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## **[CARBON CAPTURE AND STORAGE]**

The increasing greenhouse gas emission contributes to global warming and many long term effects. Carbon capture and storage (CCS) is the potential mitigation to address large scale green house gas emission which may require technological advancements and large capital investments. However, in comparison to other mitigation techniques, CCS will remain strong in the long term future compare to forestry means.

*Keywords: carbon, carbon capture and storage, CCS, carbon abatement, global warming*

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# Introduction

Carbon is an essential element of life. Every living organism on earth contains some sort of carbon. In different forms, Carbon dioxide (CO<sub>2</sub>) has been supporting plant growth ever since the existence of plants. Because of autotrophic organisms that absorb CO<sub>2</sub> and produce O<sub>2</sub> as a by product, the CO<sub>2</sub> level in the atmosphere has dropped to a suitable level to support biologic growth and evolution (Hieb, 2009).

CO<sub>2</sub>, also known as a greenhouse gas (GHG), is a life necessity. It traps long wave radiation transformed from the incoming short wave radiation of the sun (Reay, 2010). As a result, air on earth gets warmer which leads to serious consequences in the biosphere on earth.

Increased CO<sub>2</sub> levels not only increase the air temperature, but also increase ocean temperature and ocean salinity. As a result, there are serious consequences as higher ocean acidity slows ocean cycles as well as air exchange (Rasmusson, 2011).

However, as figure 1 illustrates below, the carbon dioxide level has been increasing dramatically since the industrial revolution in the 1900s. It is scientifically proven that the increasing atmospheric CO<sub>2</sub> level is the sole contribution to global warming (Geographic, 2007). CO<sub>2</sub> comes from many sources; mainly from anthropogenic activities by humans. For example, about 88% of carbon emissions come from burning fossil fuels and cement production, 12% come from land use change (Geoscience, 2009).

In 1992, the concern of climate change led to the formation of the United Nations Framework Convention on Climate Change (UNFCCC). The main objective of the convention is to “stabilization of greenhouse gas concentrations in the atmosphere at a level that prevents dangerous anthropogenic interference with the climate system” (UNFCC, 2005). Furthermore, it has been suggested that global energy uses project an increase of CO<sub>2</sub> emission in the short term future due to lack of mitigations. It is also suggested that the supply of energy will continue to be primarily fossil fuels until the middle of the century where alternate energy sources mature. Interest in carbon capture and storage (CCS) can be accounted for due to the substantial reliance on fossil fuel (about 80% globally), the potential of CCS to reduce atmospheric CO<sub>2</sub> in large

quantities, and the compatibility with current production facilities (IPCC, Scientific Facts on CO<sub>2</sub> capture and storage , 2005).

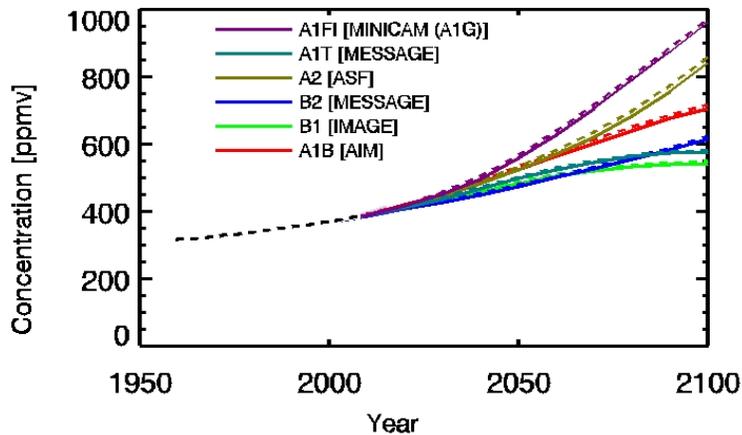


Figure 1: CO<sub>2</sub> level projection with different scenarios from IPCC (IPCC, Carbon Dioxide: Projected emissions and concentrations, 2010).

Because humans are alert, large scale mitigations have been implemented. Namely, CCS is the only large scale mitigation technique that reduces atmospheric CO<sub>2</sub>, which is implemented by humans. Carbon capture and storage is a technical method of capturing carbon dioxide (CO<sub>2</sub>) emissions in the atmosphere through extensive engineering practices, and storing it in appropriately safe locations as well as for economic recovery reasons. However, CCS is not a new technology. It has been proven to be a technically viable and environmentally friendly process to lower the level of greenhouse gases (GHG) where Sleipner in Norway was the first CCS facility put in large scale commercial operation since 1996 (ICO<sub>2</sub>N, Frequently Asked Questions, 2005).

This essay contains two major components. In the first component, carbon capture and storage will be discussed in engineering and technological terms. Specifically, the engineering aspect will focus on capturing methods, transportation techniques and storage mechanisms. In capturing methods, the three major capture methods will be explored as well as their advantages and disadvantages to determine the feasibility of certain scenarios. In transportation techniques, transporting by ship, truck and pipeline will be discussed in terms of viability on different scales. In storage mechanism, different storage means will be examined in terms of capacity. Moreover, the paper will introduce certain actions necessary to ensure operational safety as well as

challenges to a better implementation of CCS. In the second component, costs of carbon abatement will be analysed by means of CCS and forestry applications. Depending on different sectors, there are a variety of factors determining the costs of different strategies. The future dominating sector in carbon abatement will also be looked at based on effectiveness and growth of different sectors.

## Technology

### Introduction

CO<sub>2</sub> is a greenhouse gas (GHG) emitted by anthropogenic activities such as burning fossil fuels in large scale power plants, individual home heating systems, automotive engines and cement production. As figure 1, the carbon concentration graph, illustrates, CO<sub>2</sub> concentration has been increasing dramatically, which contributes greatly to global warming. In order to reduce anthropogenic CO<sub>2</sub> emissions, international mitigation protocols such as the Kyoto prototype, and an emission reduction treaty were signed across the countries to reach a significant reduction level in the near future. By capturing and storing carbon, it is the only technology available to reduce GHG emission in large quantities in point sources. Specifically, CCS involves intensive technology in capturing and concentrating industrial CO<sub>2</sub> initially, then transporting it to a suitable location for further storage.

### Capture methods

In order to determine the suitable sources, global CO<sub>2</sub> emission and concentrations statistics have to be examined. As illustrated earlier, CO<sub>2</sub> is a by-product of burning fossil fuels, primarily from power generation and cement production. Power generation is the largest emitting source in quantity out of all other major sources as shown in table 1 below. In comparison with residential and transportation sources, which are relatively small and mobile, emissions from power generation are more suitable for capture and storage as it is more stable in location as well as the bulk quantity. For this reason, the CCS discussed later in this paper will focus on the large scale power plants which are heavy point sources.

<b>Table 1: Worldwide large stationary CO<sub>2</sub> sources</b>		
<b>Process</b>	<b>Number of sources</b>	<b>Emissions (MtCO<sub>2</sub> yr<sup>-1</sup>)</b>
<b>Fossil Fuels</b>		
<b>Power</b>	4,942	10,539
<b>Cement production</b>	1,175	932
<b>Refineries</b>	638	798
<b>Iron and steel industry</b>	269	646
<b>Petrochemical industry</b>	470	379
<b>Oil and gas processing</b>	N/A	50
<b>Other sources</b>	90	33
<b>Biomass</b>		
<b>Bioethanol and bioenergy</b>	303	91
<b>Total</b>	<b>7,887</b>	<b>13,466</b>

Source: GreenFacts: [Table TS.2. Worldwide large stationary CO<sub>2</sub> sources](#)

Globally, close to 60% of the emission comes from a stationary point source as illustrated in the above table (FARLEY, 2008). According to the Intergovernmental Panel on Climate Change (IPCC), a small portion of industrial sources with fossil fuel as primary fuel have CO<sub>2</sub> concentrations exceeding 95%. These large scale point carbon sources are potential locations with the most interest to perform CCS (GreenFacts, Scientific Facts on CO<sub>2</sub> Capture and Storage, 2005).

There are three major processes of capturing industrial CO<sub>2</sub> in a power plant: capturing CO<sub>2</sub> in post combustion systems, capturing in pre-combustion systems, and altering the fuel in the burning process in order to capture CO<sub>2</sub> in the downstream. In principle, it is technologically possible to have the entire gas stream from exhaust flue to be transported and stored underground. However, the fact that the gas stream only contains a low concentration of CO<sub>2</sub> would make this approach impractical in financial terms. As a result, it is necessary to further process the low concentration flue gas to reach a concentration level feasible for transport and storage. The concentration of CO<sub>2</sub> is the core method to process captured CO<sub>2</sub> among all capturing techniques to make CCS financially possible (GreenFacts, How do CO<sub>2</sub> capture technologies work, 2005).

## Post combustion

### *Method*

The Post combustion system separates CO<sub>2</sub> from flu gas in the downstream of convention combustion equipment. Due to the fact that flu gas contains low CO<sub>2</sub> concentration, a process is required to further concentrate CO<sub>2</sub> as well as separating other combustion products such as: Sulphur dioxide (SO<sub>2</sub>), Nitrogen monoxide (NO<sub>x</sub>) and unburned hydrocarbons (HC). These are practically the same combustion products we get from vehicle exhaust fumes. Generally, the capturing process is called amine scrubbing. For instance, organic solvent such as monoethanolamine (MEA) in aqueous forms capture the small portion of CO<sub>2</sub>, typically occupying 3-15% in volume where the remaining gas is mostly nitrogen (Fennell, 2005).

To be more technical, the process can be separated into several steps. First the CO<sub>2</sub> is exposed to the liquid MEA about 15% to 30% in weight in a scrubbing column at 55 degree Celsius at a pressure of 14.5 psi (pound per square inch). The resulting loading of CO<sub>2</sub> at the exit of the column is about 0.4 mol CO<sub>2</sub> per mol MEA. CO<sub>2</sub> then is removed from the MEA mixture by boiling at 120 degree Celsius and 2 bar of pressure (Fennell, 2005). It is essentially mixing the exhaust gas with MEA which specifically captures CO<sub>2</sub>, followed by a separating technique by boiling, which makes the post combustion CO<sub>2</sub> capture feasible.

### *Advantage*

The advantage of the post combustion capturing process requires minimal facility changes. Since there are no modifications to the fuel itself as well as the burning process, the post combustion method only requires add-on capturing features which are not only cheaper than other alternatives like altering fuel but also provides flexibility to plant owners for implementing this strategy in financial and engineering terms. Since this technology has been used for years compared to alternatives, the bulk of industrial experience knowing initial cost and maintenance cost eliminates necessary financial and technological risks (Fennell, 2005).

### *Disadvantage*

On the other hand, there are disadvantages to MEA scrubbing. The organic solvent MEA (Monethanolamine) being used in this technology is known to be corrosive and will be degraded during the process of scrubbing. Despite the fact that initial cost is significantly lower than other

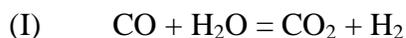
alternatives, MEA is an expensive solvent which imposes higher maintenance cost (Fennell, 2005).

## Pre-combustion

### *Method*

The pre-combustion CO<sub>2</sub> capture process requires separating and removing the carbon content in the fuel prior to the combustion process. In this process, fuel is altered to become pure carbon monoxide (CO) and hydrogen (H<sub>2</sub>) which is called the “synthesis gas”. CO<sub>2</sub>, on the other hand, is captured before the combustion process, unlike the post combustion capture (BELLONA, Technology: pre combustion, 2009).

Initially, the pre-combustion method processes the primary fuel in a reactor with steam and air to produce a “synthesis gas” containing only carbon monoxide (CO) and hydrogen (H<sub>2</sub>). Then in the next reactor, the “shift reactor,” additional hydrogen and carbon dioxide are produced by reacting carbon monoxide with steam according to equation (I).



CO subsequently reacts with steam (H<sub>2</sub>O), becoming CO<sub>2</sub>, which is a gas product removed in the same absorption based capture process as the post combustion process. The result substance of this process is a hydrogen-rich gas which can be combusted in power plants as well as vehicles where the combustion products do not contain any CO<sub>2</sub> (Fennell, 2005).

### *Advantage*

The advantage of the pre-combustion process is the high concentration of CO<sub>2</sub>. About 90% of CO<sub>2</sub> content can be removed in a power plant, as well as through the high pressure in the shift reactor, which is often favourable for CO<sub>2</sub> separation.

The pre-combustion capturing process emphasizes evolutions in the power plant industry because of the fuel. In comparison with traditional plants which combust coals directly, the pre-combustion technology separates CO<sub>2</sub> and H<sub>2</sub> prior to combustion. With impurities being removed prior to combustion, the resulting combustion product contains lower environmental contaminants such as: sulphur dioxide and particulates.

## *Disadvantage*

Compared with post combustion systems, it is more costly in energy and financial terms as the fuel conversion is more complex (Jacob, 2008). This is only viable for new plants and not existing power plants like the post combustion systems. It is significantly more expensive to invest on a gas power plant with pre-combustion systems than a similar plant with using post-combustion capture of flue gases. Not only it is more expensive to do so, but the pre-combustion technologies are also not as mature as post-combustion captures. Current existing power plants willing to retrofit with CO<sub>2</sub> capture technology will mainly choose post-combustion systems (BELLONA, Technology: pre combustion, 2009).

Within 15 to 20 years, it is expected that the cost of exercising pre-combustion CO<sub>2</sub> capture will be significantly reduced as the ongoing research will further improve the technology. Within a decade or two, we expect the energy cost of pre-combustion CO<sub>2</sub> capture to be lower than the post-combustion CO<sub>2</sub> capture (BELLONA, Technology: pre combustion, 2009).

## **Oxyfuel**

### *Method*

“Oxyfuel” is another alternative to CO<sub>2</sub> capture. As the name implies, oxygen acts as the primary fuel instead of typical air in post-combustion systems. The resulting combustion product by burning nearly pure oxygen is mainly CO<sub>2</sub> and water vapour which can be easily separated.

To be more technical, the separation of oxygen takes place in a cryogenic distillation. First the air is cooled to below boiling point, right before the liquefied oxygen, nitrogen and argon are separated. Then O<sub>2</sub> is separated and captured from the air, ready for the burning process (BELLONA, Technology: Oxyfuel, 2009).

The removal process consists of two major processes where the first one removes impurities like water vapour and carbon dioxide, and the second removal process separates desired product from air. To be more specific, a “molecular sieve” or “pre-purification unit” is usually used to remove CO<sub>2</sub> and other contaminants like hydrocarbons by catching molecules onto the sieve materials at ambient temperature. The absorbents are contained in two identical vessels where one is used to purify air and the other is being regenerated (Gases, 2003).

The second separation process utilizes a distillation system where it uses two distillation columns in series, commonly called the “high” and “low” pressure columns. Since argon has a similar boiling point to oxygen, argon is likely to stay with oxygen products. As a result, when oxygen is a desired product from the distillation process, argon has to be removed from oxygen in the distillation system. The removal of argon takes place in the low pressure column where the concentration of argon is the highest. The removed argon will be purified or processed in different manners depending on demand (Gases, 2003).

### *Advantage*

The advantage of using oxyfuel is the ease of separation of the combustion products. It generates a combustion product consisting of only water vapour and CO<sub>2</sub> which a traditional condenser will be able to separate. Having the exhaust gas stream cooled to desired temperature, the water condenses and the stream of gas becomes a stream of pure CO<sub>2</sub>. This separation practice is much easier and less energy exotic than the CO<sub>2</sub> separation in post-combustion CO<sub>2</sub> capture (BELLONA, Technology: Oxyfuel, 2009).

### *Disadvantage*

Although the whole oxyfuel process eases the separation of CO<sub>2</sub> and other combustion products, the production of oxyfuel itself consumes an enormous amount of energy. The temperature has to be cooled to -196 degree Celsius to separate the oxygen from the air. It may also require redesigning the burner because the high CO<sub>2</sub> content makes flame properties different from burning traditional fuel. Hence, the cost of running oxyfuel may pose barriers to interest in terms of investment.

To separate pure oxygen from air prior to the burning process is an expensive practice; however, there will be technologies that will easily separate oxygen from air utilizing membranes in the future. For example, Novel technologies use membrane as a filter to separate CO<sub>2</sub> and N<sub>2</sub>. However, it may take another half decade for this technology to become mature enough for the industry and market (BELLONA, Technology: Novel technologies, 2009).

# Transport

After the CO<sub>2</sub> is captured, it needs to be transported to a storage site for long term storage or EOR (enhanced oil recovery) fields for further recovery of oil. If a geological storage site is not directly under the power plant where the CO<sub>2</sub> is captured, then CO<sub>2</sub> has to be transported.

Shipping and transporting CO<sub>2</sub> is not a recent technology. Small volumes of CO<sub>2</sub> for cooling and food production have been shipped from manufacturers to consumers for decades. To have CO<sub>2</sub> shipped, the CO<sub>2</sub> content has to be cooled to -30 degree Celsius as well as compressed to higher than 18bar (261psi) in a liquid form to ease transportation and storage (BELLONA, Technology: Transport, 2009)

## Shipping and trucking

There are several transporting methods, namely, waterways, pipeline and trucking. Compared with pipelines, ship and truck transportation offers more flexibility for small scale projects in financial terms. For a small amount of CO<sub>2</sub>, it is significantly cheaper to transport by ship than pipelines. Shipping is also a good solution for projects at their initial phase where pipelines are not available. Furthermore, in the case of utilizing CO<sub>2</sub> for enhanced oil recovery (EOR), ship transport would be more ideal than pipelines when the EOR site is often off shore. In terms of EOR that may need a small quantity of CO<sub>2</sub>, the window for the operation is only several years. As a result, the investment on a pipeline for certain projects may not recover itself within the window of operation which makes shipping a better alternative.

Moreover, transporting CO<sub>2</sub> is similar to transporting LPG (liquefied petroleum gas). As the big oil companies already have ships to transport LPG, they can simply modify their ships to be CO<sub>2</sub> transport compatible. This may be the next best alternative to pipeline in terms of cost per mile when pipelines are not available.

## Pipeline transport

On the other hand, pipeline transport is not a recent technology either. Transporting CO<sub>2</sub> through pipelines has been used in the United States since the 1970s (BELLONA, Technology: Transport, 2009). Mainly for the purpose of large scale EOR, more than 40Mt of CO<sub>2</sub> is transported through pipelines each year to the site in Texas. In these long pipelines, CO<sub>2</sub> is

transported in high pressure with an ambient temperature. In most cases, the flow is driven by external forces such as compressors or motors at the upstream end; however, some pipelines have intermediate booster stations (GreenFacts, Scientific Facts on Carbon Capture and Storage, 2005).

The pipeline itself is made out of steel, which are the same pipelines that transport natural gas. This poses a challenge because CO<sub>2</sub> is corrosive and may quickly corrode the pipelines with holes. However, CO<sub>2</sub> is only corrosive when water is present, so water is usually dried out before the CO<sub>2</sub> is transported (BELLONA, Technology: Transport, 2009).

There are advantages and disadvantages in each of the transportation methods. Transporting CO<sub>2</sub> through pipelines is only feasible for a long term operation since construction and maintenance impose much higher costs than alternatives. However, it is much cheaper to do so in large scale operations transporting storing materials for a long period of time like they do in Texas since 1970s. On the other hand, shipping and trucking creates enormous flexibility in terms of shipping location, quantity and scheduling. As fuel price as well as the scale of operation increases in the future, shipping and trucking may become less feasible in terms of cost and pipeline transport may become the most favourable transportation method of CO<sub>2</sub>.

## Enhanced Oil Recovery (EOR)

Enhanced oil recovery (EOR) is a technique used by oil companies to extract more crude oil from an oil field. By injecting CO<sub>2</sub> and nitrogen mix into the oil field, the gas mixtures not only reduce the viscosity of the crude oil and enhance the flow rate but also displace the crude oil in the oil field for further recovery of crude oil and oil production. Using EOR, about 30% to 60% of more crude oil can be extracted (ENERGY, 2006).

## Storage

After the CO<sub>2</sub> is captured and transported, it requires being stored in a safe manner. CO<sub>2</sub> can be stored in a high pressure liquid form as well as in other forms to reduce cost and storage spaces depending on application. However, there are many technical restrictions in storing CO<sub>2</sub>. For instance, the storing requirements vary with different forms of CO<sub>2</sub>. The storage site has to

meet certain safety and capacity requirements, and predictions must be made prior to the storing process. Lastly, the storing site has to be monitored for safety.

There are three main ways of CO<sub>2</sub> storage, namely, geological storage, ocean storage and mineral storage. Geological storage is by far the most significant storing feature as it provides the largest storing capacity. For example, as we can see from the table 2, the Sleipner Project in the North Sea was the earliest project with the highest planned geological storage (GreenFacts, Scientific Facts on Carbon Capture and Storage, 2005).

**Table 2. Sites where CO<sub>2</sub> storage has been done, is currently in progress or is planned, varying from small pilots to large-scale commercial applications.**

Project name	Country	Injection start (year)	Approximate average daily injection rate (tCO <sub>2</sub> day <sup>-1</sup> )	Total (planned) storage (tCO <sub>2</sub> )	Storage reservoir type
<b>Weyburn</b>	Canada	2000	3,000-5,000	20,000,000	EOR
<b>In Salah</b>	Algeria	2004	3,000-4,000	17,000,000	Gas field
<b>Sleipner</b>	Norway	1996	3,000	20,000,000	Saline formation
<b>K12B</b>	Netherlands	2004	100 (1,000 planned for 2006+)	8,000,000	Enhanced gas recovery
<b>Frio</b>	U.S.A	2004	177	1600	Saline formation
<b>Fenn Big Valley</b>	Canada	1998	50	200	ECBM
<b>Qinshui Basin</b>	China	2003	30	150	ECBM
<b>Yubari</b>	Japan	2004	10	200	ECBM
<b>Recopol</b>	Poland	2003	1	10	ECBM
<b>Gorgon (planned)</b>	Australia	~2009	10,000	unknown	Saline formation
<b>Snøhvit (planned)</b>	Norway	2006	2,000	unknown	Saline formation

Source: GreenFacts, [Table TS.5. Sites where CO<sub>2</sub> storage has been done, is currently in progress or is planned](#)

## Storage requirements

In order to have a feasible geological storage site, there are several requirements. First the site must have adequate capacity and injectivity. In terms of storage capacity, porosity is critical because it usually decreases as depth increases due to compaction of soil and subsurface materials. The permeability of the subsurface material has to be sufficiently high enough for CO<sub>2</sub> injection.

Furthermore, a high sealing capability is also critical for a mass storing unit. In order to have a satisfactory sealing capability, the storing unit should consist of shale, salt or anhydrite materials to eliminate leakage. If leaking happens to overlying water reservoirs, serious consequences could result.

Lastly, the geological storing site has to be stable enough to contain the CO<sub>2</sub> content. The geological site shouldn't compromise its structural integrity by storing CO<sub>2</sub> content. If the site integrity is compromised with the storage, huge costs may incur in the future.

Regardless of the site configurations, storing CO<sub>2</sub> materials have to meet certain requirements for safety and spatial purposes. The CO<sub>2</sub> has to be stored as liquid instead of gas since gaseous CO<sub>2</sub> not only occupies more space but also leaks more easily than liquid CO<sub>2</sub>. As a result, CO<sub>2</sub> is compressed to a liquid form called "supercritical CO<sub>2</sub>" with a temperature of 31.1 degree Celsius and 73.9 bar (1072 psi) in pressure (BELLONA, Technology: Storage, 2009).

## Site characterization

In order to ensure safe storage for a geologically long period of time, hydrogeology, geochemistry and geomechanics have to be considered. As discussed earlier, the sealing capability is an important consideration factor in choosing a storage site. The above horizons of the storage unit have to be assessed carefully because a CO<sub>2</sub> leakage would migrate through the above horizons.

To accurately characterize a potential storage site, the reservoir data is the only information engineers rely on. For instance, fluids from nearby wells or storage sites, seismic data and regional hydrodynamic pressure gradients are the sample data they collect. The site selection is solely based on the site characterization data. However, the most important

information includes geological site description to ensure seal properties, and seismic surveys to define and understand the underground structure to determine possible leakage. In addition, pressure measurements are needed to determine the isolation of deep and shallow groundwater (BELLONA, Technology: Storage, 2009).

## Predictions

In order to predict the performance of a storage site, designs of a drilling or transportation operation, models and simulations are utilized for assessments.

During operations, simulation models are first compared to actual field observations, and then recalibrated for further extrapolation. The CO<sub>2</sub> storage models come from existing oil and gas models which provide excellent baseline information. The models are able to predict possible hazardous impacts during the operations. Operational adjustments such as changing injection rates or changing the composition of the storing materials then are being assessed in terms of safety and feasibility through the computer models. However, existing CO<sub>2</sub> storage computer models are considered to contain a lot of uncertainties due to the complexity of the subsurface and they need a tremendous amount data as well as recalibration to provide useful and accurate information (BELLONA, Technology: Storage, 2009).

## Geological storage

Geological storage by far stores the most captured and transported CO<sub>2</sub>. However, the effectiveness depends on the trapping mechanisms, which are a combination of physical and geochemical trapping. Geological storage in general takes place at a depth of 8000m or deeper, which is deep enough to maintain the CO<sub>2</sub> in a liquid state with the existing pressure. Since the density of CO<sub>2</sub> at supercritical state is lower than water, a cap has to be placed on top of the reservoir to prevent leakage (Brook, 2006). A physical cap can be introduced where CO<sub>2</sub> is trapped within pores by a well sealed cap rock. Chemical trapping or mineral storage can also be introduced as the CO<sub>2</sub> first dissolves in water, which then actively reacts with rock minerals to form carbonate minerals that remain underground for a long period of time (GreenFacts, Geological storage technology and mechanisms, 2005).

As mentioned above, geological storage is the cheapest method of storing CO<sub>2</sub> and yet it is the most environmentally acceptable option. The cost of storage is between 0.50 to 8.00 US dollars per tonne of CO<sub>2</sub> injected in saline formations, depleted oil and gas reservoirs. Additional costs for monitoring incur about 0.10 to 0.30 US dollars per tonne of CO<sub>2</sub>. The cost is relatively cheaper for onshore storage sites where the site is shallower with high permeability (BELLONA, Technology: Storage, 2009).

## Ocean storage

Ocean storage is an alternative when geological storage is not viable. Due to the solubility of CO<sub>2</sub>, there is a natural exchange of CO<sub>2</sub> between the ocean surface and our atmosphere at an equilibrium state. However, increasing the CO<sub>2</sub> level in sea water would increase acidity, and as a result interrupt the oceanic ecological balance. This remains an environmental controversy. To store CO<sub>2</sub> in the ocean, it must be either in a solid state or liquid state where a lake of CO<sub>2</sub> is injected into the sea floor. Currently, the ocean takes up CO<sub>2</sub> at 7GtCO<sub>2</sub> per year. Over the past 200 years, the ocean has taken up about 500 GtCO<sub>2</sub> of the total 1300 GtCO<sub>2</sub> of anthropogenic emissions (GreenFacts, Scientific Facts on Carbon Capture and Storage, 2005). In terms of depth, the table below shows the fraction of CO<sub>2</sub> retained for ocean storage in different depths, with predictions of 100 year intervals into the future. Ocean storage is less environmentally feasible and acceptable than geological storage. As a result, there will be less CO<sub>2</sub> stored in the ocean in the future as shown in table 3.

*Table 3. Fraction of CO<sub>2</sub> retained for ocean storage as simulated by seven ocean models for 100 years of continuous injection at three different depths starting in the year 2000.*

Year	Injection depth		
	800 m	1500 m	3000 m
<b>2100</b>	0.78 ± 0.06	0.91 ± 0.05	0.99 ± 0.01
<b>2200</b>	0.50 ± 0.06	0.74 ± 0.07	0.94 ± 0.06
<b>2300</b>	0.36 ± 0.06	0.60 ± 0.08	0.87 ± 0.10
<b>2400</b>	0.28 ± 0.07	0.49 ± 0.09	0.79 ± 0.12
<b>2500</b>	0.23 ± 0.07	0.42 ± 0.09	0.71 ± 0.14

Source: GreenFacts, [Table TS.7. Fraction of CO<sub>2</sub> retained for ocean storage](#)

## Monitor and security

It is necessary to monitor the CO<sub>2</sub> storage for safety and learning purposes. Prior to monitoring underground storage, a baseline survey is necessary to compare with the operation. It is useful to establish a baseline to distinguish ecological CO<sub>2</sub> flux and hazardous CO<sub>2</sub> releases. Measurements on injection rates and pressure, distribution of underground CO<sub>2</sub> as well as monitoring injection well integrity, potential environmental hazards and network design are monitored to not only ensure injection and environmental safety but also act as a verification tool (ICO2N, 2007). Monitoring being the main quantitative verification tool of CO<sub>2</sub> storage assures carbon is being stored and contained in an expected manner. On the other hand, monitoring also provides early detection on potential hazardous leakages and seepage that may require mitigation (BELLONA, Technology: Storage, 2009).

## Knowledge gaps

The knowledge on carbon capture and storage is based on the knowledge of basic chemistry and earth science as well as the experience of related gas and oil geological activities from the past. Although there are no technical difficulties that could hinder a CO<sub>2</sub> capture and storage operation, it is a relatively new technology with knowledge gaps still remaining. For instance, a detailed quantitative risk assessment on potential human health is lacking as well as an assessment on environmental impacts of seafloor CO<sub>2</sub> seepage. A leakage detection technique has yet to be developed as well as a global regulatory framework on the structure of the new CCS technology which may become the future dominating sector in reduction of green house gas emission. (BELLONA, Technology: Storage, 2009).

It takes extremely complex scientific practices to ensure a safe storage. In comparison to the different storing mechanisms, geological storage is more feasible than ocean storage. In terms of environmental controversy, ocean storage has a much higher potential to cause environmental hazard as storing CO<sub>2</sub> directly in the sea floor is more dangerous than storing materials underground where direct contact is less likely. As EOR becomes more popular since costs can be recovered, there will be more CO<sub>2</sub> stored for EOR than any other methods in the future.

# Cost

## Cost comparison

In order to reduce greenhouse gas emissions, there are means of mitigation in the power sector and forest sector. Carbon capture and storage is by far the most dominating technology to reduce emission from power plants. On the other hand, plantation forestry would be an example of mitigation in the forestry sector. However, there are costs that incur by implementing CCS and plantations. Depending on locations and methods, there are different reasons and factors affecting the cost.

In terms of cost, a global cost curve of greenhouse gas abatement opportunities is shown below (figure 2). The timeline is set at 2030 where the technologies and policies will assume to be more mature on mitigating greenhouse gases. In comparison to the cost of CCS and forestation in terms of greenhouse gas mitigation, CCS is generally more expensive than forestation per tonne of CO<sub>2</sub> in Euro dollars. For instance, for a new coal CCS plant or CCS with enhanced oil recovery technology, it is approximately 15 Euro dollars to mitigate a tonne of CO<sub>2</sub> (new coal is mainly pre-combustion style of capture). It takes about 33 Euro dollars for a coal retrofitted power plant to capture a tonne of CO<sub>2</sub> (coal retrofit refers to mainly post combustion style of capture). As we can see, it is more expensive to implement post combustion capturing practices than pre-combustion.

However, CCS in general is capable of mitigating a larger quantity of CO<sub>2</sub> on a yearly basis than forestry practices. For example, a coal retrofit CCS project is able to consume a substantial higher amount of emission than most of the reforestation strategies in figure 2. Numerically, industrial CCS is capable of mitigating up to 25 GtCO<sub>2e</sub> per year where forestation only mitigates 17 GtCO<sub>2e</sub> per year at its max. On the other hand, there are cases where avoiding deforestation in Asia costs the same as industrial CCS yet avoiding deforestation yields a higher amount of emission reduction. As a result, in most cases, carbon abatement is generally cheaper in the forest sector than the power sector; however, it is more effective in carbon abatement in the power sector than forest sector.

## Global cost curve of GHG abatement opportunities beyond business as usual

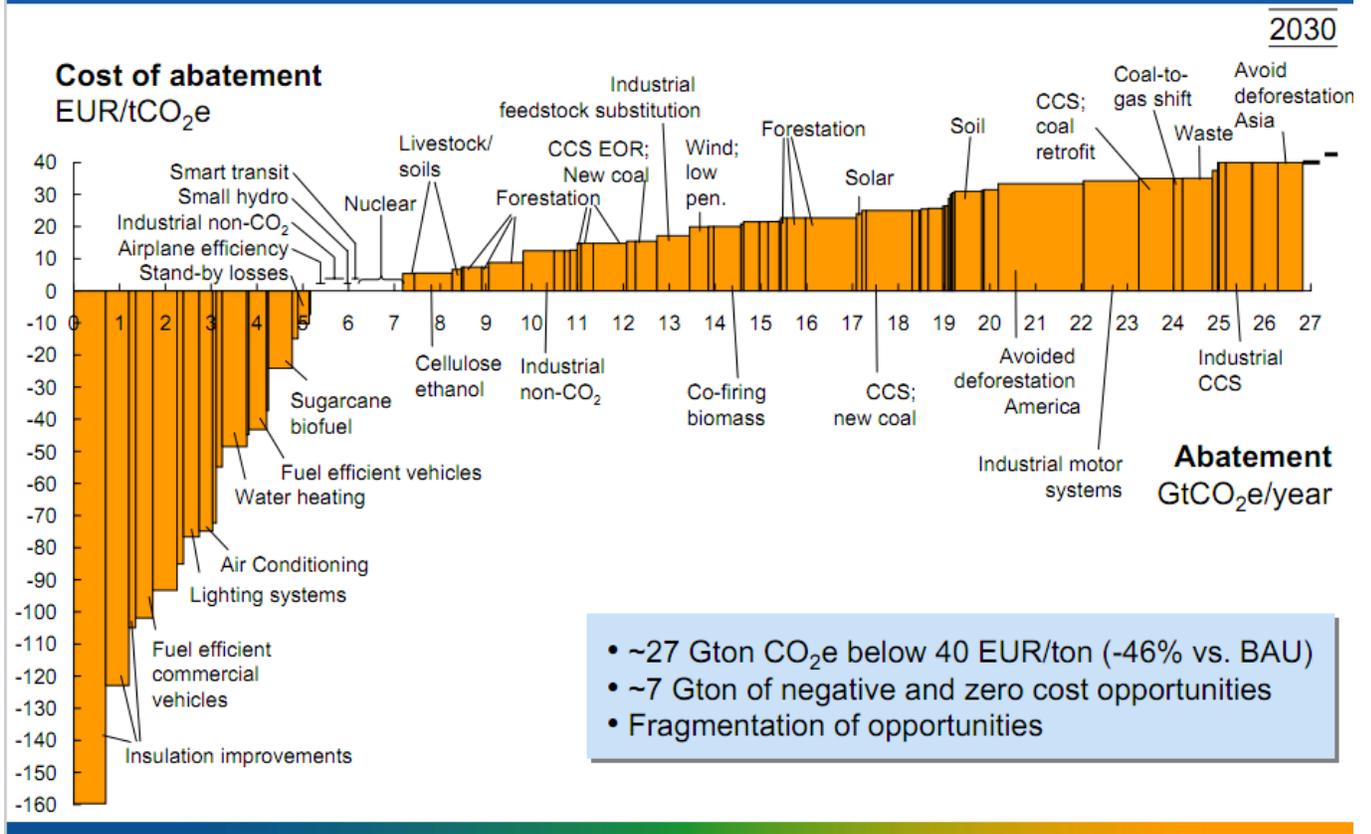


Figure 2: Global cost curve for greenhouse gas abatement measures (Vattenfall, Global Mapping of Greenhouse & Gas Abatement Opportunities, 2007).

## Cost in the power sector

Specific to the power sector, the graph below illustrates the potential abatement technologies and costs (figure 3). Apparently, the CCS technology with EOR or a new coal power plant with CCS has the lowest cost in abatement but is least effective. On the other hand, the highest cost method, a gas power plant with CCS and EOR technology, costs up to 40 dollars per tonne CO<sub>2</sub> and consumes approximately 5 GtCO<sub>2</sub>e a year, compared to the lowest cost method 1.5 GtCO<sub>2</sub>e 15 dollars per tonne CO<sub>2</sub>. In comparing the cost of the highest cost method of about 8 dollars per tonne CO<sub>2</sub> per year and the lowest cost method of about 10 dollars per tonne CO<sub>2</sub> per year, the highest cost method actually yields a lower cost than the lowest cost method only on a large scale operation, mitigating a larger quantity of emission. As a result, the cost of abatement in the power sector lowers as scale of operation increases.

Furthermore, the selection of primary fuel is also affecting the cost of carbon abatement in the power sector. For instance, implementing CCS with EOR on a gas powered power plant costs the most and yet most effective; however, implementing the same CCS and EOR strategies on a new coal power plant is the least expensive and yet the least effective in terms of emission reduction. If primary fuel is the determinant of abatement cost in the power sector, the cost of primary fuel in the future will determine the cost of carbon abatement.

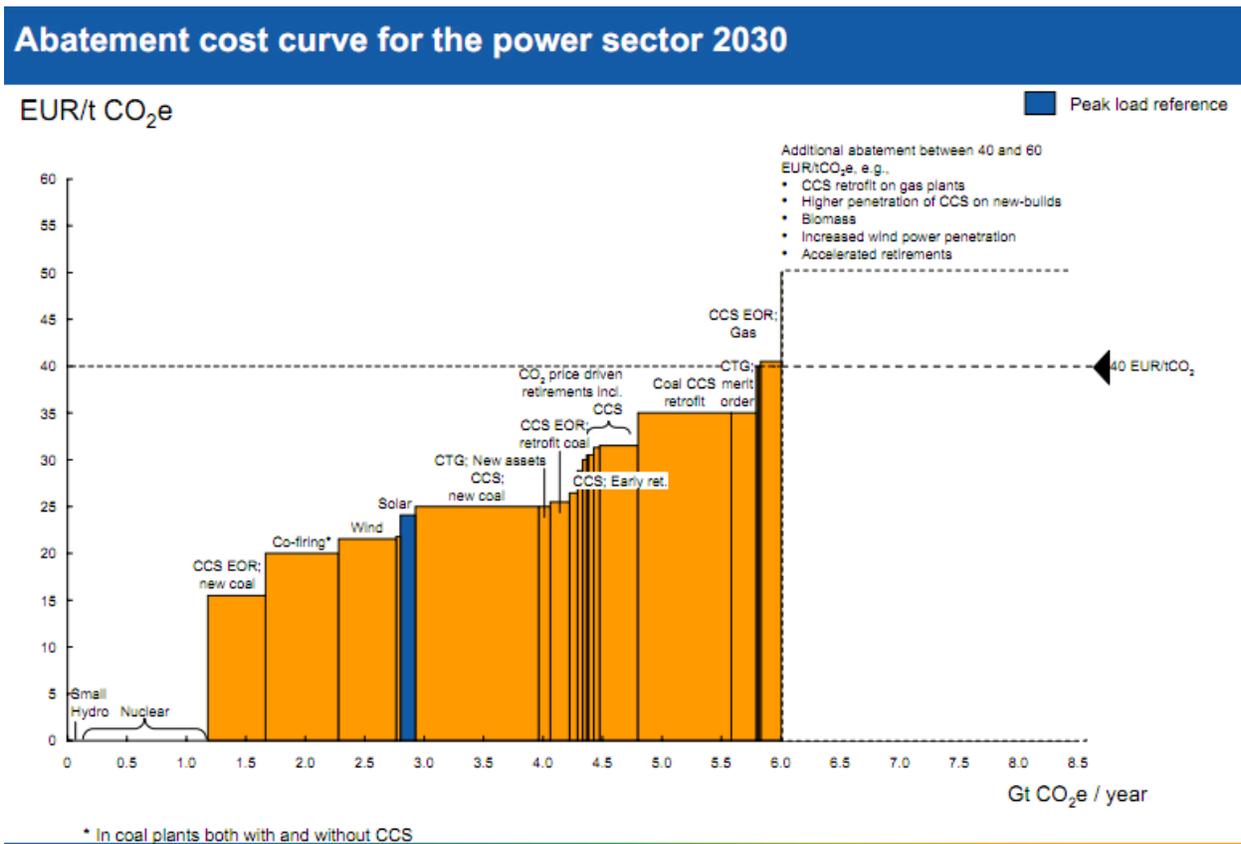


Figure 3: Abatement cost curve for the power section only in year 2030 (Vattenfall, Global Mapping of Greenhouse & Gas Abatement Opportunities, 2007).

## Cost in the forest sector

In comparison to the power sector, the majority of abatement opportunities in forestry sector are focused on decreased deforestation and reforestation. Depending on regions, reforestation may be more effective in reducing carbon emission than decreased deforestation.

For instance, avoiding deforestation in Asia has a more profound effect in carbon abatement in terms of quantity than any forestation methods as figure 2 depicts.

However, in terms of cost of avoid deforestation and reforestation, it differs among different regions. For instance, avoiding deforestation is much cheaper in Africa than avoiding deforestation in Asia but the effect is much more profound in Asia than Africa. This is perhaps due to heavier population in Asia having to be subsidized when deforestation is decreased. The cost of avoiding deforestation is substantially higher in Asia than Africa.

Forestation costs differently depending on the quantity of emissions being mitigated. As a result, low cost opportunities do exist like tier 1 forestation as well as avoiding forestation in Africa as figure 4 shows; however, the low cost opportunities are substantially less effective than higher cost opportunities in terms of carbon abatement. Depending on region and strategies, the costs and effectiveness vary greatly.

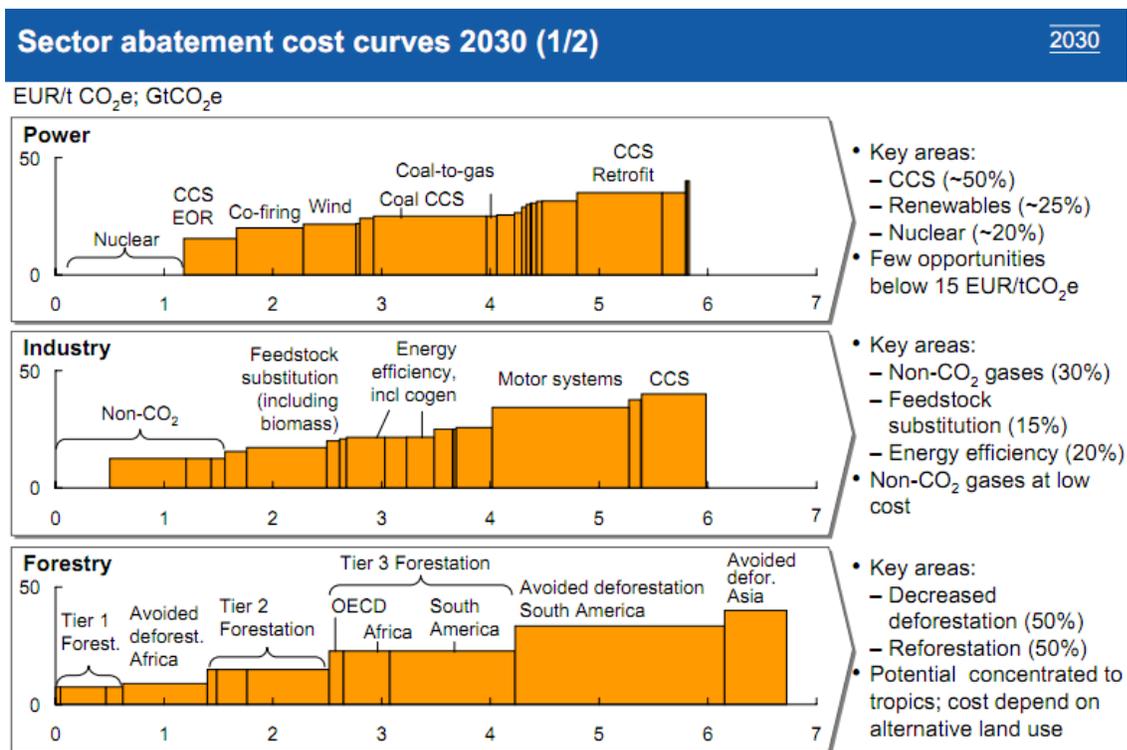


Figure 4: Abatement cost curves for different sectors by year 2030 (Vattenfall, Global Mapping of Greenhouse & Gas Abatement Opportunities, 2007).

# Future opportunities

Currently, the power sector has the smallest potential in carbon abatement due to immature technology in CCS (figure 5). The forest sector on the other hand has a strong initial phase but a low growth rate of 6% to 8%. In comparison to the power sector, it is growing by 20% in 10 years from now, and 10% for the following 10 years. There is no doubt CCS will defeat any forestry applications by means of carbon abatement.

Since the effectiveness of CCS is potentially higher than most forestry applications in terms of emission reduction. Improving technologies will also bring down the cost of implementing CCS. By 2030, the power sector will become the largest sector with the greatest potential in carbon abatement.

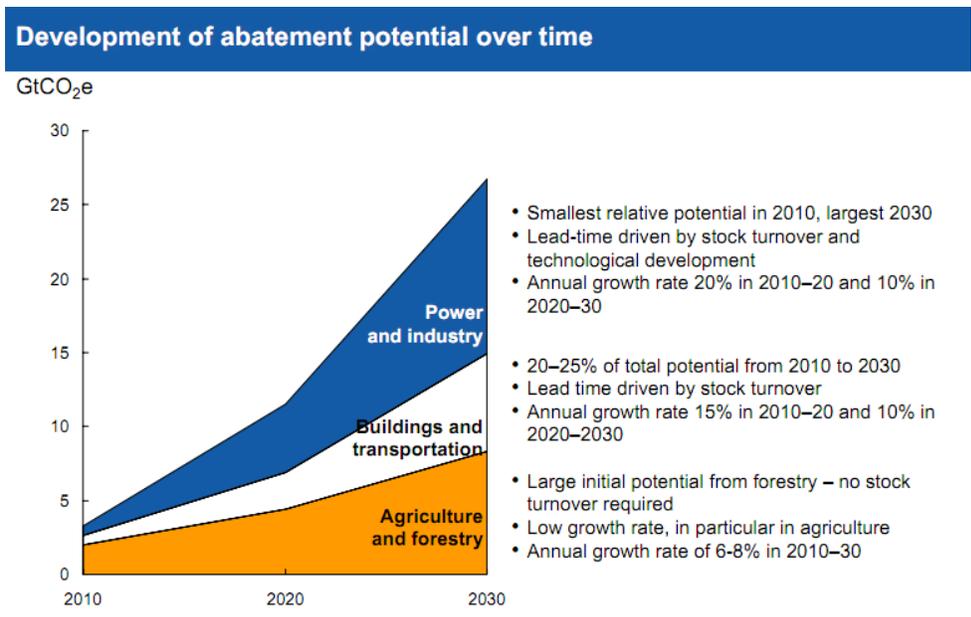


Figure 5: Development of abatement potential over time up to year 2030 (Vattenfall, Global Mapping of Greenhouse & Gas Abatement Opportunities, 2007).

# Conclusion

Carbon capture and storage is a technological advance allowing large scale emission mitigation. There are advantages and disadvantages depending on the application, scale and cost. There is no doubt pre-combustion will become the dominating capturing method in the future due to its high efficiency in CO<sub>2</sub> capture. Enhanced oil recovery will be used more frequently by means of CO<sub>2</sub> storage to further recover the cost of implementing CCS. However, as carbon capture and storage remains to be an immature and growing sector in carbon abatement, it not only requires continuing studies as well as data collection to improve operational safety, but CCS also needs a global political framework in the future for international CCS implementations.

Location is the dictator in cost in carbon abatement among different strategies in the forest sector. However, the fuel type determines the cost in the power sector. It also depends on scale and quantity of mitigating emission. In general, the higher the scale in operation yields a lower cost per tonne per yearly basis in carbon abatement. In comparison with alternative carbon abatement techniques, CCS for now is not as viable as forestry applications in financial terms. It requires more time and experience to make CCS into a cost viable option in carbon abatement.

Apparently, there is a huge demand on carbon mitigation. Reducing carbon emission is not necessarily a government action nor the responsibility of a multibillion business. Rather, everybody has the responsibility to share the load. It may be as simple as improving home insulation or switching to high efficiency lighting fixtures. These are low cost negative abatement cost opportunities which yield money in return. They are steps that people should start to consider.

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