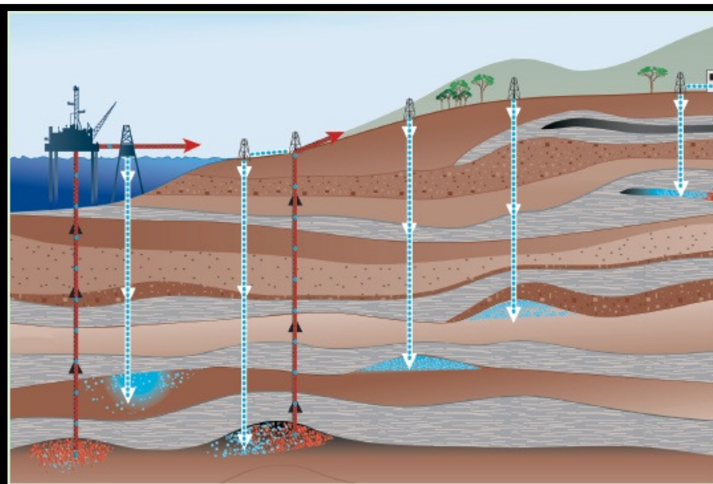

The Current State of Carbon Capture and Storage

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11/23/2009

Letter of Submittal

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23/11/2009

Prof. G. E. Schneider
Professor of Mechanical Engineering
University of Waterloo
Waterloo, ON

Dear Professor Schneider,

I am glad to submit this report titled The Current State of Carbon Capture and Storage. This report has been completed for the project aspect of fall 2009 offering of ME 459: Energy Conversion.

Carbon Capture and storage is currently a very pertinent topic when deciding energy policy. The stakeholders in the success of this technology are huge. Therefore, an in depth review of the current state of this technology is important to ensure the science and political communities are singing the same tune, and that there is strong technological background for this technology to succeed.

This report is to be prepared by me and I have not previously submitted a report on this topic for any academic or professional purposes.

Sincerely,

Mohammed Adham
I.D. #20203556

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1.0 Scope

In the fight to reduce the amount of carbon emitted by the burning of fossil fuels, carbon capture and storage is being touted as a clean feasible option to mitigate the release of CO_2into the atmosphere. In 2005 the Intergovernmental Panel on Climate Change released a special report on carbon capture and storage which brought the technology to the spotlight [1]. This report focuses on the technical aspects of the technology and feasibility behind carbon capture and storage, as well developments in carbon capture and storage the since the release of this report. There has been a large influx of research funds into the technology in since 2005, and new and innovative ideas have been proposed to further the efficiency and practicality of this technology [2] [3]. There were many sceptics of the technology at the time of the IPCC report, and further research has been done to investigate solutions to some of the concerns [4]. There have been many concerns of the overall environmental impact of storing carbon dioxide, such as potential leakages. There have also been many concerns over the cost of carbon capture and storage, and whether the burning of fossil fuels will remain a low cost solution after the cost of capture and storage of CO_2 [5]. This report will also look at the current industrial state of carbon capture and storage, specifically how industry is investing in the technology and estimates on how long adoption of this technology will take to go mainstream.

2.0 Summary

Carbon capture and storage is a process in which carbon dioxide is captured from industrial production, transported to a storage site, and stored. This is done to prevent the carbon dioxide from being emitted into the atmosphere. The 2005 International Panel on Climate Change report on carbon dioxide capture and storage outlined the underlying technology behind these processes.

The first stage is carbon dioxide capture. This is done by one of three methods: post combustion capture, pre-combustion capture, or oxyfuel capture. These methods all produce a stream of high concentration high pressure carbon dioxide gas. Post combustion capture is the most used technique and is also the only technique that applies to the majority of coal firing plants. Post combustion is also the most economically viable solution for carbon capture. After the carbon dioxide is captured, it is transported to a storage site. This is done by means of pipelines, ships, train or truck. There is currently a mature market in the field of carbon dioxide transportation by means of pipelines. This is the most economically viable method of carbon dioxide transport. Finally, the carbon dioxide is stored. This is done either by geological or mineral storage. There are currently a number of geological storage projects in progress. These involve storing carbon dioxide in geological formations around 800 meters below the surface of the earth. There are a number of dangers related to storage of carbon dioxide, and monitoring measures are being developed to mitigate these risks.

Since the 2005 release of this report, there has been a number of papers released on the topic. For the most part, the underlying technology has not changed much, but more and more research has been committed to the subject. This has led to projections as to where the technology is going, and that it is currently a viable means for carbon emissions mitigation.

A number of conclusions are drawn from this research. The technologies for carbon capture and storage are sound, but there are currently no streamlined examples of its use in industry. The energy efficiency of these methods remains low, and uneconomical. Storage safety remains a concern. Recommendations include further research, and immediate public funding for trial projects.

3.0 Introduction

The reduction of carbon dioxide into the atmosphere is paramount [1]. One means to achieve this goal is carbon capture and storage. In 2005, the International Panel on Climate Change released a report on Carbon Dioxide Capture and Storage. This report is detailed in Section 4.0. Carbon capture and storage is a three part process. The methods of carbon capture are outlined in section 4.1. Capture is followed by transportation, which is outlined in section 4.2. Finally, after transportation, the carbon dioxide is stored, which is outlined in section 4.3.

Since the release of the International Panel on Climate Change report, there has been an influx of research into the field of carbon capture and research. The current status of this technology is outlined in section 5.0, and section 5.1 outlines some basic equations for case studies that are to be carried out.

Conclusions are drawn on the procedure and discussion in section 6.0. These conclusions are followed by a number of recommendations in section 7.0.

4.0 2005 IPCC Report of Carbon Capture and Storage

In 2005, the International Panel on Climate Change (IPCC) released a special report titled Carbon Dioxide Capture and Storage. This was a report pared by a panel of scientists based on a consensus of peer-reviewed journals. This report envisaged the overall goal of using carbon capture and storage to mitigate the release of carbon dioxide into the atmosphere [1].

4.1 What is Carbon Dioxide Capture and Storage

Carbon dioxide capture and storage is the term used to describe the process of using a range of technologies to reduce the emissions of carbon dioxide into the atmosphere. The emission of carbon dioxide into the atmosphere is prevalent in a number of industries, such as the combustion of fossil fuels for power generation, or the production of iron, steel, hydrogen, and ammonia.

There are three main components to carbon capture and storage: capture, transport and storage. As of 2005, there were three large scale applications of carbon storage, with the largest project capturing and storing 1-2Mt of carbon dioxide per year. A large scale operation that this report envisions as necessary to significantly curb the emissions of carbon dioxide into the atmosphere would be in the area of storing 500Mt per year. At time of IPCC report, the maturity of each of the technologies is listed in Table 1: Maturity of Carbon Capture and Storage Technologies .

Component	Technology	Research	Demonstration	Economic Feasibility	Mature Market
Capture	Post-Combustion			X	
	Pre-Combustion			X	
	Oxyfuel Combustion		X		
	Industrial Separation				X
Transportation	Pipeline				X
	Shipping			X	
Geological Storage	Enhanced Oil Recovery				X
	Gas or Oil Fields			X	
	Saline			X	

	Formations				
	Enhanced Coal Bed Methane Recovery		X		
Ocean Storage	Direct Injection (dissolution)	X			
	Direct Injection (lake bed)	X			
Mineral Carbonation	Natural Silicate Minerals	X			
	Waste Materials		X		
Industrial uses of CARBON DIOXIDE					x

Table 1: Maturity of Carbon Capture and Storage Technologies [1]

It is clear from this table that in 2005, no feasible means of storage were at or near market maturity in storage. Industrial demand of carbon dioxide does not make up for the estimated supply of the process. 2% of current carbon dioxide sources from industry have 95% concentration of carbon dioxide emissions; these are the focus of initial carbon capture and storage

4.2 Carbon Dioxide Capture

The main purpose of capture is to produce a stream of gas with a high concentration of carbon dioxide, at a high pressure, that it can be easily transported. With current technology, if the stream of gas does not have a high concentration of carbon dioxide it becomes economically infeasible to capture and store carbon, as will be discussed in section 4.3. Therefore, the current focus of carbon dioxide capture is on power plants and other large scale industrial processes. The emission stream needs to be almost purely carbon dioxide for storage underground. There is current operational equipment to separate carbon dioxide in large industrial plants, in a number of different processes. Currently, there no applications of carbon dioxide capture at a large scale (500Mt). The three main methods of capture of carbon dioxide are post combustion, pre-combustion and oxy fuel combustion. These processes will be described in detail in the following sections. Figure 1: Carbon Dioxide Capture processes, presents an overview of the methods of carbon capture. It should be noted that each of the three most common processes use very different methods to generate power and heat.

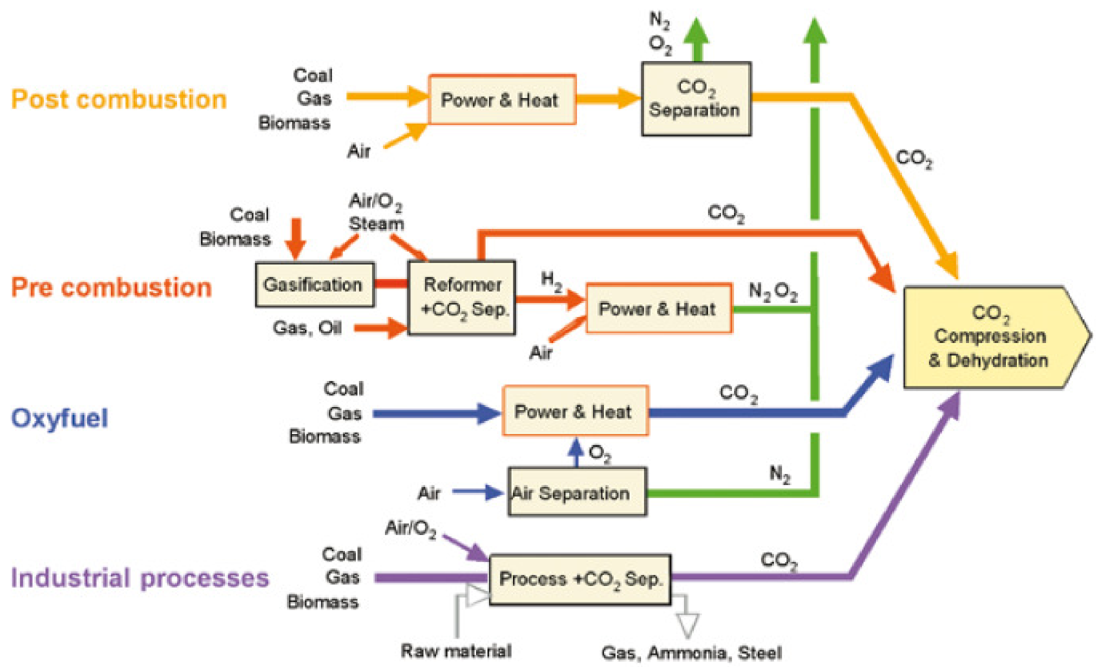

Figure 1: Carbon Dioxide Capture processes [1]

Current post and pre combustion methods can capture around 85-95% of carbon dioxide from flue gases. Capture rate higher than this are larger and much more expensive systems that are not inside the scope of this report. Overall, capture and compression of carbon dioxide will require roughly 10-40% more energy than a system that does not capture emitted carbon. This is a startling number, as it shows that there is a serious blow to efficiency in the capture stage. As opposed to pre and post combustion systems, oxyfuel capture can technically capture close 99.9% of carbon dioxide from flue gases.

4.2.1 Post Combustion Capture

The principle of post combustion capture is the process of separating carbon dioxide from flue gases produced by combustion of the primary fuel. For centuries, the direct firing of fuels in air has been the most economical method to extract the fuels stored energy. Post combustion capture is then considered strategically important if it is to be retrofitted to current plants that currently produce large amounts of carbon dioxide. The focus of post combustion capture is generally geared towards coal plants, as these are one of the most common sources of carbon dioxide that fire fuel directly in air. Generally, the flue gasses of a coal plant will be composed of CO_2, N_2, O_2, H_2O, SO_x, NO_x, as well as other particulates. This stream is far from pure carbon dioxide. While there are a number of current technologies to separate carbon dioxide from this flue gas, most studies have shown that chemical solvents prove to be the preferred method. Figure 1: Carbon Dioxide Capture processes outlines a process flow of the chemical separation of carbon dioxide gas from the flue gas of the plant.

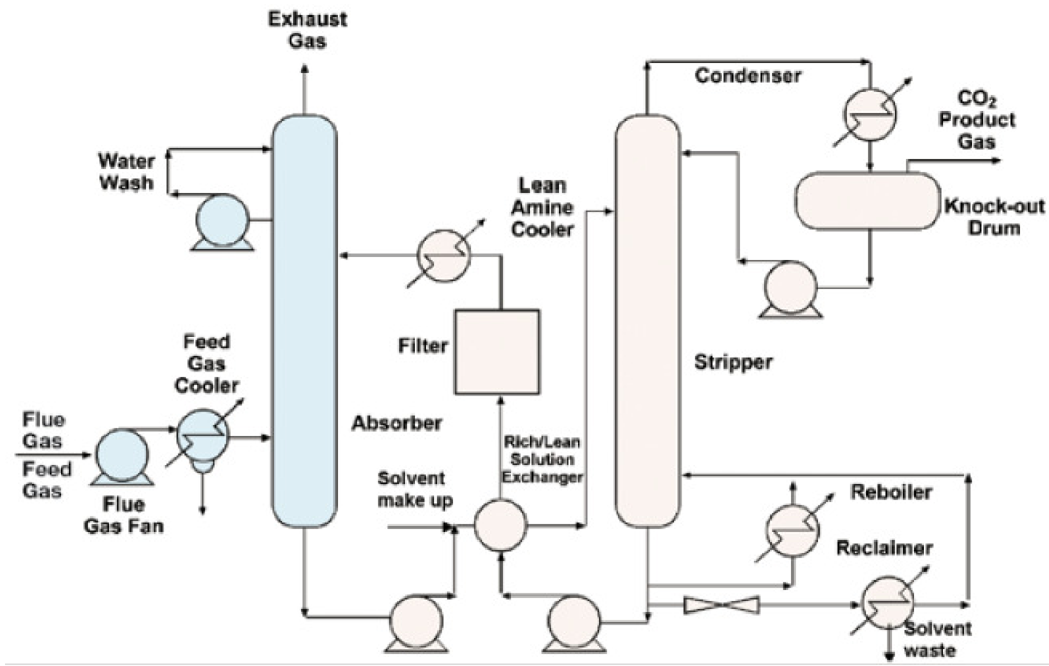

Figure 2 Process Flow Diagram for Post Capture Recovery [1]

The precise thermodynamic aspects of post combustion capture are outside the scope of this report. It should be noted that the key parameters to the entire capture system are: the flue gas flow rate, the carbon dioxide concentration in the flue gas, concentration of carbon dioxide removal, solvent flow rate, and overall energy consumption. In general, carbon dioxide removal rates vary from 80-95%, where more expensive systems are more effective.

4.2.2 Pre Combustion Capture

While pre combustion capture of carbon dioxide may seem like a backwards principle, it is a fledging new technology. In this capture technique, the primary fuel is treated in a reactor with steam and air to produce a gas that is a mix of carbon dioxide and hydrogen, called syngas. This gas mixture can then be separated into gas stream and a hydrogen gas stream. This hydrogen gas stream is then used to generate electricity, or for other industrial purposes. This is a relatively new technology compared to open air firing of fuels, and is therefore more costly than post-combustion systems. In general the carbon dioxide concentrations of mixture are in the 15-60% range.

The production of syngas is generally done in one of two ways. One is through the steam reforming, which is currently the most popular form of hydrogen production. The steam reforming chemical reaction is shown in (1).

$$C_xH_y + xH_2O \leftrightarrow xCO + \left(x + \frac{y}{2}\right) H_2 \quad \Delta H = +ve \ (1)$$

The second method of syngas production is through partial oxidation, as shown in (2).

$$C_xH_y + \frac{x}{2O_2} \leftrightarrow xCO + \left(\frac{y}{2}\right) H_2 \ \Delta H = -ve \ (2)$$

Both of these processes are then followed by the shift reaction to convert carbon monoxide to carbon dioxide by adding steam, as indicated by equation (3).

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad \Delta H = -41 \, kJ \, mol^{-1} \ (3)$$

One important aspect to note is the significant amount of energy needed for the shift reaction. The carbon dioxide is then separated from the syngas.

The carbon dioxide separation is again most commonly done through physical solvents. The most commonly used solvents are shown in Table 2: Common Solvents for Pre Combustion CaptureTable 2: Common Solvents for Pre Combustion Capture

Solvent	Type	Chemical Name
Rectisol	Physical	Methanol
Purisol	Physical	N-methyl-2-pyrolidone (NMP)
Selexol	Physical	Dimethyl ethers of polyethylene glycol (DMPEG)
Benfield	Chemical	Potassium carbonate
MEA	Chemical	Monoethanolamine
MDEA	Chemical	Methyldiethylamine
Sulfinol	Chemical	Tetrahydrothiophene 1,1-dioxide

Table 2: Common Solvents for Pre Combustion Capture [1]

4.2.3 Oxyfuel Combustion

The third and final carbon dioxide capture mechanism is oxyfuel combustion. In oxyfuel combustion, oxygen instead of air is used for combustion of the primary fuel. Therefore, the flue gas is primarily carbon dioxide and water vapour, as nitrogen and other gases are not introduced. In oxyfuel combustion, the flue gas is around 80% carbon dioxide. Water, which is a by product of the oxyfuel reaction is then removed by cooling and compressing the flue gas stream. Oxyfuel combustion requires the upstream separation of oxygen from air (in the area of 95-99%), which is quite energy intensive. The oxyfuel thermodynamic cycles is presented in Figure 3: Oxyfuel turbine combined cycle. It is important to note that the actual separation of carbon dioxide from the flue gas is not done by a solvent, as in other methods, but only by a cooler/condenser.

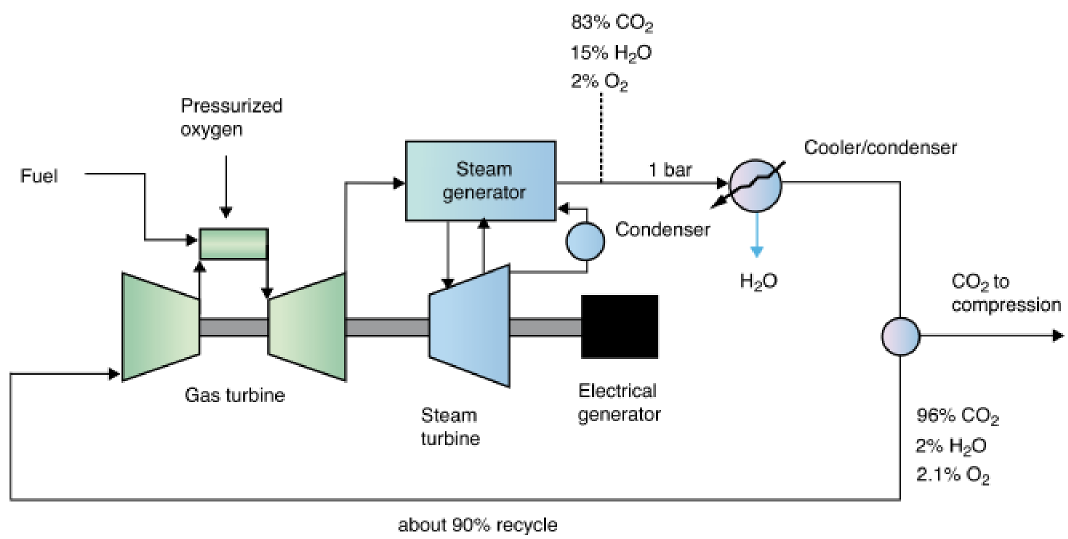

Figure 3: Oxyfuel turbine combined cycle [1]

Oxyfuel combustion plants will generally operate at temperatures nearing 3500 degrees Celsius, which is far higher than the normal operation temperatures of power plant materials. For this reason, oxyfuel combustion remains largely unpopular due to its high cost and relatively new technology.

4.3 Carbon Dioxide Transport

The next stage in carbon capture and storage is transportation. Unless an emitting plant is located directly above the prospective storage site, transportation of carbon dioxide will be required. There are typically three methods of transporting carbon dioxide: pipelines, trucking, rail and by ship.

Carbon dioxide pipelines currently operate in mature market stage. Gaseous carbon dioxide is compressed to 8Mpa and transported through pipelines. As of 2005, pipelines in the USA transport over 40Mt of carbon dioxide per year. For carbon dioxide to be transported through pipelines, it needs to be in a near pure state, as moisture is highly corrosive. The cost of transporting carbon dioxide that is not pure is much higher due to the need to use pipelines with corrosive-resistant materials. Otherwise, normal manganese based pipelines will be sufficient.

Where pipelines are not available, tankers and rail are also feasible solutions. In these situations, the carbon dioxide would need to be transported at temperatures well below ambient (-20 degrees Celsius), and at pressures well below 8Mpa, which would require additional energy. If the carbon dioxide needs to be transported to sea a significant distance, it can be done in a similar way as transport of liquefied petroleum gases (LPG's), and technology currently exists for these applications.

4.4 Carbon Dioxide Storage

The final stage of carbon capture and storage is the storage aspect. There are a number of methods of carbon storage: geological storage, mineral storage and deep ocean storage. Due to the very early stages of research into oceanic storage, it will be excluded from this report.

4.4.1 Geological Storage

There are generally three types of geological formations in which research has been considered for storage of large amounts of carbon dioxide: oil and gas reservoirs, deep saline formations and un-minable coal beds. These three types of storage consist of injecting carbon dioxide into rock formations beneath the earth's surface. Candidate rocks are generally porous; rocks that have once held fluids, such as natural gas or oil. There are numerous potential sites for carbon dioxide storage, both onshore and offshore. It should be noted that at the time of the IPCC report, storage of carbon dioxide in coal beds was still in the demonstration phase. At the time of the IPCC report, and to this date, there are three large scale projects world wide that currently store carbon dioxide geologically: the Sliepner project in North Sea, the Weyburn project in Canada and In Salah project in Algeria. An overview of the Sliepner project is given in APPENDIX I- The Sleipner Project. An overview of the Salah project is given in APPENDIX II – The In Salah Project. An overview of the Weyburn project is given in APPENDIX III – The Weyburn Project.

These three projects are evidence of the feasibility of carbon storage. It is important to note that these three projects are storing carbon dioxide by different means, and not for the sole purpose of mitigating emissions. The Sleipner project is storing carbon dioxide into a saline formation. The In Salah project is storing carbon dioxide in gas reservoir. The largest of these projects is the Weyburn project, which stores 3000-5000t of carbon dioxide per day. They Weyburn project is an enhanced oil recovery project, in which carbon dioxide is injected into a geological formation to displace oil. In 2005, worldwide there was 30Mt of carbon dioxide stored in EOR projects. This is a mature market technology. These projects together combined reduce emissions of carbon dioxide by around 4Mt per year.

Many of the technologies that were developed for the oil and gas industry are now being used for geological storage. Natural gas storage, liquid waste, and acid gas disposal have been done at the Mt scale in the United States and Canada. Storage should usually take place below 800m so the ambient pressure and temperature will be sufficient to maintain the carbon dioxide at a liquid or supercritical state. Carbon dioxide will be 50-80% the density of water in these conditions. Due to this density, there will be some buoyant forces driving the carbon dioxide upwards. To solve this problem, a “cap rock” is needed to seal off the carbon dioxide reservoir. This cap rock is an impermeable layer of shale and clay rock. Due to the nature of these geological formations, usually one or more sides of the formation will remain open. This allows for lateral movement of the carbon dioxide beneath the cap rock. Therefore further considerations will be needed to ensure long term safety of the storage that is not available with technology at the time of the IPCC report.

Over the scale of several hundreds of thousands of years the carbon dioxide will dissolved into the in-situ fluids in the geological formations. The fluids will then sink, rather than float to the surface of the earth. The carbon dioxide will react with the rock minerals, so fractions of the dissolved carbon dioxide will become solid carbonate minerals. Trapping also occurs when carbon dioxide is absorbed into organic shale, replacing methane.

The distribution and capacity of storage sites varies worldwide. Table 3: Global estimate of carbon storage capacity indicated the worldwide estimates in 2005 of storage capacity of carbon dioxide. These values indicate the world storage capacity is at least 200Gt.

Reservoir Type	Lower Estimate of Capacity (Gt)	Upper Estimate of Capacity (Gt)
Oil/Gas Fields	675	900
Un-minable Coal beds	3-15	200
Deep saline formations	1000	Uncertain

Table 3: Global estimate of carbon storage capacity

Site selection for carbon dioxide storage is another important aspect of the storage process. The site must be characterized to determine if overlaying rock will provide an adequate seal. This can be done using current methods from oil and gas extraction. More experience is needed however to determine if these geological formations are able to store these amounts of carbon dioxide for such long periods of time.

The environmental impact of storage is an important consideration when choosing a site for carbon storage. In general, environmental impact of carbon dioxide storage falls into world issues and local issues. Examples of world issues include the release of carbon dioxide in quantities that may affect the global climate. Current estimates show that 99% of carbon dioxide that is stored will remain stored after 100 years. Additionally, the IPCC has determined that it is likely to continue to exceed 99% over the next 1000 years. Risk of leakages will decrease over time as we learn more about storage technologies. Local risks include leakages that effect ecosystems, groundwater, and life. Injection well failures will cause immediate and sudden releases of carbon dioxide. In these cases there is current technology for managing this type of well blowout, from a number of industries. In general, the hazard with a blowout is generally only to workers at the time of blowout, or clean up crews after the blowout. In some cases, concentration of carbon dioxide at 7-10% in the local atmosphere would cause immediate risk to human life. These types of hazards are managed currently in the oil and gas industry, and are not considered to be a roadblock to the adoption of carbon capture and storage. Leakage due to unknown faults in storage will be more gradual and diffuse. These hazards primarily affect drinking water aquifers, and ecosystems, as there is a risk of acidification of soils, and the displacement of oxygen in soils. If a fault leakage occurs in low-lying areas with little wind, humans and animals would be affected as the carbon dioxide could sit and reach lethal levels. Means of detecting leakages long before they reach the surface are therefore necessary. Current technology is promising, but more experience is necessary, and is currently underway.

Monitoring and verification of storage sites is therefore another important aspect of the carbon capture and storage process. In general, there are no current standards or procedures for monitoring leakages.

Injection rate and injection pressure are likely to be constraints in future regulation.

4.4.2 Mineral Carbonation

Mineral Carbonation is the technique of fixing Carbon dioxide to alkaline earth metal oxides, such as magnesium oxide or calcium oxide. This will create magnesium carbonate and calcium carbonate. The amount of metal oxides is greater than the amount required to for the carbon dioxide emitted by all the fossil fuels in the world. Mineral carbonation produces silica and carbonates that are stable over very long time-scales. These by products can then be disposed of in old mineshafts or used in construction. Mineral carbonation as a whole is still in the research phase. The carbonation process would take around 30-50% of the capture plant energy output, which is quite high. At current rates, carbon capture and storage using mineral carbonation would use 60-180% more energy than a non-capture and storage system. This figure is especially starling, as it indicates that some implementations would require more energy than is produced by the production of carbon dioxide. Mineral carbonation would also require significant mining operations. Generally, mineral carbonation is not viewed as a viable short term goal, due to the infancy of this technology.

4.5 Gaps in knowledge

As a whole, at the time of the release of the IPCC report on carbon capture and storage, there are some gaps in knowledge. Technology of capture and storage are currently well known. Overall integration of all the processes is still needed, and has not been implemented on a large scale. Research and development is still needed to reduce the costs of these processes to viable levels. There also needs to be improved storage capacity estimates at the global and regional scale. Research and trials also need to be improved on leakages and migration of stored carbon dioxide that model long term trends.

5.0 Current State of Carbon Capture and Storage

At the end of 2008, Jon Gibbins and Hannah Chalmers of the Imperial College London Energy Technology for Sustainable Development group released a report on the current state of carbon capture and storage. This paper noted that the IPCC report was useful, but as it is simply a compilation of peer-reviewed papers, its content represents an average of knowledge from the 5 years preceding the report.

The Gibbins paper concluded that current hurdles to deployment are not technical [5]. The report concluded that funding mechanisms are not present to reward carbon capture and storage on a long term scale. Recent publications have shown that research is being done to improve the situation [3]. It also noted that legal and regulatory frameworks largely to not exist for the transport and storage of carbon dioxide. The current hurdles to large scale adoption are generally incentives. There is no current incentive to push the technology further from a technical perspective, because further development of the technology would require significant investment. As of 2008, the principal cost of carbon capture and storage remains the capture procedure.

There have been new advances in post combustion capture. A new processing stage removes most of the carbon dioxide using wet scrubbing and aqueous amine solutions. This scrubbing occurs at around 50 degrees Celsius. While the technology presents hope for reduced costs, it remains in the research phase and is not a commercially mature technology. The paper also concludes that currently, pre-combustion pays a very large efficiency penalty due to the shift reaction, and that post combustion is currently the best method of capture using commercially available solutions. Oxyfuel combustion options remain uncompetitive with post combustion options.

Case studies are also considered. Current storage estimates for the UK show that there is enough storage capacity for 40 years of carbon dioxide in offshore sites (as of 2008). Key enabling technologies for storage that still need development for adoption in the UK include:

- Directional and horizontal drilling techniques
    - Allow for injection into impermeable strata
- Modeling techniques to determine
    - Groundwater displacement
    - Carbon dioxide migration and displacement
    - Geochemical processes to predict carbon dioxide distribution and eventual immobilization
- Seismic imaging techniques to monitor carbon dioxide location underground

The report mentions that currently, many monitoring techniques still need to be tested in field trials to determine their strengths and weaknesses.

Projections to 2050 are presented in the report. Key advances in the listed technological fields are expected as adoption of carbon capture and storage increases. Main vectors of carbon capture and storage adoption will be areas where storage is geographically feasible. The report mentions that initially, carbon capture and storage should only be used to minimize carbon dioxide in fossil fuels industries, such as LNG processing, oil-sand processing, and coal-to-liquid plants. These applications will serve as learning measures. The report also predicts that hydrogen production will increase, and will be by means of gasifying fuels. The storage of the carbon dioxide by product of gasification will then present a carbon free method of hydrogen production. This will further carbon capture and storage technologies for pre-combustion capture. Finally, the report mentions that no major technological breakthroughs are gasifying are foreseen in the future. One important note about the 2050 projections are that the report mentions that even by 2050, carbon capture and storage will not be widely used. This indicates that the technology implementations still need a significant amount of time before they are to be considered a mature market possibility.

5.1 A Case study for the Netherlands

In 2008, a case study was commission to determine the possibility of large-scale implementation of carbon capture and storage in the Netherlands [6]. Currently Netherlands produces 180Mt of carbon dioxide per year. 100Mt of that is from energy and manufacturing. The case study outlines plans to reduce these emissions by 15Mt per year by use of carbon capture and storage.

The report was focusing on determining the optimal pathway to carbon capture and storage. A pathway is defined as an overall process of carbon capture and storage, beginning with the selection of a capture site, determining transportation metrics, and storage metrics. The model used was based on electricity and fuel production and use. The model compared the cost of a system without capture, to that of a system with capture. Equation (4) calculated COE, the production cost of the energy carrier:

$$COE = \frac{\sum_{t=0}^{T} C_t/(1+r)^t}{\sum_{t=0}^{T} E_t/(1+r)^t} \quad (4)$$

Where $C_t$is the cost in year t, $E_t$is the energy production in year t (GJ), T is the project lifetime, and r is the discount rate. This is followed by the calculation of MC (5), the mitigation cost.

$$MC = \frac{\left(\frac{COE}{\eta_{end-use}} + C_{end-use}\right)_{CCS} - \left(\frac{COE}{h_{end-use}} + C_{end-use}\right)_{ref}}{\left(m_{CO_2}/\eta_{end-use}\right)_{ref} - \left(m_{CO_2}/\eta_{end-use}\right)_{CCS}}$$

Where $\eta_{end-use}$is the end use efficiency, $C_{end-use}$is the end use cost, and $m_{CO_2}$the carbon dioxide emission factor (kg/kWh). Using these calculations, it was determined that a maximum of 50Mt per year of carbon dioxide could be avoided by the year 2020, at a cost of 75$/t carbon dioxide.

6.0 Conclusions

The conclusion of this report indicates that current technology exists in mature market stages for carbon dioxide capture, transportation and storage [1]. The major hurdles to the adoption of this technology is generally attributed to costs and integration of relevant technologies into a single streamlined process [5]. There are currently projects in which carbon is captured, transported and stored on a medium scale (2Mt per year), but none on the scale to make a significant reduction in the amount of carbon dioxide in the atmosphere (500Mt).

There current are various methods of carbon capture. The only method that is currently economically feasible is post combustion capture. This procedure removes carbon dioxide from the flue gases of open fire fossil fuel combustion plants. The carbon dioxide is scrubbed from the flue gases through a solvent. The current efficiency of this process will consume 10-40% of the energy generated.

Transportation of carbon dioxide is currently done on large scales throughout the world, and is also in a mature market. The most economically feasible method is by means of pipelines, where carbon dioxide is transported at pressures of 8Mpa.

Storage of carbon dioxide is also a mature market when stored in geological formations. There are numerous systems around the world currently implementing carbon dioxide storage. The risks of these storage systems are still unknown on a large timescale. Some storage methods are still very new and require more energy than is produced in the production of the carbon.

Overall, there is adequate evidence that carbon capture and storage is a viable technology. What remains to be seen is the economic and practical feasibility of such plans. Carbon capture and storage relies on an entirely new natural resource, carbon storage space. In turning deep geological formations into effective waste dumps, further research is needed to determine the long term effects of this storage, and whether the globe has the capacity to continue to store carbon dioxide long into the future.

7.0 Recommendations

Further research needs to be done to determine accurate information on the storage capacity of the earth for carbon dioxide

Currently, there is still need to research the amount of carbon dioxide the earth can store. If this technology is to be adopted on a global scale as a sufficient means to curb carbon emissions into the atmosphere, the scientific community needs to be sure there is enough storage space on earth for sufficient time into the future, as to not create a new non-renewable resource.

Publicly funded pilot projects that streamline the entire carbon capture and storage process need to commence as soon as possible.

To determine the economic feasibility of this technology, there needs to be pilot projects underway around the world to determine that if streamlining all the procedures together will yield economies of scale for carbon capture and storage, and if efficiencies can be increased to levels where carbon capture and storage is profitable.

Current carbon dioxide storage sites need to be monitored closely to determine environmental impacts and to build new scientific models.

Research is still lacking in the area of long term storage of carbon dioxide, and the likeliness of leakages of stored carbon dioxide. Current storage sites need to be closely monitored and new research projects are required to progress this important aspect of the technology.

Regulatory frameworks for the storage of carbon dioxide need to be passed once adequate research is available.

As research into the safety and reliability of carbon storage becomes available, regulatory bodies need to pass legislation that dictates regulations on carbon storage. These regulations are needed to ensure no undue environmental hazards occur.

Research needs to be done to determine if subsidizing carbon capture and storage versus other emissions mitigation techniques is warranted.

Due to the large amount of research needed to be done to bring the overall carbon capture and storage process to a global scale, it should be determined if research funds will receive a return on investment greater than the return had the funds been invested in other carbon mitigation techniques.

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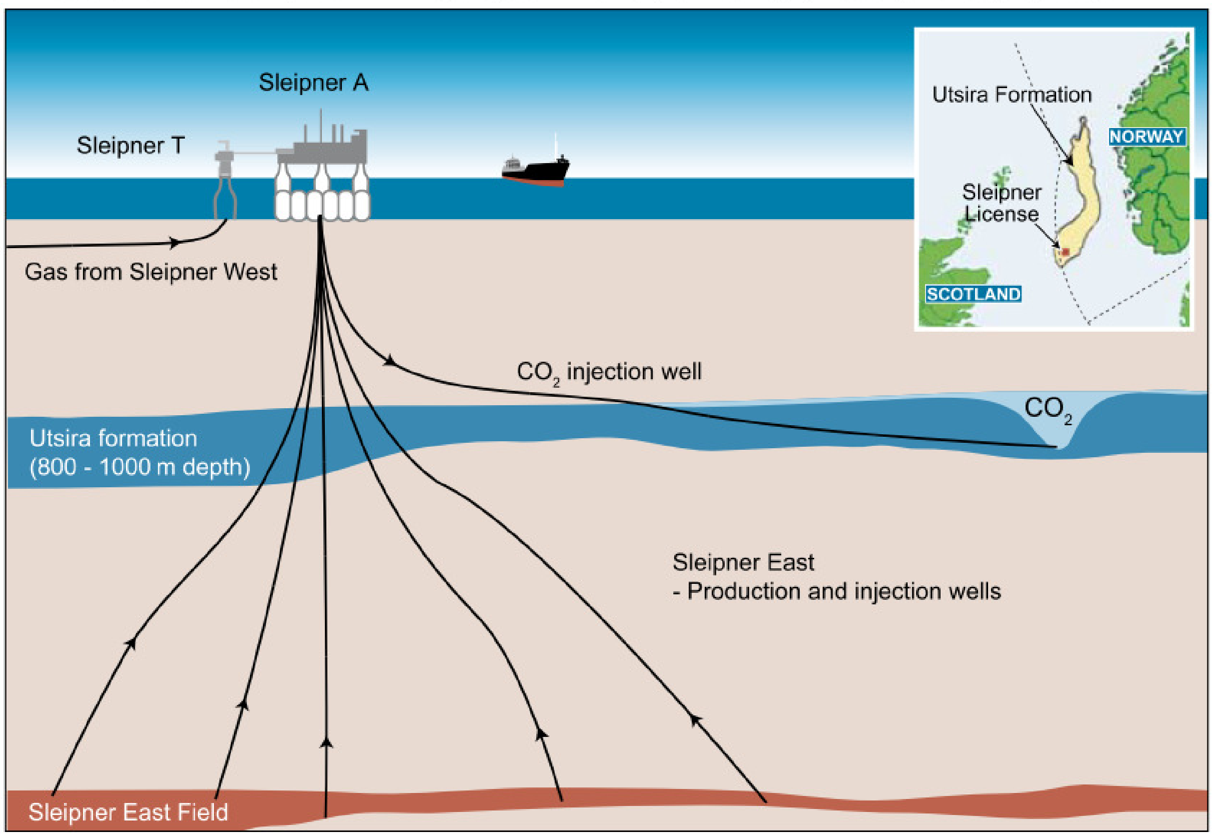
APPENDIX I- The Sleipner Project [1]

The Sleipner Project, operated by Statoil in the North Sea about 250 km off the coast of Norway, is the first commercial-scale project dedicated to geological CO_2 storage in a saline formation. The CO_2 (about 9%) from Sleipner West Gas Field is separated, then injected into a large, deep, saline formation 800 m below the seabed of the North Sea. The Saline Aquifer CO_2 Storage (SACS) project was established to monitor and research the storage of CO_2. From 1995, the IEA Greenhouse Gas R&D Programme has worked with Statoil to arrange the monitoring and research activities. Approximately 1 $MtCO_2$ is removed from the produced natural gas and injected underground annually in the field. The CO_2 injection operation started in October 1996 and, by early 2005, more than 7 $MtCO_2$ had been injected at a rate of approximately 2700 t day^{-1}. Over the lifetime of the project, a total of 20 $MtCO_2$ is expected to be stored. A simplified diagram of the Sleipner scheme is given in Figure 5.4.

The saline formation into which the CO_2 is injected is a brine-saturated unconsolidated sandstone about 800–1000 m below the sea floor. The formation also contains secondary thin shale layers, which influence the internal movement of injected CO_2. The saline formation has a very large storage capacity, on the order of 1–10 $GtCO_2$. The top of the formation is fairly flat on a regional scale, although it contains numerous small, low-amplitude closures. The overlying primary seal is an extensive, thick, shale layer.

This project is being carried out in three phases. Phase-0 involved baseline data gathering and evaluation, which was completed in November 1998. Phase-1 involved establishment of project status after three years of CO_2 injection. Five main project areas involve descriptions of reservoir geology, reservoir simulation, geochemistry, assessment of need and cost for monitoring wells and geophysical modelling. Phase-2, involving data interpretation and model verification, began in April 2000.

The fate and transport of the CO_2 plume in the storage formation has been monitored successfully by seismic time-lapse surveys (Figure 5.16). The surveys also show that the caprock is an effective seal that prevents CO_2 migration out of the storage formation. Today, the footprint of the plume at Sleipner extends over an area of approximately 5 km^2. Reservoir studies and simulations covering hundreds to thousands of years have shown that CO_2 will eventually dissolve in the pore water, which will become heavier and sink, thus minimizing the potential for long-term leakage (Lindeberg and Bergmo, 2003).



APPENDIX II – The In Salah Project [1]

The In Salah Gas Project, a joint venture among Sonatrach, BP and Statoil located in the central Saharan region of Algeria, is the world's first large-scale CO_2 storage project in a gas reservoir (Riddiford *et al.*, 2003). The Krechba Field at In Salah produces natural gas containing up to 10% CO_2 from several geological reservoirs and delivers it to markets in Europe, after processing and stripping the CO_2 to meet commercial specifications. The project involves re-injecting the CO_2 into a sandstone reservoir at a depth of 1800 m and storing up to 1.2 $MtCO_2$ yr^{-1}. Carbon dioxide injection started in April 2004 and, over the life of the project, it is estimated that 17 $MtCO_2$ will be geologically stored. The project consists of four production and three injection wells (Figure 5.5). Long-reach (up to 1.5 km) horizontal wells are used to inject CO_2 into the 5-mD permeability reservoir.

The Krechba Field is a relatively simple anticline. Carbon dioxide injection takes place down-dip from the gas/water contact in the gas-bearing reservoir. The injected CO_2 is expected to eventually migrate into the area of the current gas field after depletion of the gas zone. The field has been mapped with three-dimensional seismic and well data from the field. Deep faults have been mapped, but at shallower levels, the structure is unfaulted. The storage target in the reservoir interval therefore carries minimal structural uncertainty or risk. The top seal is a thick succession of mudstones up to 950 m thick.

A preliminary risk assessment of CO_2 storage integrity has been carried out and baseline data acquired. Processes that could result in CO_2 migration from the injection interval have been quantified and a monitoring programme is planned involving a range of technologies, including noble gas tracers, pressure surveys, tomography, gravity baseline studies, microbiological studies, four-dimensional seismic and geomechanical monitoring.

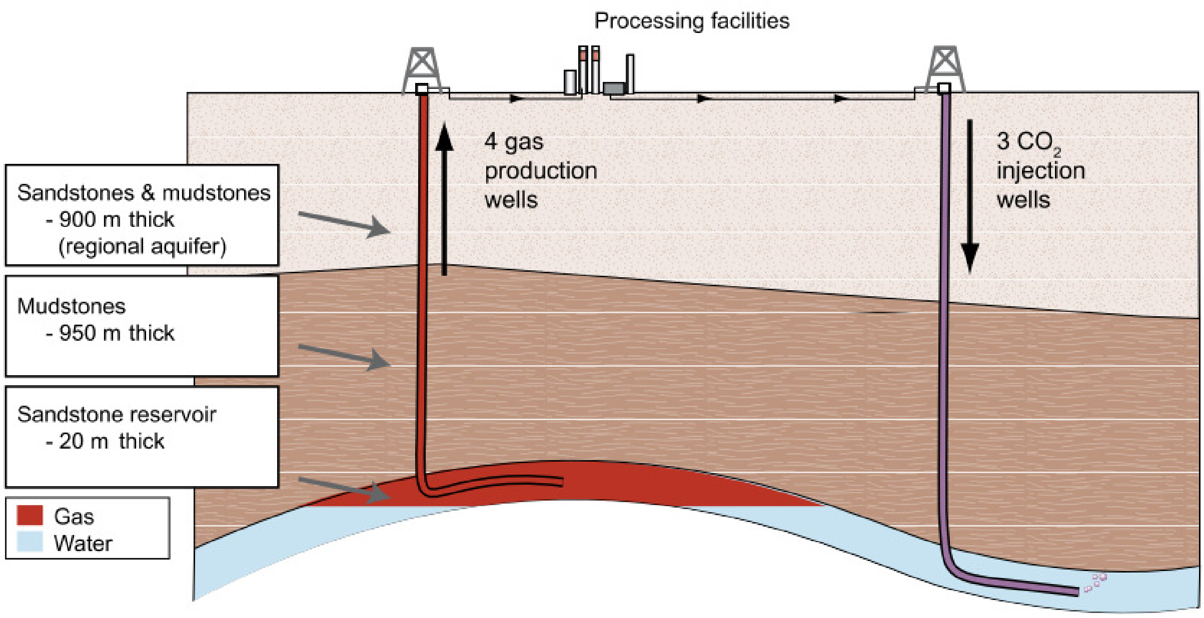


Figure 5.5 Schematic of the In Salah Gas Project, Algeria. One $MtCO_2$ will be stored annually in the gas reservoir. Long-reach horizontal wells with slotted intervals of up to 1.5 km are used to inject CO_2 into the water-filled parts of the gas reservoir.

APPENDIX III – The Weyburn Project [1]

The Weyburn CO_2-enhanced oil recovery (CO_2-EOR) project is located in the Williston Basin, a geological structure extending from south-central Canada into north-central United States. The project aims to permanently store almost all of the injected CO_2 by eliminating the CO_2 that would normally be released during the end of the field life.

The source of the CO_2 for the Weyburn CO_2-EOR Project is the Dakota Gasification Company facility, located approximately 325 km south of Weyburn, in Beulah, North Dakota, USA. At the plant, coal is gasified to make synthetic gas (methane), with a relatively pure stream of CO_2 as a by-product. This CO_2 stream is dehydrated, compressed and piped to Weyburn in southeastern Saskatchewan, Canada, for use in the field. The Weyburn CO_2-EOR Project is designed to take CO_2 from the pipeline for about 15 years, with delivered volumes dropping from 5000 to about 3000 t day^{-1} over the life of the project.

The Weyburn field covers an area of 180 km^2, with original oil in place on the order of 222 million m^3 (1396 million barrels). Over the life of the CO_2-EOR project (20–25 years), it is expected that some 20 $MtCO_2$ will be stored in the field, under current economic conditions and oil recovery technology. The oil field layout and operation is relatively conventional for oil field operations. The field has been designed with a combination of vertical and horizontal wells to optimize the sweep efficiency of the CO_2. In all cases, production and injection strings are used within the wells to protect the integrity of the casing of the well.

The oil reservoir is a fractured carbonate, 20–27 m thick. The primary upper seal for the reservoir is an anhydrite zone. At the northern limit of the reservoir, the carbonate thins against a regional unconformity. The basal seal is also anhydrite, but is less consistent across the area of the reservoir. A thick, flat-lying shale above the unconformity forms a good regional barrier to leakage from the reservoir. In addition, several high-permeability formations containing saline groundwater would form good conduits for lateral migration of any CO_2 that might reach these zones, with rapid dissolution of the CO_2 in the formation fluids.

Since CO_2 injection began in late 2000, the EOR project has performed largely as predicted. Currently, some 1600 m^3 (10,063 barrels) day^{-1} of incremental oil is being produced from the field. All produced CO_2 is captured and recompressed for reinjection into the production zone. Currently, some 1000 tCO_2 day^{-1} is reinjected; this will increase as the project matures. Monitoring is extensive, with high-resolution seismic surveys and surface monitoring to determine any potential leakage. Surface monitoring includes sampling and analysis of potable groundwater, as well as soil gas sampling and analysis (Moberg *et al.*, 2003). To date, there has been no indication of CO_2 leakage to the surface and near-surface environment (White, 2005; Strutt *et al.*, 2003).