# EUSUSTEL

European Sustainable Electricity
Comprehensive Analysis of Future European Demand and
Generation of European Electricity and its Security of Supply

# WP3:
# $CO_2$ Capture and Sequestration (CCS)

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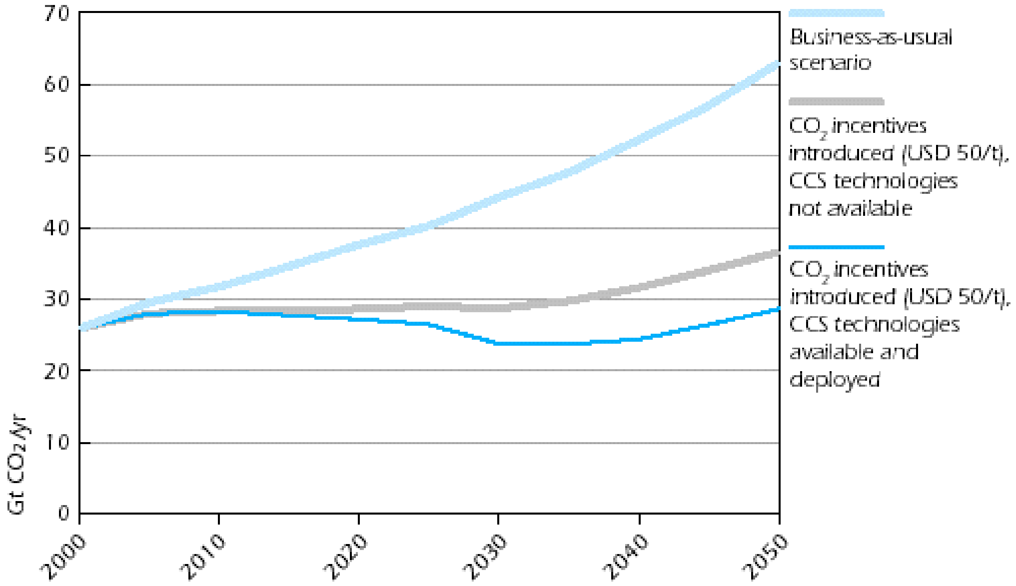
# 1. Introduction

Fossil fuel combustion produces $CO_2$, the main anthropogenic greenhouse gas which, if released into the atmosphere, is responsible for enhancing the greenhouse effect, leading to global warming. This may have a substantial detrimental impact on many ecosystems, people and economies, especially in the most vulnerable parts of the world. **The problem is global and so the solutions need too.**
It is now generally accepted that limits will have to be placed on the atmospheric concentration of $CO_2$ and other greenhouse gases in the atmosphere, and that emissions of $CO_2$ will need to be reduced significantly below their current level, in order to stabilize the atmospheric concentration of $CO_2$ at a reasonable level. The third report of the IPCC (International Panel on Climate Change) shows that with a concentration stabilized about 450ppm (360ppm today) of $CO_2$ (most optimistic scenario for concentration), the prediction is an increased by 1,5 to 3,9°C of the 1990's temperature until 2100 which should have **main consequences on the earth climate**.

Fossil fuels will continue to provide a large proportion of the world's commercial energy in the near future (still up to **90% of the energy system is expected to be supplied by fossil fuels in 2030**) The world will need a technology of $CO_2$ emissions reduction during its transition to a much less carbon intensive economy, which may take at least fifty years. Since we cannot avoid using fossils fuels, CCS represents one of the best options to continue using fossil fuels during that period, reducing substantially the emissions of $CO_2$ in the atmosphere. Besides, in the early stages of a possible future hydrogen economy, a sequestration of $CO_2$ emissions will be necessary because hydrogen will be produced mainly from fossil fuels.

The figure below presents an **assessment** of the possible impact of carbon dioxide capture and storage technologies, on $CO_2$ emissions under the following scenarios:
- Business-as-usual (no new $CO_2$ abatement policies);
- $CO_2$ capture and storage technologies are available and could be deployed due to worldwide introduction of relatively strong $CO_2$ abatement policies (represented by a tax of US$50 per ton of emitted $CO_2$);
- The same $CO_2$ abatement policies are introduced but CCS technologies are not available.

If the $CO_2$ abatement **policies** are only based on substituting fuel whenever possible by nuclear energy, renewables and energy efficiency measures without any efficient CCS technology, it will not be possible to reduce enough $CO_2$ emissions. Data in the figure below indicate that CCS technologies significantly increase the impact of $CO_2$ incentives. The analysis reveals that for the same $CO_2$ abatement policies, annual emissions of $CO_2$ in 2050 are 25% lower when CCS technologies are available.



*Assessment of $CO_2$ emissions until 2050,* The Prospects for $CO_2$ Capture and Storage, IEA WOE 2004

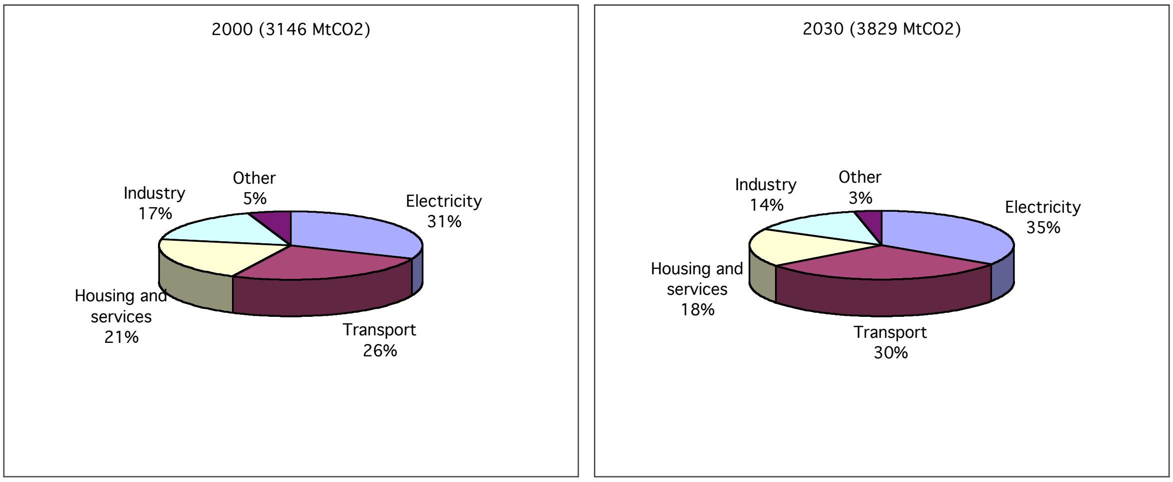
There are **two main difficulties** in the setting up of a real policy for the $CO_2$ capture and sequestration. The first one is the **time scale**. Even if the production of oil progressively decreases in the coming decades, engine fuels will have to be produced anyway from gas or coal. A switch to an economy where fossil fuels are replaced by renewables is still far away. Therefore, CCS technologies will be required at least for large centralized emission sources.
The second one is the **quantity** of $CO_2$ to be stored. In order to reduce significantly $CO_2$ emissions at a worldwide level, it will be necessary to store huge quantities of $CO_2$.

# 2. Description of technologies (state of art and trends)

Three stages for technologies can be studied: capture, transport and storage.

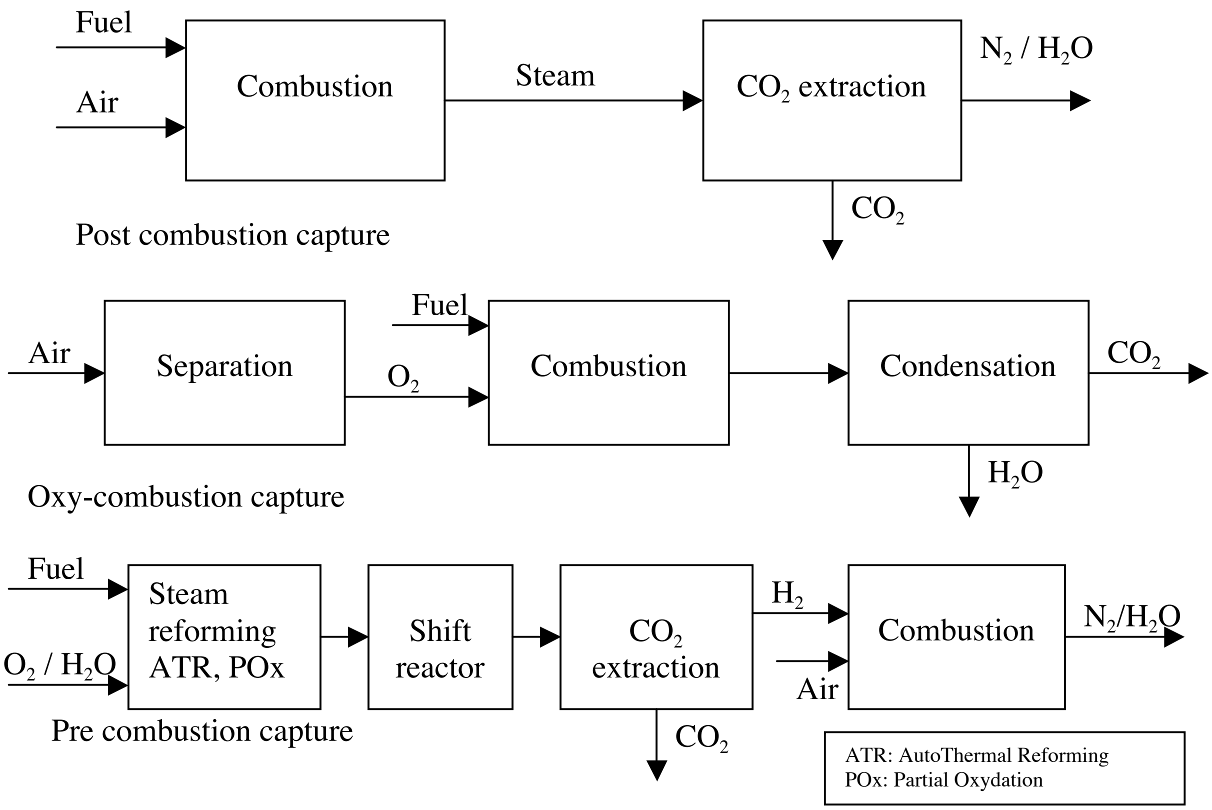
## 2.1. Capture

Capture of $CO_2$ is best carried out at **important point sources of emissions**, such as power stations as well as other large industrial production plants. **Thermal power stations**, coal-fired especially, are the chief target with **40%** of the carbon emissions (about 7 billions $tCO_2$ / year in 2004). **Industries** like steel plants, cement plants, iron plants, refineries and petrochemical plants are also very important carbon dioxide producers with 3,7 billions $tCO_2$ per year in 2004 (about **20%** of all the emissions). E.U. emissions split is somewhat different with 31% (35% in 2030) from thermal power plants and 17% (14% in 2030) from industry.



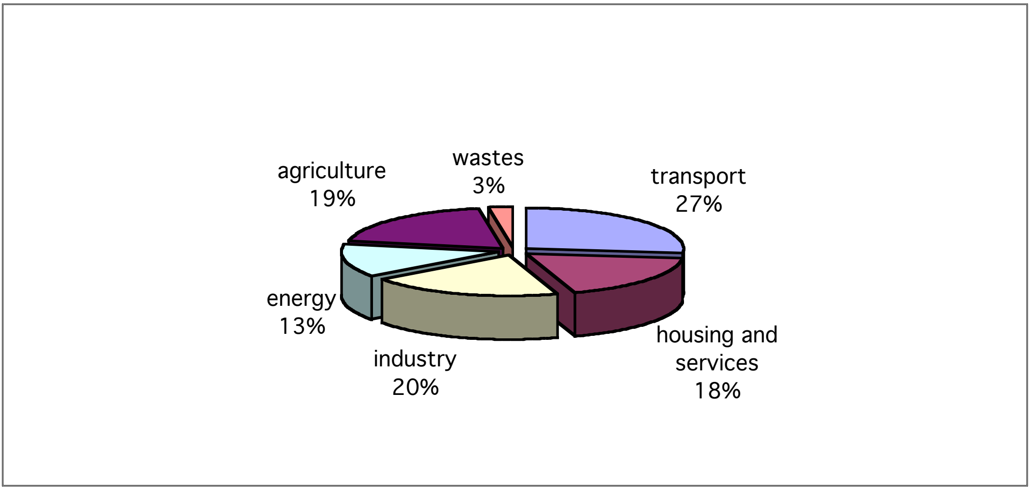

Carbon emissions in 2000 and 2030 by sectors in Europe, IEA

$CO_2$ is more easily captured if$CO_2$ emissions are concentrated. Three types of capture pathways can be used:
***Post combustion***: $CO_2$ is captured from flue gases. Though requiring some thorough retrofit, this process can be used for existing units.
***Oxy-combustion***: Pure oxygen is used or the combustion process, which means that $CO_2$ is not diluted with nitrogen and can be much more easily recovered from flue gases.
***Pre combustion***: Synthesis gas is produced from the primary fuel and then $H_2$ is separated from CO2. Then hydrogen can be used for generating energy, without $CO_2$ emissions.




Types of $CO_2$ capture

As indicated in the graph below, industry and energy sectors represent 33% of the carbon emission in France. About 120 millions tons of carbon can potentially be captured and stored each year



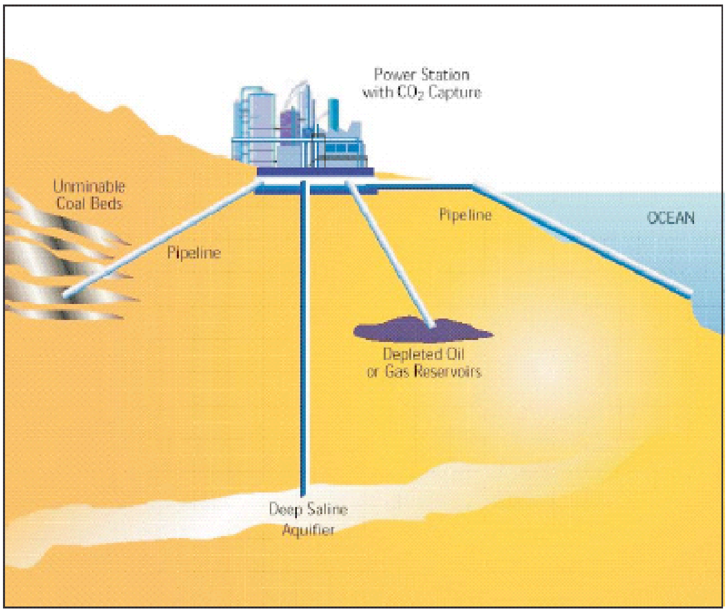

$CO_2$ emissions by sectors in France, 2001 (base: 557 millions tons of $CO_2$ / year)

## 2.2. Transport

**Pipelines** represent the most common way for transporting large quantities of $CO_2$ Moreover, petroleum and gas industries have lots of **experience** in this type of transportation system. Since $CO_2$ is a molecule non toxic (at small concentrations but it can be lethal for human if it replaces oxygen) and not flammable the risks are limited.

Carbon dioxide is usually carried at a high pressure as a supercritical phase. An alternative option consisting in liquid phase transportation is presently investigated at the IFP (Institut Français du Pétrole)

## 2.3. Storage




*Options for storage of $CO_2$*, Putting carbon back into the ground, IEA 2001

For storage, the main point is to ensure enough injection capacity during the injection phase and control the integrity of the storage site on the long term. This last point is of utmost importance to gain the **social acceptation of population**. Large information is needed and knowledge of all the environment impact is required. It should be in particular ensured that there would be no leak in the environment. If any reversibility of the storage has to be arranged in such a way that it will be possible to intervene on a site as long as long term integrity has not been proved.

In 1998, more than 500 sites of sequestration for natural gas were used of about 164Gm3. They were chiefly in the USA, Germany, France, Italy and Canada (Stevens and al, 2001)

## Geological storage

*Oil and gas reservoirs:*

$CO_2$ storage can be used to enhance the recovery factor of oil reservoirs (Enhanced Oil Recovery). Between a quarter or a half of ton of $CO_2$ needs to be used for one barrel of oil. But the quantity stored is just a few part of it. The goal is to increase both the oil recovery, maximize the quantity of stored carbon dioxide while decreasing the cost and ensuring the long term integrity of the storage.

**The oil &gas industry has an important expertise** in geosciences and participates in major $CO_2$ storage research and development projects. These industries should be able to offer storage services in the future and participate to CCS projects.

It is difficult to increase the recovery of gas with this technology because already 60 to 70% of the quantity of hydrocarbon can be easily recovered. In addition to that, the $CO_2$ concentration in the produced gas is increasing and need to be separated adding thus some extra cost for the $CO_2$ storage. Anyway, the potential of Carbon storage associated with Enhanced Gas Recovery (CSEGR) is **important,** presents **high value products** and needs further developments.

*Deep aquifers*

Deep saline aquifers which contain non drinkable waters represent an interesting opportunity for natural gas or carbon dioxide storage. In 1995, 85 deep aquifers were used to store gas with 12 out of them located in France. A seasonal storage is commonly applied to natural gas and companies have a good experience in the management of such a process. As far as carbon dioxide is concerned, one experiment has been conducted in the Utsira formation of the **Sleipner field by Statoil** since 1996. Each year, 1Mt $CO_2$ is stored in the underground between 800 and 1000 meters under the sea bed getting advantage of the Norwegian carbon emission taxation regime. The cost of this sequestration is about 15 USD per ton of $CO_2$. Mastering storage in aquifers requires an important R&D effort, mainly for better predicting the long term behavior of the $CO_2$.

*Un-mined coal beds*

Many coal beds can hardly be mined, but **high value products** could be extracted by an Enhanced Coal Bed Methane Recovery (ECBMR) method. The ruling mechanism is as follows. When $CO_2$ is put in contact with coal, it gets adsorbed and displaces methane. The nice point is that for 1 molecule of methane displaced and then recovered, 2 molecules of $CO_2$ can be stored.

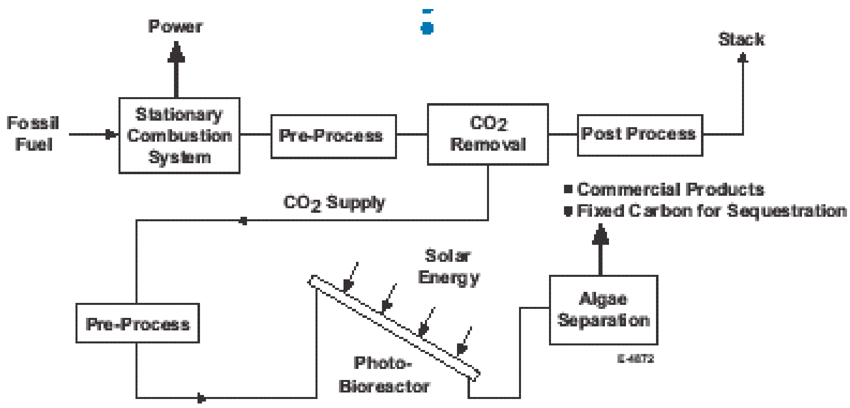
| Sequestration option | Global capacity (Gt $CO_2$) | Part of cumulated emissions 2005 - 2030 (%) |
|---|---|---|
| Oil and gas reservoirs | 100 - 1000 | 13 - 130 |
| Deep saline aquifers | 400 - 10000 | 51 - 1300 |
| Coal seams | 10 - 100 | 1 - 10 |

Comparison of geological storage capacities of hydrocarbon reservoirs, deep saline aquifers and coal seams.

## *Biological sinks*

*Seaweed:*

The efficiency of using solar energy is about 5% with seaweed and only 0.2% for other vegetation (so a best set of carbon). This trapping is supposed to take the $CO_2$ from stationary combustion systems and use the photosynthesis of **microalgae**. Output can be high value products. The Physical Sciences Inc, the university of Hawaii and Aquasearch develops a project to optimize and demonstrate an industrial-scale photobioreactor.




*Recovery and sequestration of $CO_2$ from stationary combustion systems by photosynthesis of microalgae,* project facts, DOE

Researches made by the National Renewable Energy Laboratory (NREL) of the DOE have stressed the advantage of the microalgae. They can be used for the production of biofuel with a **good efficiency**. GreenFuel Corporation is an experimentation of a bioreactor link with a cogeneration plant of 20MW. During a sunny day, about 82% of the $CO_2$ and 86% of the NOx are consumed. Scientists of the NREL estimate a cost of 46 billion dollars every year to produce all the biofuel for algae to the USA needs. This must be compared with 100 to 150 billion dollars for the petrol.
But it does not settle the sequestration of the carbon due to the combustion of the biofuel.

*Methalogens bacteria:*

It consists of a conversion of $CO_2$ into $CH_4$ by a family of bacteria: **the methalogens**. Major hopes are made in this technology because of high value products. But the produced methane has to be trapped without any leak because of important consequences on global warming (24 times greater than $CO_2$). As with the microalgae, it's not a long time sequestration of carbon due to combustion of methane

## *Mineralisation*

The goal is to fix the carbon into a solid product, mainly **calcium carbonate** because it is a widely available mineral. Kinetics is a major difficulty and, presently in order to reach fast enough kinetics high amounts of grinded minerals are required.
For example, a coal station of 500MW emits about 7200 $tCO_2$ every day and need 20 000 tons of minerals for the carbon sequestration into carbonate.

## *Ocean*

Although this type of storage has the **largest capacities**, due to the eventual acidity effect which could be detrimental on the seawater fauna and flora, ocean $CO_2$ storage does not receive a lot of attention. Indeed, environmental impacts are hardly defined and the social acceptation is very difficult (i.e. experimentation in Kona Coast, Hawaii). Because it has few reservoirs to store carbon dioxide and high emissions, Japan is the leader in this technology.
Three types of sequestration can be used:

*Injection in intermediate deep (1500 – 2000 meters)*

In order to minimize the environmental effect and avoid the most populated area, injections have to be made at a deph of at 1500 meters. Simulations show a sequestration time about centuries in the absence of any hydrodynamic instability.

*Injection in high depth (up to 3000 meters)*

At this depth, $CO_2$ is denser than water and it's feasibly to create a lake of $CO_2$ liquid on the sea bed. Even if the sequestration will be more secured, local **environmental impacts on fauna and flora would be very important** and need specific ground installations.

*Drop of $CO_2$ blocs*

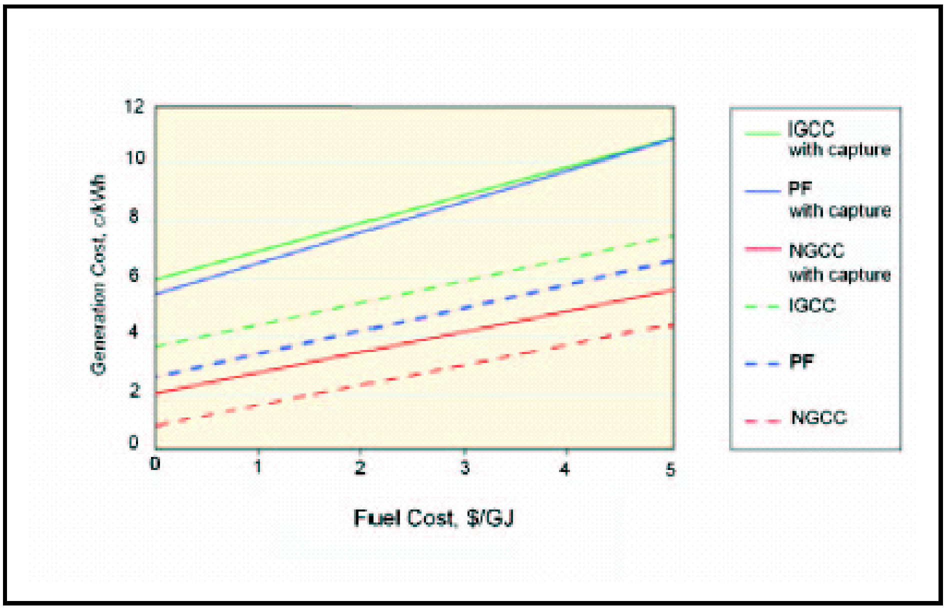
With a density of 1.5t/m3, blocs will fall from a boat to the sea bed quickly. But the **population may not accept** this type of storage.

Many countries are carrying out studies on geological storage and make data basis. One of the great advantages of the geological storage is its **reversibility**. Carbon dioxide can be removed in large extent. But developments have to be done on the sequestration security on the long-term.
Another problem is the **mix between carbon dioxide and other gases** (NOx, SOx…) in the storage. Carbon alone is quite harmless but certainly not a mix of gases. For precautionary measures, experimentations can be stopped but they are necessary for the future of the carbon storage.
Nevertheless, the capacities are very important and will be determining for the global warming.

## Legal aspects

The international conventions (London convention 1972, United Nations Convention on the Law of the Sea 1982…) do not refer explicitly to carbon dioxide. The issue is thus to determine whether the $CO_2$ can be regarded or not as a natural or industrial waste or if some value can be attached to it.
Except for the mining law which could applied to onshore geological storage in depleted hydrocarbon reservoirs, a **legal framework has to be created for $CO_2$ storage at least for storage in saline aquifers**.

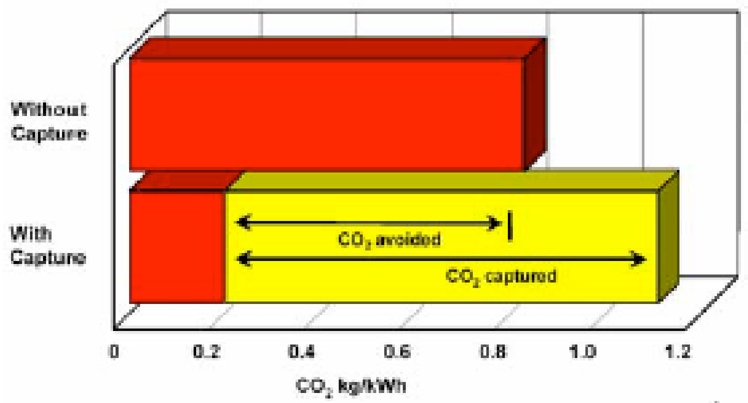
The next graph shows the cost of the sequestration in different electric power plants The NGCC technology is the less influenced by the capture system.




*Costs of electricity generation with and without $CO_2$ capture and storage,* Putting carbon back into the ground, IEA 2001

IGCC: Integrated Gasification in Combined Cycle
PF: Pulverized Fuel
NGCC: Natural Gas in Combined Cycle

One of the most notes is the difference between the carbon avoided and captured. In fact, the capture of $CO_2$ required lots of energy. The same production of power or products needs more fossil fuel and so increases the production of carbon. **Power stations efficiency decrease of 6 to 12%**.




Importance of efficiency reduction and difference between $CO_2$ avoided and captured

Steam → Split-up → Compression → Transport → Storage

| Split-up | Compression | Transport | Storage |
| --- | --- | --- | --- |
| 50-60€/t | 8-10€/t | 0.5 - 10€/t for 100km | 2-8€/t |

The global cost is between **50 and 100€/t$CO_2$** with a large part (about 60%) for the capture. This cost must be compared with the price of carbon on the Powernext market (**28,90€/t** the 11/07/2005) and with the European penalties (40€/t$CO_2$ until 2008 and **100€/t$CO_2$** between 2008 and 2012)

# 3. Future breakthroughs (time horizon 2030) and relevance to electricity generation

Industrial sequestration is a young area of research. The first project has been developed only a few years ago. The main goals of research are:
Geological storage: Scientists have to solve at the same time short to medium term concerns essentially related to the $CO_2$ injectivity and long term issues like storage site integrity. Knowledge of physical and chemical reactions involved during the storage are necessary, as it is for the monitoring and the surveillance of the $CO_2$ evolution in the underground.
Ocean sequestration: **impacts on the biomass** have to be studied with large information to the population.
**An important decrease of the costs is required** mainly for the capture, which represent up to 70% of the global cost expressed per tons of avoided $CO_2$. A decrease by a factor 2 for the capture cost should be targeted for the implementation of an economic CCS process. A cost of 20 to 30€/t$CO_2$ is aimed by years 2015 to 2020.
A **legal framework** has to be created for the $CO_2$ storage and for the **liability** of carbon tanks.

| | | Benefits | Handicaps |
|---|---|---|---|
| Chemistry | | Permanent storage<br>Fixing with heat emission<br>Output with increasing of value | Slow reactions<br>High quantities of output |
| Biology | Seaweed | Don't need a concentrated gas<br>Can absorb NOx and SOx<br>Low environmental impact<br>Potential valuation<br>Potential production of biofuel | Low efficiency<br>Short time sequestration |
| | Bacterium methalogen | Methane production | Low efficiency<br>Short time sequestration |
| Geological | Deep aquifer | Very important capacity of storage<br>Industrial experimentation<br>Reversibility | Needs research on long time behavior<br>Poorly characterized<br>Security |
| | Oil and gas reservoir | Increase recovery factor<br>Increase quality of oil product<br>Important capacity of storage<br>Petrol industries expertise<br>Reversibility | Needs define most appropriate reservoirs<br>Less capacity of storage<br>Less evenly distributed |
| | Un-mined coal beds | Methane production<br>Reversibility | Very few capacity of storage<br>Injectivity questionable<br>Long term storage integrity |
| Ocean | Intermediate deep | Light ground installations<br>Very important capacity of storage | Environmental impact |
| | High depth | Very important capacity of storage | Local environmental impact<br>Important ground installations |
| | Drop of $CO_2$ blocs | Very light ground installations | Bad social acceptation |

# 4. Bibliography and web sites

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