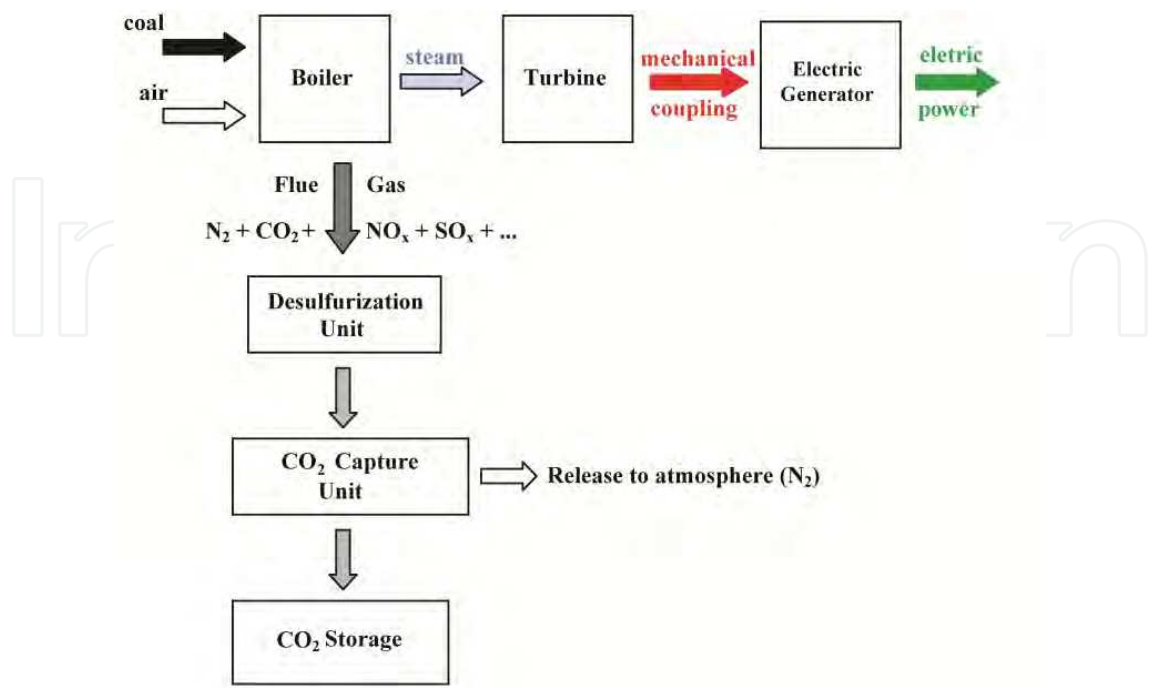


Fig. 5. Coal thermoelectric plant with carbon capture

Today there are a series of CO₂ separation methods already developed or under development, among them the more used are:

- Chemical absorption;
- Physical adsorption;
- Oxy-combustion.

Various factors influence the choice among these separation methods: available space for allocation and consumption of energy by the separation plant, concentration of CO₂ in the gases to be processed, pressure of these gases, level of purity and percentage of CO₂ separation.

2.1.1 Chemical absorption

Chemical absorption is a widely used process with a series of pilot plants distributed around the world. The oldest commercial CCGS plant is located in Sleipner, Norway and has used this process since 1996 (Solomon, 2007).

The process entails using a solvent, normally an amine, which chemically reacts with CO₂, forming a compound. As shown in Figure 6, this reaction occurs in an absorption tower, whose size basically depends on the flow of the flue gas from the industrial process. The compound thus formed is transferred to the regeneration unit where its temperature is raised to release the CO₂. The solvent free of CO₂ then returns to the absorption tower to repeat the cycle.

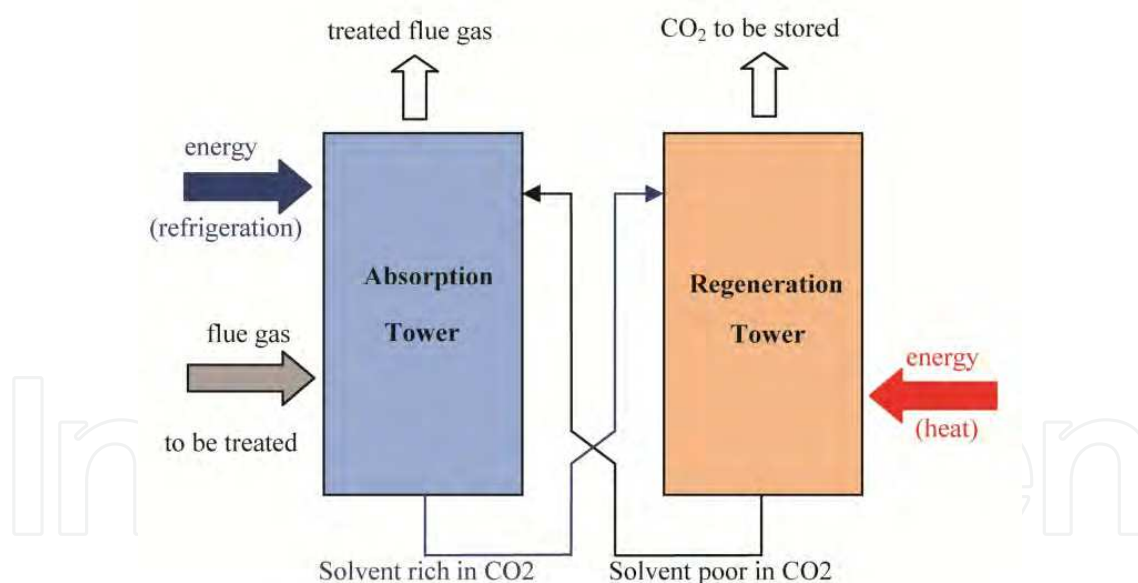
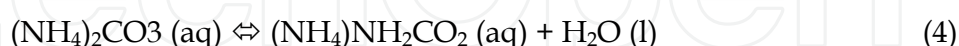
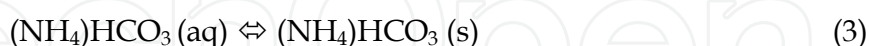
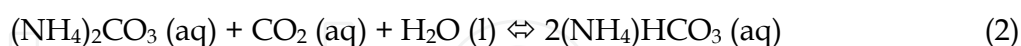


Fig. 6. Absorption and regeneration processes

One example of commercial chemical absorption processes is the chilled ammonia process (CAP), which was developed by Alstom Power and is utilized in pilot plants to capture carbon developed by that company in partnership with American electric utilities. The first pilot plant, with generating capacity of 1.7 Mwatts, was the Pleasant Prairie thermoelectric plant of WE Energies in Wisconsin. The second was the Mountaineer thermoelectric plant, with capacity of 20 Mwatts, owned by American Electric Power in West Virginia (Sherrick et al., 2009). This plant operated from October 2009 to May 2011, for a total of over 6,500 hours,

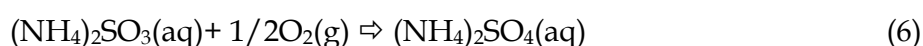
and reached the goal of validating the technology, capturing over 50 KtCO₂ in this period and permanently storing over 37 KtCO₂ in a saline aquifer located at a depth of 2,400 meters.

The overall chemical reactions associated with the CAP are defined by equations 1 to 4:



These reactions are all reversible and their directions depend on the pressure, temperature and concentration in the system. The equations are exothermic from left to right and endothermic from right to left, requiring the removal or addition of heat.

Besides capturing CO₂, the CAP also removes other residual gases in its cleaning and cooling stages, such as SO₂, SO₃, HCl and HF. Equations 5 and 6 show the overall chemical reactions associated with the removal of SO₂.



2.1.2 Physical adsorption

Physical adsorption consists of capturing CO₂ by the surface of a solid material, such as activated charcoal or a zeolite, placed in the path of the flow of the gas targeted for removal of CO₂. The CO₂ adsorbs to the surface of the solid particles by surface forces (non-chemical forces). The adsorption process is facilitated by keeping the process at low temperature or high pressure. Once the adsorbent material reaches a determined CO₂ saturation level, the exhaust gas flow is diverted to another path and the chamber containing the adsorbent material is heated or its pressure is reduced to release the CO₂, in a process called desorption.

An example of the physical adsorption is a project for hydrogen production units in Port Arthur, Texas run by the company Air Products. This was one of the three projects chosen in Phase II of the Industrial Carbon Capture and Sequestration Program (ICCS) of the US Department of Energy (US DOE). The Port Arthur Units 1 and 2, whose block diagrams are shown in Figure 7, work based on the traditional process of reform of natural gas by the action of steam.

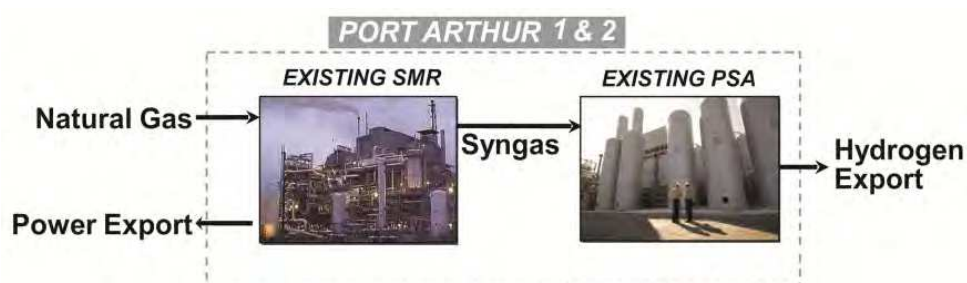


Fig. 7. Port Arthur 1 and 2 -Hydrogen production units - Source: Air Products (2011)

Equations 7 and 8 show the chemical reactions that produce hydrogen from methane.



Equation 7 is highly endothermic, consuming a high amount of heat, while equation 8 is slightly endothermic, producing only a small amount of heat. After the reformation process, which is carried out in the steam methane reformer (SMR) unit, the synthetic gas (syngas) generated is composed basically of hydrogen and carbon dioxide associated with some impurities, depending on the composition of the natural gas reformed. The syngas is then sent to the adsorption unit, which works by the principle of pressure swing adsorption (PSA) to separate the hydrogen to be exported.

The project, which received funding of US\$ 284 million from the US DOE, will include a CO₂ separation unit and a drying and compression unit in the process (Figure 8), besides interconnection with an existing pipeline to send the CO₂ to the site for geological sequestration. The units are slated to start operating at the end of 2012 and start of 2013 and will capture 1 MtCO₂ per year.

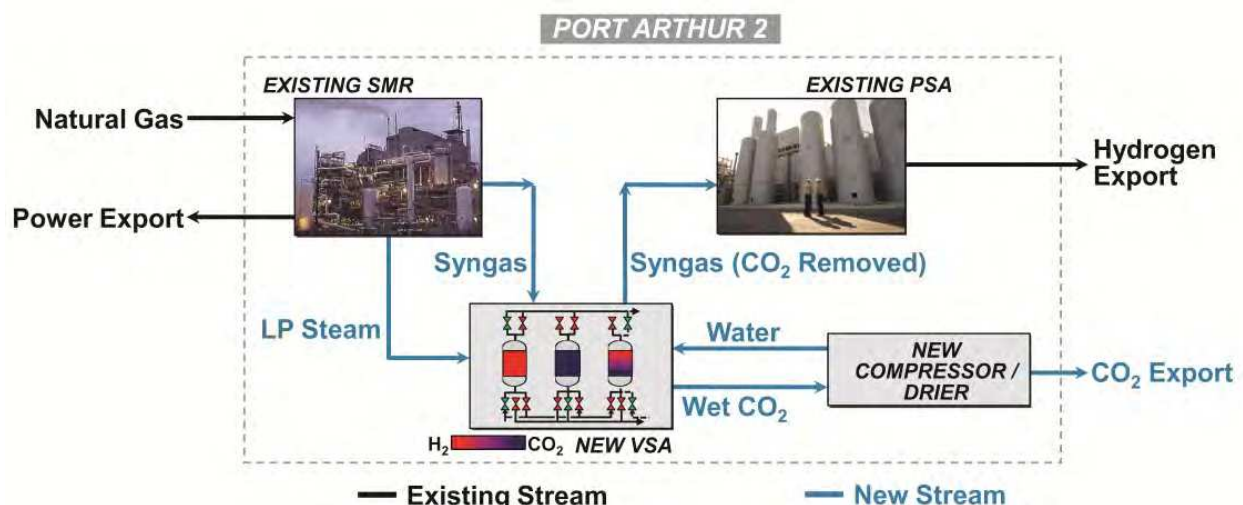


Fig. 8. Port Arthur 2 with CO₂ separation and compressor/drier units

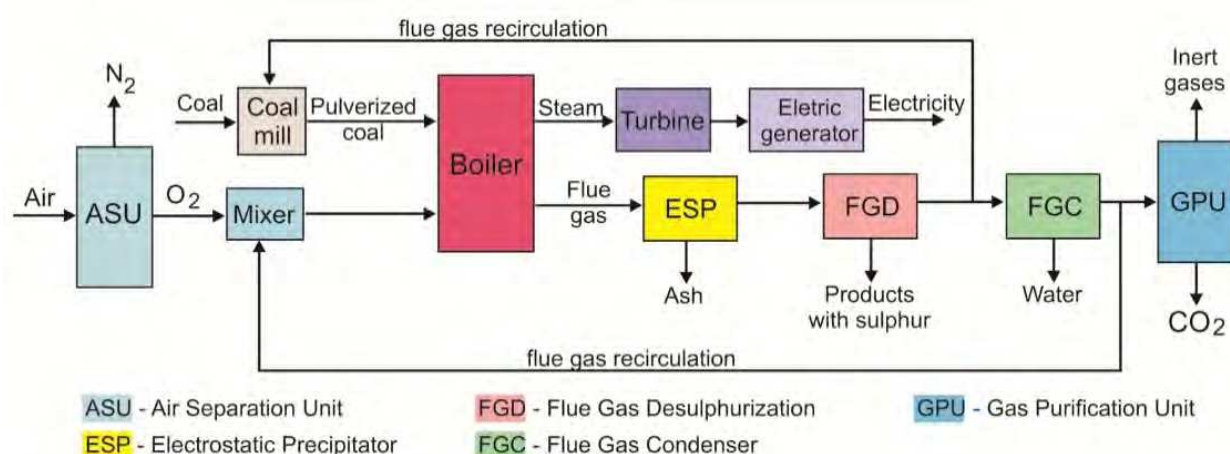
The vacuum swing adsorption (VSA) process is a variation of the PSA process, whereby the adsorption is carried out at a pressure near atmospheric pressure and the desorption occurs by producing a vacuum in the chambers.

2.1.3 Oxy-combustion

In theory the oxy-combustion process involves burning a fuel using O₂ instead of air as the oxidant. In this process, the N₂ is separated in advance, eliminating the presence of nitrous oxide (N₂O) in the exhaust gas. Since the sulfur removal units are already obligatorily included in industrial processes that burn fossil fuels, except for particulates and other impurities the exhaust gas contains a high concentration of CO₂. However, all oxy-combustion systems in practice work with a mixture of O₂ with recirculated exhaust gas. Therefore, the oxy-combustion only increases the CO₂ concentration in the exhaust gas,

making its separation more feasible. As a result, the oxy-combustion process must be associated with at least one of the other separation processes. The Figure 9 shows a diagram of oxy-combustion system in a pulverized coal power plant.

The Carbon Capture and Low Emission Coal Research program mandated by the American Recovery and Reinvestment Act (ARRA), signed into law by President Obama in February 2009, calls for investment of US\$ 3.4 billion for research aimed to make burning or gasification of coal an activity with low GHG emissions. One of the simplest ways to modernize a coal power plant is to introduce O₂ separation units to feed the burners of the boilers.



Source: Alstom Power (2011)

Fig. 9. Oxy-combustion system in a pulverized coal power plant

2.2 Dehydration

The objective of dehydration is to reduce the level of moisture of the CO₂ as much as possible so that it will be less prone to cause erosion in the mechanical elements involved in the injection process.

2.3 Compression

To be transported, CO₂ needs to be compressed. The compression range depends on how it will be transported. For pipeline transport, the CO₂ needs to be compressed in the range between 1100 and 3100 psi to assure single phase flow, because above 1100 psi, CO₂ remains in single phase within a broad range of temperatures. Since pipelines are subject to great temperature variations, it is important to avoid the formation of two phases, which can cause pressure spikes that can in turn rupture pipes (Barrie et al., 2004).

The pressure required is much lower for transport in tank trucks, railcars or ships, because the temperature can be kept low through thermal insulation, something that is uneconomic in the case of pipelines. Therefore, pressures of 250 to 400 psi are sufficient to keep the CO₂ in the liquid phase.

2.4 Transport

As indicated above, there are four ways of transporting CO₂ between the emission source and the underground injection site:

- Tank trucks;
- Trains made up of tank cars;
- Tanker ships; and
- Pipelines, which in the case of CO₂ are called carbon pipelines.

Of these four transport means, only pipelines are viable for EOR projects, where the distances can run into the hundreds of kilometers and the volumes of CO₂ are in the millions of tonnes per year. This high carrying capacity compensates for the high costs of building, maintaining and operating a carbon pipeline.

Because of the high initial investments and operating expenses of a carbon pipeline and the large damages that could be caused by a rupture, as well as the fact it may cross land held by many owners, special attention must be given to the commercial, legal and insurance aspects to minimize the economic risks. Suppliers and consumers of the CO₂ carried by pipeline along with the line operator must participate in detailed multilateral agreements with well-defined rights and obligations. The other types of transport are feasible for industrial processes that use CO₂ as an input, in cases where the quantity is small and does not compensate the cost of building and operating a pipeline and/or when the production and consumption sites are very close.

2.5 Injection

In this step, the CO₂ is injected through injection wells, basically into three types of geological formations:

- Exhausted or declining oil reservoirs;
- Saline aquifers; and
- Coal beds.

2.5.1 Injection in exhausted or declining oil reservoirs

The option for injection in oilfields where production is waning serves another function besides carbon sequestration: it maximizes oil recovery. This process is called enhanced oil recovery (EOR). The standard production process always involves injection of water to maintain the producing pressure. The EOR process, shown in Figure 10, involves injection of water and CO₂ in alternation. The CO₂ injection increases the oil's fluidity, releasing the oil stuck in the rock pores, while the water, which is by nature not compressible, pushes the oil toward the producing well.

An example of the injection of CO₂ in EOR projects is the Weyburn project, located on the border between Canada and the United States. It has been in operation since 2000. The CO₂, with 95% purity, captured in a coal gasification plant in Beulah, North Dakota, is carried by a pipeline to an oil production field in Weyburn, Saskatchewan, where it is injected (Zouh et al., 2004). Figure 11 shows the pipeline in yellow that connects Beulah and Weyburn. The red dots show possible derivations for use of the CO₂ in new EOR projects in the region.

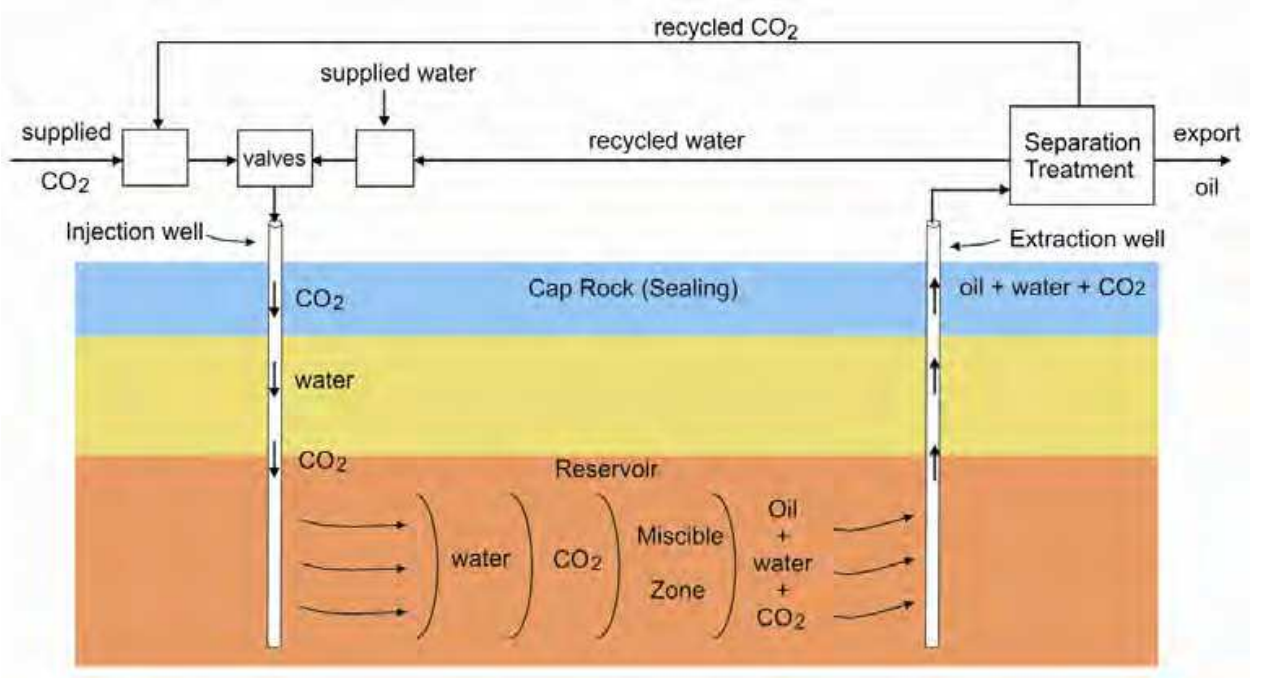


Fig. 10. Enhanced Oil Recovery (EOR) Process

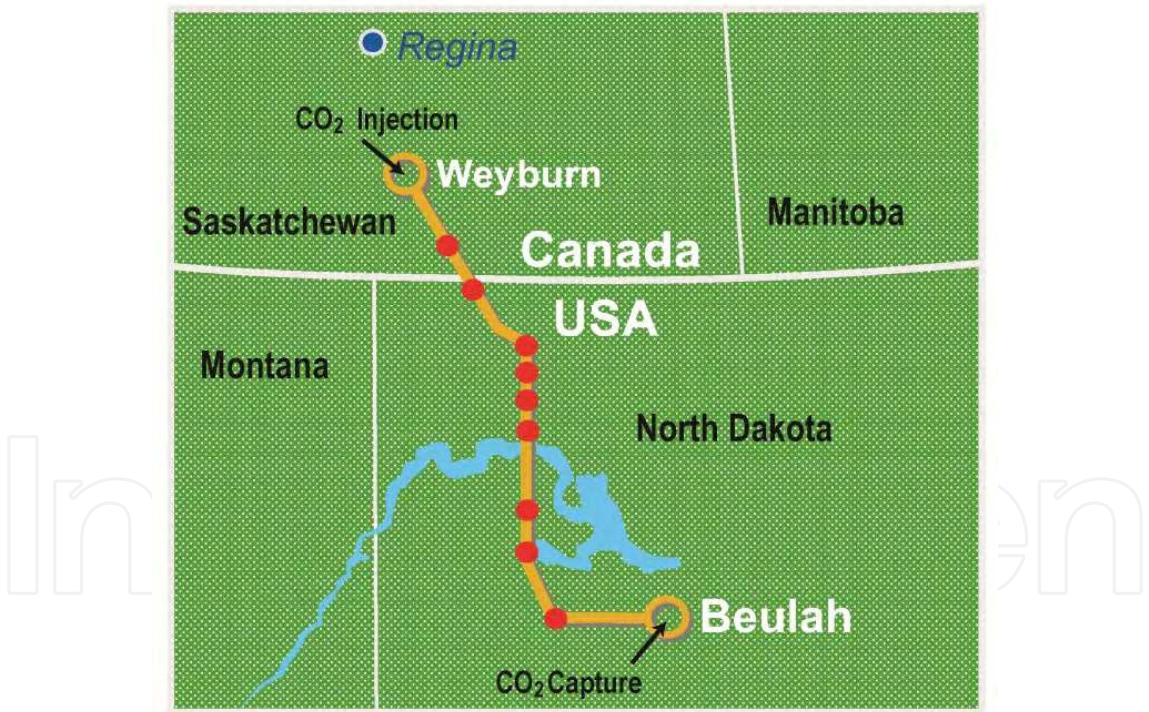


Fig. 11. Carbon pipeline linking Beulah and Weyburn – Source: Cenovus Energy (2011)

Figure 12 presents a graph of oil production in Weyburn since the start of the operation in December 2010. The brown area represents the increase in output because of the EOR process if the process had not begun in 2000, production in December 2010 would have been approximately 10 thousand barrels per day (10 kbopd). The EOR boosted this output in December 2010 to roughly 28 kbopd.

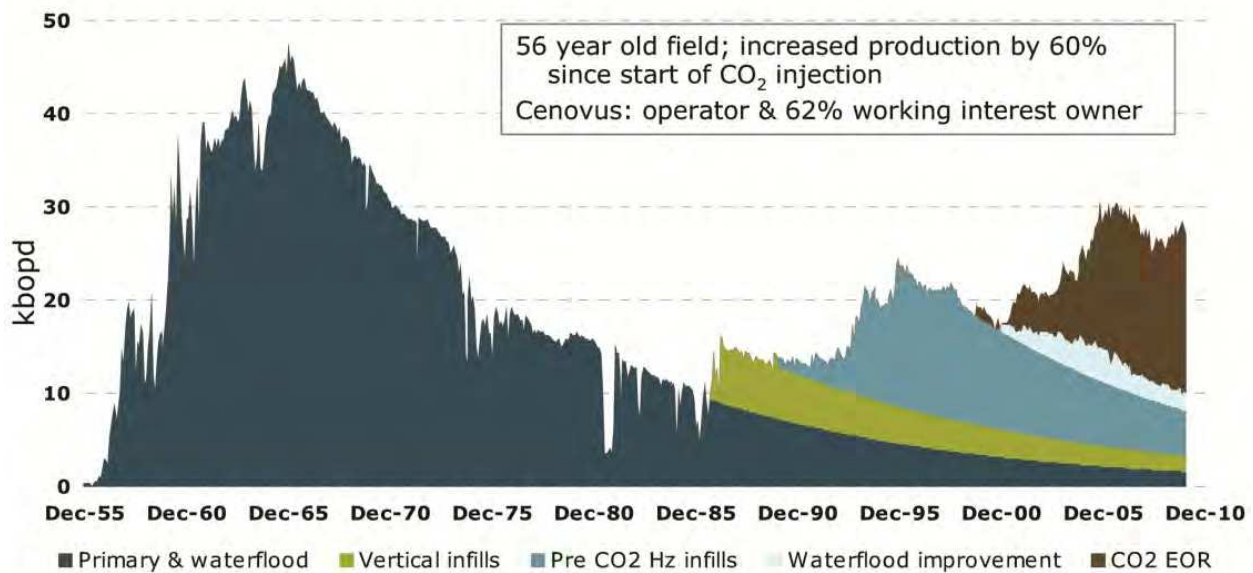


Fig. 12. Weyburn Historical Oil Production - Source: Cenovus Energy (2011)

2.5.2 Saline aquifers

Saline aquifers exist in the great majority of the world's regions. Since this water cannot be used for drinking or farming, the option to store CO_2 in these aquifers appears very promising. The first project to capture carbon of this type was developed by Norway's Statoil in its Sleipner natural gas field in the North Sea.

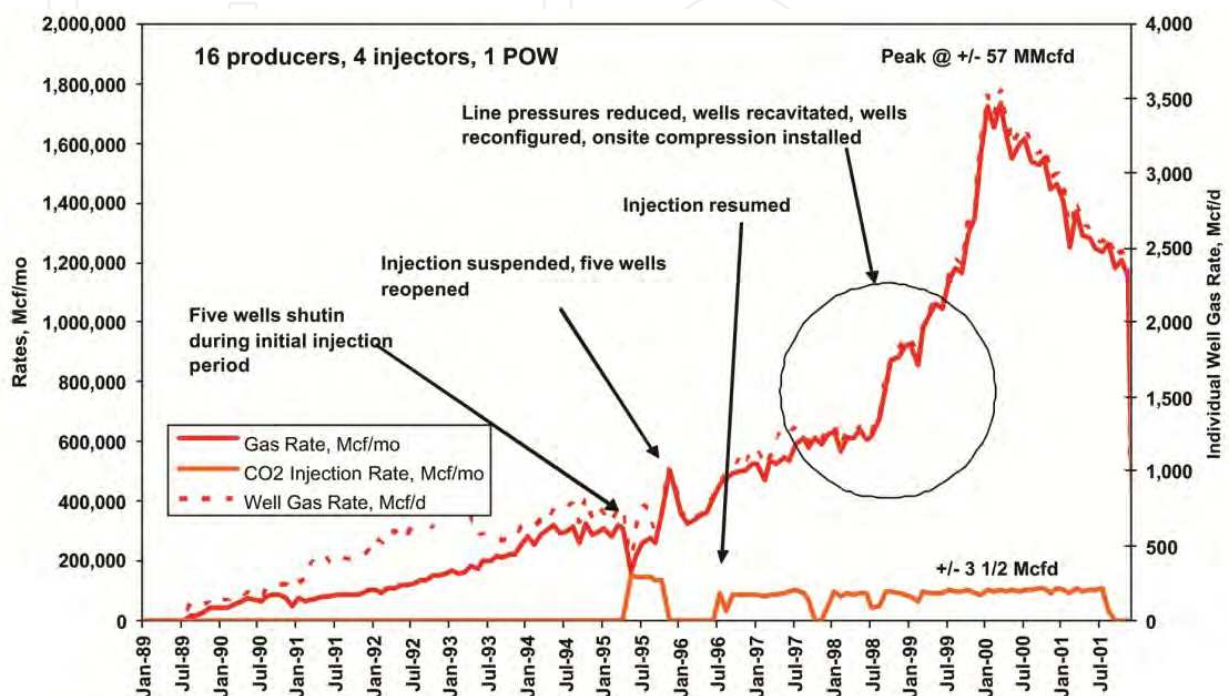
According to Statoil, the percentage of CO_2 in the natural gas of its Sleipner field is approximately 9% (BGS, 2011), which is above the level tolerated by its consumers. In 1991, the Norwegian government introduced a tax of US\$ 50 dollars per tonne of CO_2 emitted. These two aspects combined (standards required by consumers and government taxation) prompted Statoil to develop the geological capture project.

Physically the project is composed of two platforms. On the first one the natural gas rich in CO_2 is extracted. This gas is sent to the second platform where the CO_2 is separated by chemical absorption, then compressed and injected into a saline aquifer located 1000 meters beneath the seabed. According to the projections of a special report of the IPCC (IPCC, 2005), the total storage capacity of the Sleipner project is 20 MtCO_2 , of which nearly 11 MtCO_2 had already been stored by the end of 2008 according to Statoil.

2.5.3 Coal beds

For the storage of CO_2 in coal beds to be feasible, this process must be associated with the production of methane from the bed. The injection of CO_2 enhances the production of methane, hence the name enhanced coal bed methane recovery (ECBM). The process is being studied by, among others, the Swiss Federal Institute of Technology (ETH) and other research organizations funded by European Commission and US Department of Energy (US DOE). These studies aim to obtain the necessary knowledge to apply the technology in large scale.

A pilot ECBM project financed by the US DOE was developed in the San Juan Basin in New México, with the use of 4 CO₂ injection wells and 16 methane production wells, besides an observation well. The methane production started in July 1989 and the CO₂ injection began in April 1995 and continued until August 2001, when the operations were suspended to study the results. Figure 13 shows the results of the variations in methane output as a result of the injection of CO₂ (Reeves & Clarkson, 2003).



Source: US DOE.

Fig. 13. Evolution of Production/Injection of the UCBM Pilot Project of Alison

2.6 Storage and monitoring

Storage and monitoring are considered to be single step, because monitoring is required to assure that the CO₂ stored will not leak out to the atmosphere. According to the report of the Special Intergovernmental Panel on Climate Change (IPCC, 2005), this monitoring aims to verify possible leaks or other aspects indicating deterioration of the storage over the long term, to assure there are no risks to the environment. Various technologies can be used to perform different types of monitoring:

- Monitoring of the injection flow and pressure;
- Monitoring of the underground CO₂ distribution;
- Monitoring of the integrity of the injection wells;
- Monitoring of the local environmental effects; and
- Monitoring by a network of sensors placed at points distant from the injection sites.

All the data gathered by these monitoring efforts are fed into computer systems equipped with “intelligent” software as part of a risk management system, which besides indicating tendencies that can foretell risky situations and determine operational changes, also indicates mitigation routes in case of leaks or malfunctions of the system.

3. Risk assessments

Risk is the product of the probability of a negative event's occurrence and the magnitude of the consequences. Risk management is a tool used to make decisions to help manage adverse events. For proper assessment of risks, it is necessary to identify all the possible causes of risk and their consequences. This can be done by preparing a chart showing the series of risk-posing events that can lead to a catastrophe, as shown in Figure 14.

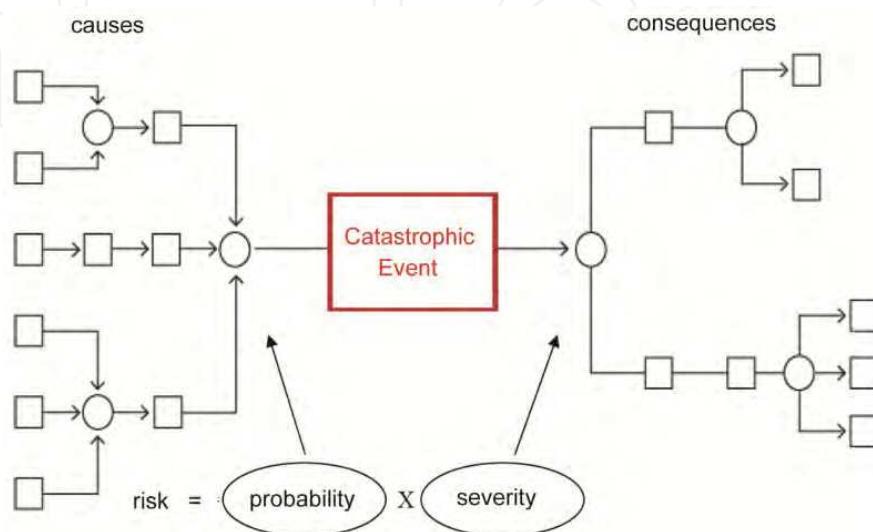


Fig. 14. Series of Risks

Normally in industrial undertakings, the causes of events with large adverse effects are treated by managing the technology, that is, by specifying the equipment and materials, preparing rules and procedures, training programs, etc. The effort to reduce risk is concentrated in diminishing the probability of the occurrence of the causes that can trigger a series of events that lead to catastrophe and to assess the consequences. These consequences are analyzed by using the data on the area surrounding the project, its population and natural resources. Therefore, contingency plans are drawn up for mitigation of the catastrophic events if they occur. However, the focus is on the causes.

The risks of CCS projects are hybrid in nature, meaning they are a combination of technological and natural risks, because the possibility of leaks and other problems does not depend on the technology alone. The size of the reservoir, demographic changes, seismic behavior of the region, micro-climate and many other factors can modify the characteristics of the process and thus its complexity. Hence, there is less control over the causes that can lead to a catastrophic event, and it is important to monitor and identify anomalies in the process that can require taking action to control the emergency, by application of contingency plans prepared in advance.

The magnitude and complexity of the events involved in CCS projects prevent the application of traditional risk management based on administrative procedures and operational controls. Unlike an industrial plant, the CCS process is part of a natural formation that is responsible for its final function. The activities of the people in the surrounding area and the possibility of seismic events that trigger natural geophysical and geochemical changes in the reservoir are just some of the aspects that must be considered to

manage the risk of a CCS project. This imposes the need for an adaptive intelligence able to accompany this dynamic interplay of factors.

The complexity of managing the risks of a CCS process depends on a series of aspects inherent to each project, among them the following:

- Separation technology;
- Separation and injection flow;
- Distance between the separation and injection sites;
- Injection purpose (besides carbon sequestration);
- Characteristics of the storage reservoir;
- Monitoring technology; and
- Substances that form the gas to be injected.

The varying combination of these aspects will determine the analyses that must be undertaken.

3.1 Risks in the separation, dehydration and compression steps

Due to their individual character, the risks of these steps are similar to those involved in the industrial process that will be the source of the CO₂. In the case of Weyburn, the CO₂ comes from the coal gasification plant in Beulah, while in the Sleipner project it comes directly from the natural gas production well. In any event, the addition of CO₂ separation, dehydration and compression units increases the complexity of the endeavor, raising the cross-risks and consequently changing the risk analysis drastically.

3.2 Risk during transportation

According to a study by the Pipeline & Hazardous Materials Safety Administration (PHMSA) of the U.S. Department of Transportation (US DOT), in that country in 2008 there were 5,580 Km of carbon pipelines in operation, mainly involving enhanced oil recovery (EOR) projects. These pipelines are located in North Dakota (ND), Wyoming (WY), Utah (UT), Colorado (CO), New Mexico (NM), Texas (TX), Oklahoma (OK), Mississippi (MS) and Louisiana (LA). Most of these lines cross sparsely populated regions, a characteristic that reduces the severity factor of the risk associated with transporting the CO₂. This is clearly intended, since the severity reflects the direct effects of possible accidents on people. Nevertheless, while effects on natural biomass may not directly affect local populations, they can cause secondary effects on more distant population centers. If these effects are neglected for not being direct, the losses can be greater and broader in scope, ceasing to be local and becoming regional.

In densely populated and highly industrialized regions such as Central and Northern Europe, carbon pipelines linking CO₂ sources with storage sites will have to traverse populated areas, potentially prompting public opposition. The current risk perception places the risks of onshore storage above those of onshore transportation. This is understandable because people have lived for decades with oil and gas pipelines but are not accustomed to the idea of having geological formations beneath their feet containing millions of tonnes of CO₂ “ready to escape”. But while onshore storage projects may face

low acceptance, offshore projects require a much greater investment in constructing the necessary pipelines.

Failures of carbon pipelines can be caused by holes or complete ruptures. In both cases the failure can be the result of:

- Corrosion;
- Construction defects;
- Materials defects;
- Soil movement;
- Operational errors; and
- Human activities in surrounding areas.

The climatic and geological aspects of the area where a carbon pipeline is or will be installed directly influence the effects suffered by the materials used in their construction. Besides this, these aspects also influence the choice between a buried or aboveground pipeline. In the case of failure of a high-pressure underground pipeline that causes a large leak, the pressure will fall rapidly, releasing a large quantity of energy. This energy will cause the soil above to be ejected, potentially resulting in large damages to structures and loss of lives.

Accidents in densely populated areas represent a greater risk both in terms of probability and severity. This fact requires a larger investment in security and ongoing monitoring of urban expansion in the areas through which the pipeline passes.

The main aspects that influence the amount of CO₂ that can escape during an accident are: internal diameter of the pipeline, size of the hole, operating temperature and pressure and distance between shut-off valves.

Because CO₂ is heavier than air, when released in large quantities it behaves differently than gases that are lighter than air. The release of CO₂ occurs in the form of a cloud that moves near the ground and its progress depends closely on the local topography and weather.

The most important aspect to be analyzed is the impact of CO₂ leaks on human health. In this respect, the concentration and exposure time are the two factors that must be assessed. A CO₂ concentration of 150,000 parts per million (ppm), or 15% by volume, can cause a person to lose consciousness in less than one minute. Exposure for one hour to concentrations between 100,000 and 150,000 ppm can cause mortality ranging from 20% to 90% (Koornneef et al., 2010).

3.3 Risk of leakage to the atmosphere

When injected, the CO₂ is less dense than the saline fluids of the reservoirs, so it can migrate to other geological formations or to the surface. The escape to the atmosphere, besides causing risks to human health and the environment in nearby areas, also obviously reduces the effectiveness of the effort to control GHG emissions intended by the CCS project in the first place. The leakage of high concentrations to the atmosphere can have catastrophic effects on the local biota.

- CO₂ leakage to the surface can occur because of:
- Pre-existing geological fractures or faults;

- New geological fractures caused by seismic movements;
- Abandoned production or injection wells; and
- Long-term changes in the properties of the reservoir's rock formations.

In an EOR project, the drilling of new injection wells continues until no longer economically feasible. The abandoned wells, although sealed with cement, can provide paths for CO₂ to escape. This can happen due to degradation of the sealing materials. Contact with CO₂ in brackish water increases the attack on cement by around tenfold in comparison with freshwater (Barlet-Goué'dard et al., 2009). The Weyburn project currently has over 1,000 wells along its extension. One of the assumptions of the studies conducted there is an increase in 100 years in the permeability of the sealing cement from an initial level of 0.001 md to 1 md (Zhou et al., 2004).

Changes in the porosity and permeability of the reservoir's rocks can be caused by the effect of the chemical interactions between the carbonic acid and the minerals forming the rocks. Carbonic acid is generated directly by the reaction of CO₂ with the water present in the reservoir. This effect is stronger in storage projects that use saline aquifers, such as the Sleipner project, but is also occurs on a lesser scale in EOR projects, such as Weyburn.

A study carried out at the University of Nottingham (Patil et al., 2009) to assess the possible effects of CO₂ employed injection at a controlled rate. The study utilized two types of ground: a pasture and a fallow plowed field awaiting planting. The results showed that the concentration of CO₂ displaced the O₂ from the soil and reduced its pH. The consequences of these alterations were impairment of the action of earthworms and reduced grass growth in the pasture and crop germination after planting, with consequent diminished productivity of both the pasture and planted field.

3.4 Risk of underground movements

One of the most important aspects that must be analyzed regarding injected CO₂ is its capacity to carry metals in the underground that can contaminate groundwater.

A comprehensive risk assessment must consider the main composition of the storage reservoir's rock formation. There are basically two types of formations:

- Carbonate rocks (calcite, argonite, dolomite. etc.); and
- Silicate rocks (quartz, feldspar, etc.).

The presence of saltwater, as in storage in saline aquifers, is important because it promotes the formation of carbonic acid, which reacts with the surrounding minerals and can carry the metals present in them. This transport can contaminate nearby potable water aquifers.

In the case of silicate rocks, the carbonic acid reacts very slowly with the rock so there is practically no change in the porosity and permeability. In contrast, carbonate rocks react more quickly with the CO₂, altering the porosity and permeability. This effect, however, is damped by the rapid increase of the pH of salt water, which leads to a decrease of acid action on the rocks (Wilson et al., 2007).

An example where the risk of underground movement is present is the project developed by In Salah Gas (ISG), a joint venture among British Petroleum (33%), Statoil (32%) and

Sonatrach, the Algerian national oil company (35%). The gas produced by the production wells in the Sahara Desert region has an average CO₂ concentration of 7%, a level that needs to be lowered to under 0.3% for the gas to be exported to Europe. Therefore, a purification plant was built at the Krechba Oásis, 700 Km from Algiers (Iding & Ringrose, 2009). The purified methane is sent northward in a pipeline that connects to the Algerian gas exportation network, while the captured CO₂ is pressurized, carried by pipeline and injected in a saline aquifer located below the gas field. The main risk of this undertaking is the possibility of migration of the CO₂ toward a drinking water aquifer that lies above the gas reservoir. Investigations demonstrated that the upper part of the reservoir where the CO₂ is being injected has a thick layer of schist that seals this reservoir. However this risk of groundwater contamination should be given priority attention, in this desert region, where there have historically been violent conflicts involving water rights.

Another risk associated with underground movement is the possible generation of seismic events due to the alteration of the underground geophysical characteristics. Such seismic events, besides potentially generating geological fractures capable of releasing large amounts of stored CO₂, can also unleash other catastrophic events that damage structures and endanger lives.

3.5 Risk of using hydrocarbon reservoirs for sequestration

The analysis of the risks of using depleted hydrocarbon reservoirs for geological sequestration of carbon or the employment of CO₂ injection for enhanced oil recovery (EOR) is a complex process that must consider constant changes in the risk factors over time and the various types of wells. In a given reservoir, there can be five basic well types:

- Production well;
- Injection well;
- Sealed wells without monitoring instrumentation;
- Sealed wells with monitoring instrumentation; and
- Monitoring wells.

The status of a well can change, altering the set of instrumentation necessary and the ranking of the importance of the data necessary for risk management. Additionally, the change in the status of a determined well alters the entire system and affects the ability to monitor the system. Therefore, the risk management system must be adaptable to accompany the system's evolution.

4. Policy and regulation

Governments play an essential role in CCS, by setting safety standards and other requirements for operation and obtaining public support. The deployment of CCS projects relies on the approval of civil society, who must believe that the injected CO₂ will stay stored in the reservoir for thousands of years. To this end, the analysis of possible risks associated with the escape of CO₂ is an essential stage in the life cycle of the storage system and aims to promote and ensure the safety of the activity to the environment and to human health, contributing to the technology's acceptance.

One of the main sticking points for the expanded use of carbon sequestration, mainly in densely populated areas, is the acceptance of the people living above or nearby the reservoir that will be used. The same situation exists for the location of sanitary landfills, prisons, power plants or any other large project with potentially negative impacts. While society at large agrees on the need for such undertakings, those most closely affected generally feel otherwise, often because of a lack of knowledge of the real risks involved. This is the well-known “not in my backyard” conundrum. In the case of carbon sequestration, the benefits accrue to the population of the entire planet, not just a region or state, making this contrast between the general welfare and local concerns as stark as it possibly can be. Winning public support thus requires a major effort to educate the public about the real risks of geological storage of carbon. A real example of the public acceptable importance is the project of Shell in Barendrecht, Holland. This project planned to store some 10 MtCO₂ over a period of 25 years, captured from Shell’s hydrogen gasification plant at the Pernis refinery near Rotterdam. The CO₂ would be transported by a pipeline about 20 km and injected in two depleted natural gas fields over a mile deep under the city of Barendrecht. Despite many public hearings held by the city council and strong support of the central government, through approval of by the Dutch Senate, Ministry of Economic Affairs and Ministry of Housing, Spatial Planning & the Environment, the project faced strong opposition from the citizens of Barendrecht and it finally had to be canceled.

The geological storage in saline aquifers and other formations located on continental shelves is the best option. The study carried out by Dutch researchers (Broek et al., 2009) shows the technical and economic feasibility of a network of carbon pipelines linking power plants and industries that emit high amounts of CO₂ to the Utsira aquifer. This aquifer is located below the North Sea, between Great Britain and Norway. Testing has been conducted there since 1996, including through the Sleipner CCS pilot plant run by Statoil. The study took into consideration the perspectives for growth of emissions due to increased energy demand and for growth of taxation on emissions from €25/tCO₂ in 2010 to €60/tCO₂ in 2030.

In most countries the regulation of CCS is the responsibility of the central (federal) government. In the United States, Australia and Canada there is shared responsibility among the federal, state (provincial) and local spheres. The specific legislation to regulate the activities involved in CCS should start from existing laws on extraction and processing of fossil fuels. Countries like Norway, Canada and Spain are involved in this process of formulating the CCS regulation based on the regulatory powers under existing legislation on exploitation of oil and gas or through amendment of those laws to extend their scope.

Another consideration is the fact that many likely places for CO₂ injection lie in international waters and many such schemes involve emissions from multiple countries. Hence, international agreements come into play. Maritime treaties such as the London Protocol limit the exportation of trash or other materials and also the dumping or incineration of such materials on the high seas. Because the Protocol had been interpreted as prohibiting the export of CO₂ from one contracting state to another for injection into sub-seabed geological formations, it was amended in 2009 specifically to permit this. To take effect, this amendment must be ratified by at least two-thirds of the contracting states. Without this ratification, densely populated countries not located on coastlines, such as those in Central Europe, are prevented from using the option of sending CO₂ for offshore storage in geological formations beneath the continental shelf, even though the populations of the

emitting countries and the coastal ones that can provide this service may agree with it. However, only a few countries are involved in the development of CCS schemes and fewer still in offshore storage with cross-border transport of CO₂. Therefore, ratification is far from assured in the short term.

Another important international maritime accord is the OSPAR (Oil Spill Preparedness and Response) Convention for the Protection of the Marine Environment of the North-East Atlantic. It has also been amended to permit injection of CO₂ in sub-seabed formations, an amendment that is also awaiting ratification. Since this agreement only has 15 member states, only two more ratifications are necessary for it to take effect. The greater ease of ratification is also due to the fact that the Sleipner project – the largest offshore CCS project – is located in this region.

There are proposals, accepted even by the World Trade Organization (WTO), to create differentiated import taxes for products from countries with policies and commitments to reduce various emissions. The aim of this policy is to level the competitive playing field for products whose costs include environmental taxation in the country of origin (WTO&UNEP, 2009).

International accords and mechanism such as the United Nations Framework Convention on Climate Change (UNFCCC), which was created in 1992 at the United Nations Conference on the Environment and Development (Rio 92), have an important role in fostering CCS. Among the Kyoto Protocol's features is the Clean Development Mechanism (CDM), which permits developing countries, which are not required to have emission reduction targets, to develop projects to reduce GHG emissions and in return acquire Certified Emission Reduction (CER) certificates. These CERs can be traded with developed countries to enable them to meet their emission reduction goals. But due to the still-existing doubts about the capacity to guarantee the effectiveness of geological sequestration of carbon, CCS projects are not yet eligible to receive CERs. Another reason for this lack of eligibility is the political and economic dispute between consolidated fossil fuel industries and environmentalists and researchers. The first group advocates the use of CCS as a viable way to reduce emissions while the second believe this will just prolong the use of fossil fuels, thus discouraging investments to develop renewable energy sources with smaller carbon footprints.

At the Sixteenth Conference of the Parties (COP 16), in Cancun, Mexico, it was determined that CCS should be included as eligible under the CDM, and the Subsidiary Body for Scientific and Technical Advice, which had proposed the decision, was tasked with preparing the procedures for inclusion of CCS in the CDM, to be decided upon at the COP 17 in Durban, South Africa (in December 2011). The final report enumerates a series of issues about CCS that must be considered before final approval of its inclusion under the CDM, among these are:

- Robust and rigorous criteria for selecting the storage site;
- Strict plans for monitoring, aiming at adequate risk management;
- Study of migration routes; and
- Inclusion of the possibility of dissolving CO₂ in groundwater.

The items that follow illustrate the current state of CCS legislation in some countries.

4.1 Australia

In Australia the federal government shares jurisdiction with the state and territorial governments for both onshore and offshore geological sequestration (out to the 3-nautical mile limit). The federal government has sole jurisdiction on the continental shelf beyond this limit.

In June 2011, the Australian government approved the “Offshore Petroleum and Greenhouse Gas Storage (Greenhouse Gas Injection and Storage) Regulations 2011”. These regulations, issued under the authority granted by the Offshore Petroleum and Greenhouse Gas Storage Act, approved by Parliament in 2006, basically cover the following interrelated elements:

- Testing the risk of a significant adverse impacts;
- Information necessary for a declaration of a geological formation as adequate for storage;
- Local injection and storage plans;
- Incident reporting;
- Decommissioning; and
- Discharge of securities.

In July 2011, the Australian government presented its Clean Energy Future Plan, which calls for a tax of Au\$ 23 (about US \$25) per tonne of CO₂ starting in July 2012. This taxation includes all activities that emit more than 25,000 tonnes of CO₂ per year. It does not include emissions from light vehicles and farming activities. To maintain the country’s industrial competitiveness, steelmakers, coal miners and electricity generators will receive compensations. An energy security plan will assure sufficient electricity generation in the face of possible problems, since 75% of the country power is generated by coal-fired plants. Tax cuts for consumers are also planned to offset possible increases in the cost of living due to the CO₂ emission tax. The adoption of this tax was the fruit of suggestions by companies from the coal mining sector, which in 2010 proposed that the government adopts a CO₂ emission tax along with a requirement that part of the revenue be allocated to develop clean technologies to permit the companies to remain competitive in the global market.

4.2 Canada

In Canada, the central government shares jurisdiction over CCS with the provincial governments. The latter governments’ jurisdiction covers natural resources within the borders of each province, including exploration and development of non-renewable natural resources and management of power plants. This means the provinces have authority over certain aspects of CCS while others fall under federal jurisdiction, such as international and inter-provincial commerce, taxation and criminal legislation.

4.3 Norway

Norway established a CO₂ emission tax in 1991, mainly applying to offshore oil and gas extraction. Other sectors in the country with a large carbon footprint were exempted, such as fishing, metallurgy, cement making, aviation and others. The power generation sector was not affected because 98% of the country’s electricity comes from hydroelectric plants. Because of this policy of taxation centered on exploitation and consumption of fossil fuels,

the pump prices of gasoline and diesel in Norway are among the highest in Europe (equivalent in July 2011 to US\$ 2.30). But because of the many exceptions, Norway's carbon tax has not managed to reduce emissions as much as envisioned.

Regarding specific regulations on CCS, the Ministries of Petroleum and Energy, Labor, and the Environment as of May 2011 were still working on new regulations on the transport and storage of CO₂ in subsea reservoirs under the country's continental shelf. The work was being delayed due to the conflicts of interest within and among the ministries, and no draft regulations had been put out for public consultation as of that date.

4.4 European Union

Both the European Commission and the governments of the state members are involved in regulating the geological sequestration of carbon. The member states are required to put into practice the directives and regulations issued by the European Union, including the Emission Trading System (ETS) and the CCS Directive, which function as framework legislation. The CCS Directive has to be transposed to the law of each member state by June 2011. This process permits each country to develop its own legislation on CCS to fit the particular circumstances of each one, within the overall European Union framework.

4.5 United States

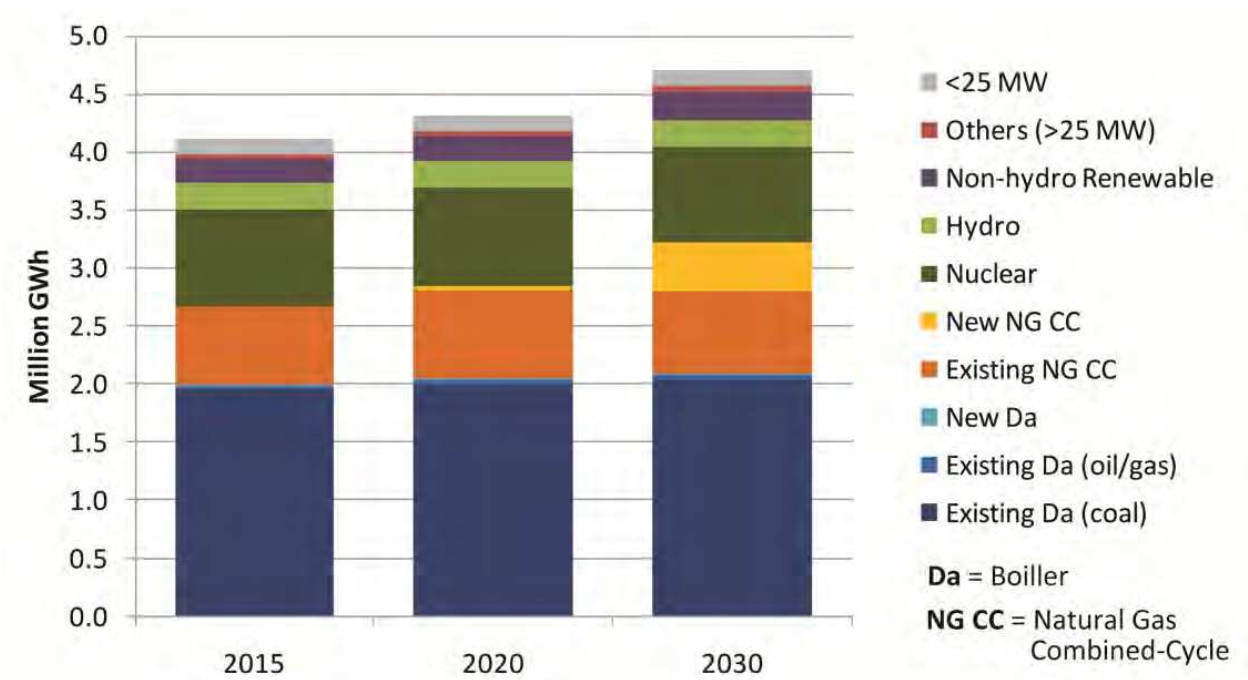
In the United States, the Clean Air Act of 1970, which was substantially amended by Congress in November 1990, with further small alterations since then, entrusts responsibility for CO₂ emissions to the Environmental Protection Agency (US EPA).

Specifically regarding GHG emissions, in December 2009 the US EPA issued a note indicating it had concluded that the current and projected atmospheric concentrations of GHGs jeopardized current and future public health (US EPA, 2009).

Due to some projections made by the US EPA and the United States Energy Information Administration (US EIA), such as slow growth of electricity demand, low natural gas prices and strong gas supply, the only projects for new coal power plants other than those already under construction are a small number of medium-sized plants subsidized by federal programs for carbon capture and storage. As seen in Figure 15, the projections indicate that the growth of electricity demand of approximately 700 TWh (tera watt hours) between 2015 and 2030 will be almost all met by the entrance into operation of combined cycle natural gas plants, utilizing gas and steam turbines in the same cycle.

Another aspect that can be observed from Figure 15 is that nearly half of the 4.1 million GWh (giga watt hours) forecast for 2015 will be generated by traditional coal-fired plants with turbines driven by steam. As can be observed in Table 3, of the current 1,266 coal power plants in the United States, more than one-third are classified as large, with average capacity of 532 MW (mega watts), which together account for 76% of the energy generated by coal-fired plants.

Based on these projections, in December 2010 the US EPA announced the preparation of rules to cover GHG emissions from power plants that burn fossil fuels and that generate more than 25 MW. The rules will establish performance standards for new emission sources (New Source Performance Standards - NSPS), applicable both to new plants and revamped ones.



Source: US EPA (2011b)

Fig. 15. Projections for distribution of power plants in the United States

Capacity (MW)	Number of units	Avg. age (years)	Avg. capacity (MW)	Total capacity (MW)	Share	Avg. thermal efficiency (Btu/KWh)
< 25	193	45	15	2,849	1%	11.154
25 - 49	108	42	38	4,081	1%	11.722
50 - 99	162	47	75	12,132	4%	11.328
100 - 149	269	49	141	38,051	12%	10.641
150 - 249	81	43	224	18,184	6%	10.303
> 250	453	34	532	241,184	76%	10.193
Totals	1,266			316,480		

Table 3. Coal-fired power plants in the United States - Source: US EPA (2011b)

Besides this, the rules will establish an emissions guide for existing units. The Agency is slated to present the proposed regulations in September 2011, and discussion is scheduled to last until May 2012, when the final versions will be presented.

4.6 Brazil

The current Brazilian Constitution, promulgated in 1988, deals with the environment specifically in its Article 225. Among other aspects, this article refers to the concept of sustainability, in line with what was presented by the United Nations World Commission on the Environment and Development (WCED/UN, 1987), according to which all people have the right to an ecologically balanced environment, essential to a healthy quality of life, and the government and the community have the duty to defend and preserve it for present and future generations. It is also determined that public authorities must require the

preparation and publicity of environmental impact studies for all activities that can potentially cause degradation of the environment. CCS can fit under this because although the aim is to benefit the environment by reducing the concentration of CO₂ in the atmosphere, it can also bring possible negative impacts that must be dealt with through preventive and/or mitigating measures.

Law 6,938/81 established the National Environmental Policy and created the National Environmental System (*Sistema Nacional do Meio Ambiente* - SISNAMA). Within the SISNAMA structure, the National Environmental Council (*Conselho Nacional do Meio Ambiente* - CONAMA) was created as the consultative and deliberative entity of the SISNAMA. CONAMA issues resolutions that create general guidelines, rules and standards.

CONAMA Resolution 01/86 contains the definitions, responsibilities and basic criteria for the use and implementation of environmental impact assessment. To build and operate any project involving an activity considered potentially polluting, it is mandatory to prepare an environmental impact study (*Estudo de Impacto Ambiental* - EIA) and accompanying environmental impact report (*Relatório de Impacto Ambiental* - RIMA). The activities listed as potentially polluting that are related to an CCS project are: (a) gas pipelines; (b) extraction of fossil fuel, which would apply in the case of using the CO₂ captured for enhanced oil recovery (EOR); (c) power plants, applicable in case of capture of exhaust gases from these plants; and (d) industrial plants, which would apply to a wide range of industrial activities, both in the petroleum industry (refineries, fertilizer plants, coal gasification plants) and others (steel mills, cement factories, chemical plants, etc.). Presentation of the EIA/RIMA set is a mandatory step of the licensing by the environmental agency (federal, state or municipal) and besides setting out the magnitude of probable impacts (positive and negative), must define the mitigating measures of the negative ones.

Annex I of CONAMA Resolution 237/97 lists which activities need to be licensed at the federal, state or municipal level. Projects whose “environmental impacts exceed the territorial limits of the country or of one or more of its states” fall under the remit of the Brazilian Institute of the Environment and Renewable Natural Resources (*Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis* - IBAMA), the federal environmental agency. Therefore, except for very small CCS projects, federal licensing is required.

Law 9,605/98, known as the “Environmental Crimes Law”, defines these crimes and the penalties that can be imposed on companies and individuals to deter commission of acts harmful to the environment. For individuals found liable, the penalties include imprisonment or other restriction of rights and fines. Companies that commit environmental crimes can receive fines and temporary or even permanent interdiction of activities. As far as the duty to pay compensation for damages, the general rule is strict liability, under the polluter pays principle, whereby the polluter is obligated to repair the damage caused to other parties and the public at large, regardless of blame or intention – it is enough to have caused the damage. So, if a company commits an environmental crime and it can be established that the owners, officers/managers acted negligently or with willful misconduct in the commission of that crime, they can be held personally liable.

5. Conclusions

An increasing supply of energy is an essential factor for economic growth and to improve living standards and quality, especially in developing countries. However, the current global energy mix, which is heavily reliant on burning fossil fuels, is responsible for the majority of GHG emissions. The search for new technologies that can reduce these emissions must be approached as a long-range policy. In the short and medium terms, due to this intense use of fossil fuels, CCS is the only technologically feasible option to mitigate GHG emissions on a large scale in a process of transition to a global energy system dominated by carbon-free sources.

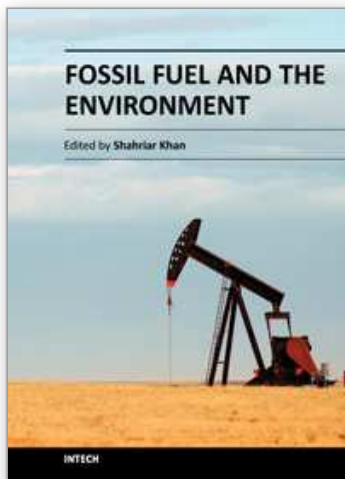
The future of the CCS industry unquestionably depends on public acceptance and government support and encouragement, positively through subsidies and/or tax breaks and negatively through prohibitions on certain activities and setting of emissions limits. In this respect, public policymakers and legislators will play a defining role. Various projects whose pilot phases have been technically approved and have public and/or private funding committed are still waiting for definition of the applicable regulations so they can be scaled up. Because the implementation of a CCS project raises operating costs, there need to be general rules and public mechanisms (tax breaks, subsidies and/or carbon trading schemes) to defray these costs.

6. References

- Air Products (2011). Port Arthur Project Update: Demonstration of CO₂ Capture and Sequestration for Steam Methane Reforming Process for Large Scale Hydrogen Production, presentation at *NETL CO₂ Capture Technology Meeting*, Pittsburgh, PA, USA, August 22 - 26, 2011
- Alstom Power (2011). Recovery Act: Oxy-Combustion Technology Development for Industrial-scale Boiler, presentation at *NETL CO₂ Capture Technology Meeting*, Pittsburgh, PA, USA, August 22 - 26, 2011
- Barlet-Goué'dard, V.; Rimmele, G.; Porcherie, O.; Quisel, N. & Desroches, J. (2009). A solution against well cement degradation under CO₂ geological storage environment. *International Journal of Greenhouse Gas Control*, 3, p. 206–216.
- Barrie, J.; Brown, K.; Hatcher, P.R. & Schellhase, H.U. (2004). Carbon dioxide pipelines: A preliminary review of design and risk. *Proceedings of VII International Conference on GHG Control and Technologies (GHGT)*
- BGS (2011). Removal of CO₂ from natural gas processing plant, Available from www.bgs.ac.uk/discoveringGeology/climateChange/CCS/RemovalCO2NaturalGas.html
- Boe, R.; Magnus, C.; Osmundsen, P.T. & Rindstad, B.I. (2002). Geological storage of CO₂ from combustion of fossil fuel. Summary Report of the GESTCO Project. Geological Survey of Norway, Trondheim
- Broek, M.; Ramírez, A.; Groenenberg, H.; Neele, F.; Viebahn, P.; Turkenburg, W. & Faaij, A. (2009). Feasibility of storing CO₂ in the Utsira formation as part of a long term Dutch CCS strategy. An evaluation based on a GIS/MARKAL toolbox. *International Journal of Greenhouse Gas Control*

- Cenovus Energy (2011). Weyburn CCS Overview, presentation at *Petrobras CCS Mission to Canada*, Regina, SK, Canada, March 21, 2011.
- EEA (European Environment Agency) (2010). Annual European Union greenhouse gas inventory 1990-2008
- Iding, M. & Ringrose, P. (2009). Evaluating the impact of fractures on the long-term performance of the In Salah CO₂ storage site. *Energy Procedia* 1 p. 2021-2028
- IEA (International Energy Agency) (2010a). CO₂ Emissions from Fuel Combustion
- IEA (International Energy Agency) (2010b). Energy Technology Perspectives 2010, Scenarios and Strategies for 2050
- IEA&CSLF (International Energy Agency & Carbon Sequestration Leadership Forum) (2010). Carbon Capture and Storage – Progress and Next Steps
- IPCC (Intergovernmental Panel on Climate Change) (1996). Climate Change 1995: The Science of Climate Change. Intergovernmental Panel on Climate Change, J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell. (eds.). Cambridge University Press. Cambridge, United Kingdom
- IPCC (Intergovernmental Panel on Climate Change) (2005). IPCC Special Report on Carbon Dioxide Capture and Storage, *prepared by Working Group III of the IPCC*
- Koornneef, J.; Spruijt, M.; Molag, M.; Ramírez, A.; Turkengurg, W. & Faaij, A. (2010). Quantitative risk assessment of CO₂ transport by pipelines—A review of uncertainties and their impacts. *Journal of Hazardous Materials* 177, p. 12-27
- MCT Brazil (Brazilian Science and Technology Ministry) (2010). Brazilian Inventory of made-man emissions by sources and removals by sinks of GHG, Brazil.
- Patil, R.H.; Colls, J.J. & Steven, M.D. (2009). Effects of CO₂ gas as leaks from geological storage sites on agro-ecosystems, *Proceedings of 3rd International Conference on Sustainable Energy and Environmental Protection*
- Reeves, S. & Clarkson, C. (2003). The Allison Unit CO₂-ECBM Pilot: A Reservoir Modeling Study. *Topical Report US DOE*
- Sherrick, B.; Hammond, M.; Spitznogle, G.; Muraskin, D.; Black, S.; Cage, M. & Kozak, F. (2009). CCS with Alstom's Chilled Ammonia Process at AEP's Mountaineer Plant. Alstom Power, Inc.
- Solomon, S. (2007). Carbon Dioxide Storage: Geological Security and Environmental Issues - Case Study on the Sleipner Gas Field in Norway. *Bellona Foundation*
- US EPA (United States Environmental Protection Agency) (2009). Endangerment and Cause or Contribute Findings for Greenhouse Gases Under Section 202(a) of the Clean Air Act; Final Rule
- US EPA (United States Environmental Protection Agency) (2011a). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009
- US EPA (United States Environmental Protection Agency) (2011b). Rulemaking of Greenhouse Gas Emissions from Electric Utility Generating Units, presentation at *NETL CO₂ Capture Technology Meeting*, Pittsburgh, PA, USA, August 22 - 26, 2011
- Wilson, E.J.; Friedmann, S.J. & Pollak, M.F. (2007). Research for deployment: Incorporating risk, regulation, and liability for carbon capture and sequestration. *Environmental Science Technology*. 41, p. 5945-5952

- WTO&UNEP (World Trade Organization & United Nations Environment Program) (2009). Trade and Climate Change WTO-UNEP Report
- Zhou, W.; Stenhouse, M.J.; Arthur, R.; Whittaker, S.; Law, D.H.S.; Chalaturnyk, R. & Jzrawi, W. (2004). The IEA Weyburn CO₂ Monitoring and Storage Project – Modeling of the Long-Term Migration of CO₂ from Weyburn. *Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies (GHGT-7)*



Fossil Fuel and the Environment

Edited by Dr. Shahriar Khan

ISBN 978-953-51-0277-9

Hard cover, 304 pages

Publisher InTech

Published online 14, March, 2012

Published in print edition March, 2012

The world today is at crossroads in terms of energy, as fossil fuel continues to shape global geopolitics. Alternative energy has become rapidly feasible, with thousands of wind-turbines emerging in the landscapes of the US and Europe. Solar energy and bio-fuels have found similarly wide applications. This book is a compilation of 13 chapters. The topics move mostly seamlessly from fuel combustion and coexistence with renewable energy, to the environment, and finally to the economics of energy, and food security. The research and vision defines much of the range of our scientific knowledge on the subject and is a driving force for the future. Whether feasible or futuristic, this book is a great read for researchers, practitioners, or just about anyone with an enquiring mind on this subject.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Victor Esteves and Cláudia Morgado (2012). Carbon Capture and Storage - Technologies and Risk Management, Fossil Fuel and the Environment, Dr. Shahriar Khan (Ed.), ISBN: 978-953-51-0277-9, InTech, Available from: <http://www.intechopen.com/books/fossil-fuel-and-the-environment/carbon-capture-and-storage-ccs-technologies-and-risk-management>

INTECH
open science | open minds

InTech Europe

University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China

Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

© 2012 The Author(s). Licensee IntechOpen. This is an open access article distributed under the terms of the [Creative Commons Attribution 3.0 License](https://creativecommons.org/licenses/by/3.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

IntechOpen

IntechOpen