EG4013 – MEng Engineering Report (Winter Progress Report) **January, 2015**

Review of the *Winter Report* 'A Feasibility Study of Carbon Dioxide Capture and Storage' by Michael Ewen

The manuscript investigates currently available technologies for CO_2 capture, transport and storage for mitigating GHG emissions in concentrated flow streams (i.e., carbon-based power stations). Mr Ewen undertook literature review on current technologies for capture (adsorption, absorption within pre-, post-combustion and oxy-fuel technologies), transport (pipelines) and storage of CO_2 in geological formations.

The manuscript is relatively well-written with a small number of typos and unrevised sentences. Few sentences are confusing and disconnected with no clear objectives and inter-connectivities. Most of all, the paper is well-structured with clear division, although with diffuse linkages between sections, leading to a relatively easy and smooth reading. A few general comments,

1. The main aim of *Abstracts* is to briefly describe the work undertaken by the author. In general *Abstracts* are divided in 4 parts: (i) motivation, (ii) main objectives, (iii) summary of the main procedures / techniques / technologies (optional) and (iv) main findings. The current *Abstract* encompass all of them.

2. The main *Introduction* section usually has the same (but more in-depth and descriptive) four parts of the *Abstract* and a brief summary of the remaining of the work. In addition, it is always expected a few clear statements -re main background (thus recent innovations related to the main topic), initial literature review and, most of all, technological / scientific gaps in the current understanding. Also, it is expected a summary of the remaining sections at the end of the *Introduction*. Current *Introduction* covered (in some extent) all of above but lacked explain/summarise the main state-of-the-art aspects of the subject area.

3. You must avoid use *colloquial (informal / personal)* writing.

4. A few *References* follows different standards with missing fields and no clear distinction between articles, conference proceedings, reports (internal or external), book chapters, books, communications (internal or external) etc. A few *references* used in the manuscript are incomplete and/or wrong. Regardless of the chosen citation style (e.g., ACS, AIP, AMS, IEEE, AIAA, etc) any reference **must** contain the following fields:

   (a) For journal papers: Authors, Paper Tittle, Journal Name, Volume, Pages, Year of publication;

   (b) For books: Authors, Book Tittle, Publisher, Year or Edition;

   (c) For book chapters: Authors, Chapter Tittle, Book Tittle, Editors, Publisher, Year or Edition;

   (d) For conference papers: Authors, Paper Tittle, Conference Tittle, Place (Country and/or City) where the conference was held, Year of the conference;

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(f) For PhD Thesis and MSc Dissertations: Author, Tittle, Institution (University and Department/School), Year.

Thus, for example:

[1] P.L. Houtekamer and L. Mitchell, 'Data Assimilation Using an Ensemble Kalman Filter Technique', *Monthly Weather Review*, 126:796-811, 1998.

[2] K. Pruess, 'Numerical Modelling of Gas Migration at a Proposed Repository for Low and Intermediate Level Nuclear Wastes', Technical Report LBL-25413, Lawrence Berkeley Laboratory, Berkeley (USA), 1990.

[3] K. Aziz, A. Settari, *Fundamentals of Reservoir Simulation*, Elsevier Applied Science Publishers, New York (USA), 1986.

[4] R.B. Lowrie, 'Compact higher-Order Numerical Methods for Hyperbolic Conservation Laws', PhD Thesis, Department of Aerospace Engineering and Scientific Computing, University of Michigan (USA), 1996.

5. Quality of a few figures is poor. Also, figures and tables **must** be referenced in the main text – they can not just 'float around'! In addition, figure/table captions should be self-contained, i.e., with a good description of the figure/table highlighting the most relevant aspects/information that the author wants to convene.

6. The main objectives of the Winter report are:

   (a) Student can get familiar with:

      i. fundamental science and technologies of the main subject areas (through an in-depth literature review);

      ii. main techniques to assess/investigate the problem that will be used during the Spring term.

   (b) Student can narrow the project towards his main interests. With this in mind he can plan his research activities during the Spring.

   Mr Ewen decided that his main focus during the Spring is to investigate storage technologies and the energy/exergy impact on the whole power generation process. However there is no specific plans on how this will be achieved.

The paper describes technologies related to CCS work-flow. Although there is no clear plan for activities/tasks to be undertaken during the Spring term, Mr Ewen managed to make a relatively in-depth review of the current technologies that he will use in the second part of his project.

In the attached scanned document:

- **PE:** Poor English;
- **SC:** Sentence(s) is/are very confusing and do(es) not make much/any sense.

Appendix C:

Plagiarism Awareness Declaration Form

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A Feasibility Study of Carbon Dioxide Capture and Storage

Submitted by

Michael Ewen

Supervisor: Dr Jefferson Gomes

This Project Progress Report was submitted as part of the requirements for the MEng degree in Engineering (Chemical) at the School of Engineering, University of Aberdeen

19 January 2015

Abstract

motivation

As the world's population continues to grow, there is ultimately a higher demand for energy globally. To live in an entirely fair society, this demand must be met, so as to not leave certain peoples at an inherent disadvantage in life. However, alongside meeting this increased demand, there is also an obligation to provide energy that is cleaner, or obtained in a more efficient manner. This is necessary due to the threat of anthropogenic climate change, a phenomenon thought to be caused by the increased volume of greenhouse gases expelled to the atmosphere, predominantly through the burning of fossil fuels.

process

Carbon dioxide accounts for a large portion of the greenhouse gases in the atmosphere, with its main source being the power generation industry. As such, it is essential that methods are developed to restrict the volume of carbon dioxide that is emitted in power generation. One such option is carbon dioxide capture and storage, a process which allows for the continued use of fossil fuels, whereby the carbon dioxide is separated from the fuel, either before or after combustion, and then sequestered deep underground.

It is possible to utilise the sequestration process for enhanced oil recovery. Enhanced oil recovery has been in widespread use for many years, but with a different goal – to use a minimal amount of CO_2 to recover as much oil as possible. Now however, it is being analysed as a method for sequestering CO_2 – to store as much CO_2 underground while still recovering the maximum amount of oil possible.

obj

This report will provide a brief outline of the carbon dioxide capture and storage process, looking in detail at different methods of capture and storage. The limitations and potential of carbon dioxide capture and storage will also be assessed.

finding / summary

Alongside this, the report will clarify the work to be undertaken in the coming semester.

Contents

List of Tables

List of Figures

List of Abbreviations

AGECC	Advisory Group on Energy and Climate Change
AGR	Acid Gas Removal
ASU	Air Separation Unit
CCS	Carbon Dioxide Capture and Storage
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EOR	Enhanced Oil Recovery
EU ETS	European Union Emissions Trading System
H_2	Hydrogen
H_2O	Water
IEA	International Energy Agency
IGCC	Integrated Gas Combined Cycle
LGS	Long-term Geological Storage
MEA	Monoethanolamine
NO_x	Nitrogen Oxides
SO_x	Sulfur Oxides

1. Introduction

Energy could be said to be one of the most vital resources of human life, the need for energy outweighs almost every other requirement for our existence. The Advisory Group on Energy and Climate Change (AGECC) projects that the global economy will "double in size" [1] by 2030. In line with this, the demand for energy will also grow significantly [1]. As such, it is vital that means are developed to provide more energy, and further develop global power networks to allow PE developing countries to improve their citizens' lives, and their economic standing [1].

Alongside this need for more power generation, there must also be a commitment to reducing the amount of greenhouse gases emitted. This is due to the threat of anthropogenic climate change. This phenomenon, directly influenced by the amount of greenhouse gases emitted to the atmosphere, could bring forth dire consequences, such as rising sea levels, an increased frequency of extreme weather events and an impact on global ecosystems [2].

The energy used by the human race is the largest net contributor of greenhouse gases to the atmosphere, accounting for approximately 60% [1], of total emissions worldwide.

The ideal solutions then, are to either use less energy, or to ensure that in its production a minimal amount of damaging gases are emitted. As a result, the power generation industry must be reformed. Carbon dioxide (CO_2) emitted from fossil fuel combustion is the predominant greenhouse gas, accounting for 57% of all emissions [3]. As such, reducing the level of CO_2 emitted would have a great effect on total greenhouse gas emissions.

Government initiatives have been set out in the UK, and on a broader scale to attempt to limit greenhouse gas emission. The Climate Change Act (2008) has set a target of an 80% reduction of emissions from the 1990 level by 2050, and a 34% reduction by 2040 [4].

Across Europe, financial incentives are in place to reduce greenhouse gas emissions, by way of the European Union Emissions Trading System (EU ETS). This scheme spans 31 countries and 11,000 power generation facilities, and operates on the premise of there being a maximum total allowable amount of emissions for participants in the system. This total amount declines over time, ensuring overall emissions are reduced.

SC PE

Each facility in the scheme either receives a certain allowance of greenhouse gas emission for the period or buys said allowance at auction. If the facility is within its allowance at the end of the period, then it can sell any remaining budget to installations which may have strayed above their allowance. This places a financial burden on facilities to ensure their emissions are as low as possible, as any firm not purchasing extra allowances to cover any excesses can be subject to heavy fines. Thereby financially incentivising plants to become more efficient. [5]

With a goal of meeting the UK and EU targets in reducing greenhouse gas emissions, there are various schemes in place, such as an increased contribution from renewable or nuclear energy.

Another option, which allows for the continued use of fossil fuels for the immediate future is carbon dioxide capture and storage (CCS). This method will be analysed in detail including its benefits, potential drawbacks, where and how it can be implemented and whether it is a feasible option for reducing CO_2 emissions on a global scale.

SC/PE

Were CCS to be further developed and implemented, it would provide a long-term means of storing CO_2 underground, and as such this CO_2 would not be emitted to the atmosphere. The process has three main stages; capture, transport and storage.

colloquial?

Capturing CO_2 involves the separation of CO_2 from the fuel, either prior to, or after combustion. There are ~~in existence~~ processes that achieve this separation, but not on the scale that would be required for CCS to be implemented on full-scale power generation [6].

The transport of CO_2 requires the compression and dehydration of the gas prior to doing so. However the transport of compressed gases, by way of pipeline or tanker is a well-established practice, and should provide little to no obstacle.

SC

Storage of CO_2 would be performed at a depth of greater than 800 metres [6], to cause the CO_2 be in a supercritical state, and thus be a far more dense fluid with a smaller volume. The trapping would be performed initially in a physical manner, with the principal requirement being the presence of a cap rock. Over time the CO_2 would dissolve in the formation water, causing further immobilisation. The injection of CO_2 is already a widely performed feat, particularly in enhanced oil recovery (EOR). The main challenge to be overcome is the insufficient quality of existing monitoring equipment at a sub-surface level.

obj

To complete an analysis of CCS as a whole, this report will examine closely the technologies associated with CO_2 capture, transport and storage. The potential for CO_2 storage globally will be assessed, alongside the potential for sequestration to occur alongside EOR. Integrated Gas Combined Cycle (IGCC) plants, and their linkage to CCS will also be briefly investigated.

Finally the report will lay out the work to be done, including energy and exergy balances, and a review of the current technologies used to monitor the sub-surface movement of CO_2 in geological formations.

In chapter 2, an overview of the CCS process will be presented, including present technologies and their limitations, the projected amount of CO_2 that can be stored globally and the potential for CCS to be combined with IGCC plants.

Chapter 3 will contain a more in-depth analysis, looking in detail at the chemical processes required at each stage.

Chapter 4 will briefly discuss the current methods of transporting CO_2.

Chapter 5 will exhibit the requirements for geological storage, and the various trapping methods, as well as the total potential for CO_2 storage globally by enhanced oil recovery and long-term geological storage.

Chapter 6 will look briefly at the changing goals of EOR.

Chapter 7 will present the work to be done in the spring term.

2. CCS potential & obstacles

CCS is an attractive option for reducing global CO_2 emissions in the near future, as it would allow the continued use of fossil fuels for some time, without increasing the risk of calamitous climate change occurring.

In terms of capture, absorption processes using chemical solvents are the most attractive option for post-combustion capture, but these processes are yet to be demonstrated on the scale required for power generation plants. They are currently used in the food and beverage industry, but would require scale up of between 20% and 50% for use in a 500 MW power generation facility [6].

?

Similarly pre-combustion capture processes are yet to be demonstrated at the scale required for implementation in power generation. Pre-combustion does present an attractive option when implemented alongside IGCC plants, but these come with a very significant capital investment.

?

Oxy-fuel combustion capture, which could potentially allow for a 100% CO_2 capture efficiency appears to be a great option for the future, but is currently only in the early developmental stage.

?

Use before definition!

CCS does seem to be becoming more prevalent, as the International Energy Agency (IEA) presents a list of 24 active sites for sequestration in 2015, across 9 countries, with a projected 45.7 Megatons of CO_2 being stored in the year. This is most likely still not enough however, with hundreds of projects being required to allow enough injection to properly offset the current emissions [6 11].

You used "justified" alignment before, why did you change to left alignment?

3. CO_2 Capture Techniques

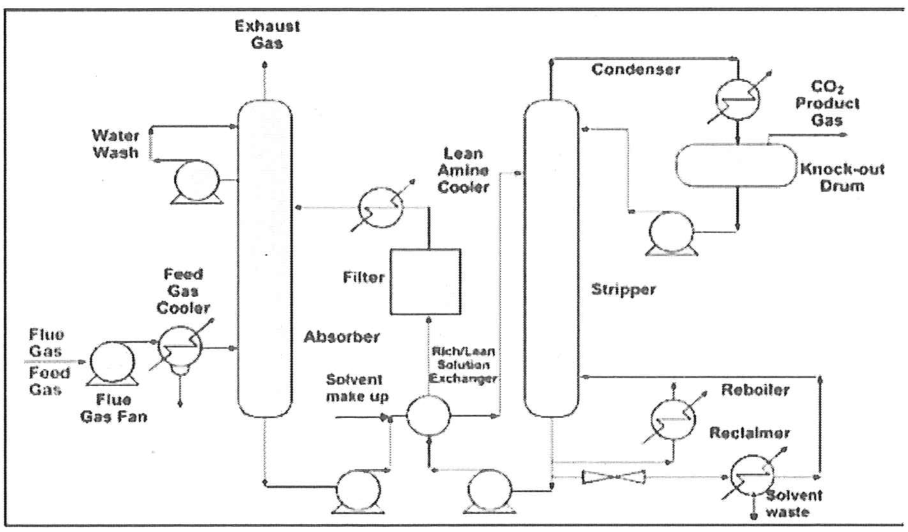
There are four main techniques for carbon dioxide capture; post-combustion, pre-combustion, capture from industrial process streams, and oxyfuel combustion capture [6]. This report will focus on the capture related only to combustion of fuel, as this accounts for a far larger fraction of CO_2 released to the atmosphere [6].

Post-Combustion

Post-combustion capture involves the separation of CO_2 from the exhaust stream of the combustion process. Post-combustion capture using chemical solvents will be analysed. The most common solvent in use is monoethanolamine (MEA) [7].

Initially, the fuel is combusted in air in the traditional method, and the heat produced is used to generate power. The flue gas that is produced in combustion comprises mainly nitrogen (N_2), CO_2, water (H_2O) and trace carbon monoxide (CO), and nitrogen and sulfur oxides (NO_x) and (SO_x).

It is necessary to remove acidic gases such as SO_2 and NO_2 from the flue gas, as these can affect the performance of the chemical solvent [7]. The remaining gas is then sent to a conventional absorption system, displayed in Figure 1 (taken from IPCC,2005);



poor quality!

Figure 1: Post-Combustion Absorption System [6]

In this system, the flue gas is initially cooled to ~40 °C to maximise the absorption. The gas is then contacted counter-currently with the MEA, allowing absorption of CO_2, to approximately 0.4 mol CO_2 per mol MEA [7]. At this point, the flue gas having had CO_2 extracted is vented to the atmosphere, and the rich solvent is fed to the stripper. The stripping column operates at ~120 °C and 1.5 – 2 bar [6 7], and here the CO_2 is separated and captured, and the MEA, containing 0.1- 0.2 mol CO_2 per mol MEA, is cooled and fed back to the absorption column [7].

The captured CO_2 is then dehydrated and compressed for transport. The fraction of CO_2 captured is generally of the range 80-95% of the total present [6].

The main energy expenditure in this system is the heating of the stripping column. As such, the efficiency of production of energy is slightly decreased, due to the duty required for the reboiler. [7]

As has been stated, post-combustion capture does require a degree of scaling up. However, as there is no radical change to the overall process, it is possible in theory to retrofit the required apparatus to existing power generation facilities, which is one benefit of this method. While retrofitting existing plants would reduce efficiency, it removes the capital cost of a new build [6].

Improvements that are being sought after related to this capture technique are [7];

- The development of better solvents, with the aim of reducing energy consumption, and reducing solvent and packing deterioration over time.
- Heat integration of the absorption process, again to save energy
- The development of a solvent that could simultaneously remove CO_2 and Nitrogen and Sulfur Oxides

Pre-Combustion

This capture technique is closely linked with integrated gas combined cycle plants (IGCC), where coal is combusted by partial oxidation to produce synthesis gas [8]. With pre-combustion CO_2 capture, the CO_2 is captured prior to burning of the fuel, and thus either almost pure H_2, or low carbon liquid fuels are combusted, resulting in far lesser damaging emissions.

The removal of CO_2 in pre-combustion capture is generally achieved by a two-step process, the first stage being the production of synthesis gas, a mixture of carbon monoxide and hydrogen, by steam reforming or partial oxidation (as in IGCC plants). Steam reforming is performed by the addition of steam, and follows Equation 3.1 [6];

$$C_xH_y + xH_2O \leftrightarrow xCO + \left(x + \frac{y}{2}\right) H_2 \quad (3.1)$$

Partial oxidation involves the addition of oxygen, and the reaction follows Equation 3.2 [6];

$$C_xH_y + \frac{x}{2}O_2 \leftrightarrow xCO + \frac{y}{2}H_2 \quad (3.2)$$

Having formulated synthesis gas, a gas water shift reaction is then performed by adding steam. This follows the reaction path in Equation 3.3 [6];

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (3.3)$$

At this point, the CO_2, which accounts for between 15-60% of the stream at between 2-7 MPa [6], is removed from the gas stream, and any H_2S that is in the gas is also extracted. The CO_2 is then dehydrated and compressed for transport, while the H_2 is burned to power turbines.

This process, utilising steam reforming in an IGCC plant is displayed in Figure 2 (taken from Padurean, A (2012));

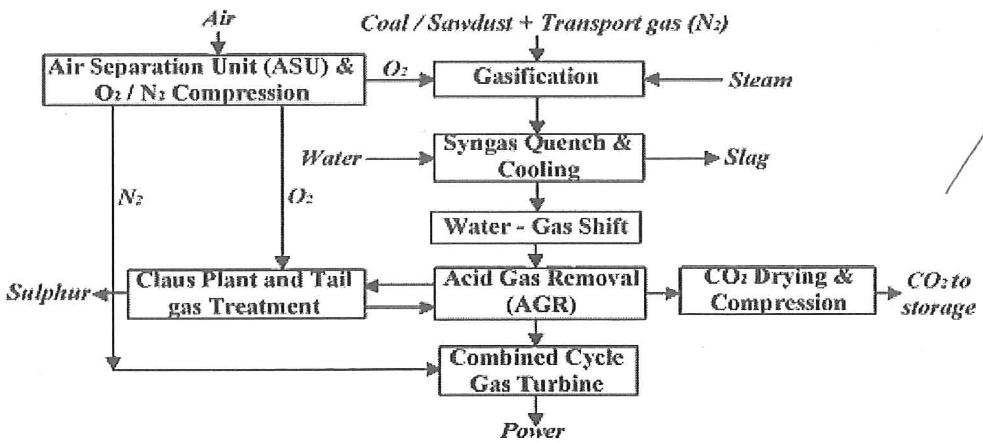


Figure 2: Flow Chart of IGCC pre-combustion (Steam Reforming) [9]

An IGCC plant using CCS would be able to reduce its CO_2 emissions by 80-90% [8]. However, there is an energy penalty incurred by the capture process, and so it would be more costly to produce energy [8].

A significant drawback of pre-combustion capture in IGCC plants is that significant capital investment is required, as retrofitting is implausible. Additionally, hydrogen burning turbines are less efficient than the traditional model [10]. It is thought however, by 2020, IGCC plants could be improved to the extent that their efficiency, with CCS employed, could be at the same level it is today without capture, making them a very attractive option for any new builds [6 11].

The main challenge here is to reduce the plant capital cost, so as to make IGCC plants a more attractive option in the near future.

Oxy-fuel Combustion

Oxy-fuel combustion is a relatively novel concept. It operates under the premise that fuel is burnt in surroundings containing only O_2. As such, the exhaust gas of the reaction contains mainly CO_2 and H_2O (vapour). Subsequently H_2O can be easily removed from the flue gas by condensation, and the remaining CO_2 is purified, dehydrated and compressed for transport. Figure 3 displays the oxy fuel combustion system, adapted from Kenarsari et al;

left alignment.

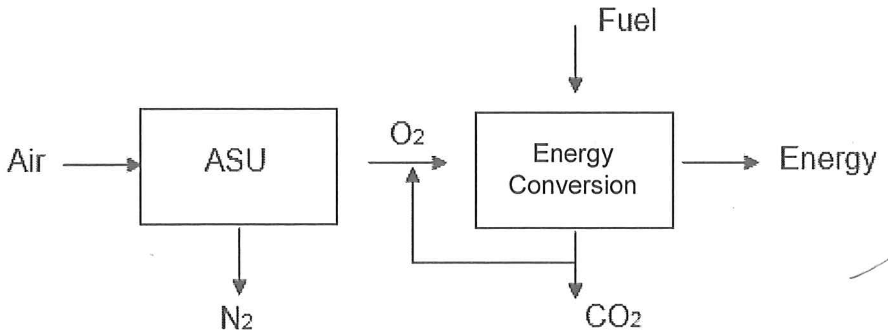


Figure 3: The oxy fuel system [12]

If a fuel is combusted in pure oxygen, its combustion temperature would be approximately 3500 °C. This is higher than is acceptable in current applications. This is the driving factor behind the CO_2 stream being recycled to the combustion reaction to cool the reaction [6].

After condensation of H_2O, the flue stream will contain 80-98% CO_2. With an oxy-fuel combustion system, it is possible to achieve near 100% capture of CO_2 [6]

The benefits of an oxy-fuel plant are apparent in the excellent rate of CO_2 capture and the absence of production of nitrogen oxides. However, oxy-fuel combustion based power plants are yet to be fully developed. There are small-scale prototype plants operating, namely the Schwartze Pumpe power station in Germany. This station appears to be displaying some success, and there are further plans in place to build and subsequently optimize plants in the immediate future. However, as of 2012, oxy-fuel combustion had yet to be developed at a large scale power generation facility. [13]

Left alignment

4. CO_2 Transport

The transport of CO_2 is a well-established practice. The main methods of transport are by tanker, or by pipeline. The method chosen will mainly be dependent on the location of the plant in relation to the storage site.

A pipeline is a large capital expense, but is the cheapest option when operating costs are taken into account [8].

There are already established networks of CO_2 transport, particularly in the USA, where there are over 2500 km of dedicated pipelines which carry 50 Mt CO_2 per year to various EOR projects [6].

For transport by pipeline, CO_2 is generally subjected to at least 100 bar to avoid the presence of two-phase flow [14].

And tanker?

5. CO_2 Storage

The final stage of the CCS process is to sequester CO_2 deep underground where it will theoretically remain for vast periods of time. Injection of CO_2 in this manner has been practised since the early 1970s, when it was first utilised as a form of EOR [6].

There are a number of geological formations that allow for the long term storage, in the range of thousands of years, of CO_2. These include but are not limited to depleted oil and gas fields, fresh water aquifers and saline aquifers. There is believed to be a capacity of approximately 2000 Gt CO_2 available for storage globally. Depleted oil and gas reservoirs account for at least 675 Gt CO_2 and deep saline aquifers comprise space for approximately 1000 Gt CO_2 [6]. Unmineable coal seams are another potential storage formation, but their capacity is relatively unknown, with estimates ranging from 3 Gt CO_2 to 200 Gt CO_2 [6].

Currently, the Sleipner field in the North Sea, the In-Salah field in Algeria and the Weyburn project in Canada account for 3-4 Mt CO_2 stored underground each year collectively. A larger storage plan is in place for Gorgon, Australia where it is planned to store 3-4 Mt CO_2 each year at one site. However, originally planned to begin in 2009 [6], capture and storage is now planned to start in 2015 [15].

The storage facilities that the IEA project to be feasible in 2015 are presented in Table 1. As can be seen, the majority of the storage projects are related to EOR, suggesting the financial incentive of extracting more oil is more persuasive than tax breaks offered by governments, for example in the US for companies partaking in LGS. ?

It can also be seen that a significant number of these fields are projected to begin storage in 2015, suggesting there is a shift occurring towards CCS in industry, whether it be for LGS or EOR.

Table 1: Projected Storage for 2015 [15]

Country	Name	Start Year	Capacity ($MtCO_2\ yr^{-1}$)	Type
Algeria	In-Salah	2004	1	LGS
Saudi Arabia	Uthmaniyah	2014	0.8	EOR
Brazil	Lula	2013	0.7	EOR
UAE	Emirates	2015	0.8	EOR
Norway	Sleipner	1996	0.9	LGS
Norway	Snohvit	2008	0.7	LGS
Australia	Gorgon	2015	3.7	LGS
China	Jilin	2015	0.8	EOR
China	Qilu	2015	0.5	EOR
China	Shengli	2015	1.0	EOR
Canada	Quest	2015	1.1	LGS
Canada	Redwater	2015	0.5	EOR
Canada	Boundary Dam	2014	1.0	EOR
Canada	Great Plains	2000	3.0	EOR
USA	Decatur	2014	0.9	LGS
USA	Cofeyville	2013	1.0	EOR
USA	Enid	1982	0.7	EOR
USA	Kemper	2014	3.5	EOR
USA	Lake Charles	2015	4.5	EOR
USA	Port Arthur	2013	1.0	EOR
USA	Century	2010	8.4	EOR
USA	Val Verde	1972	1.3	EOR
USA	Lost Cabin	2013	0.9	EOR
USA	Shute Creek	1986	7.0	EOR

There are various requirements for geological formations to be suitable for long-term storage. The area must be geologically stable, the rock which is to sequester the CO_2 must be of adequate porosity, and there must be a layer of caprock, to prevent the CO_2 rising to the surface. This occurs as CO_2, even in its dense phase, is less dense than the formation water.

This caprock must exist at 800 m or further below ground, as it is desired to store CO_2 at this depth so it exists in its dense phase [6].

Alongside these conditions, circumstances deep underground must also be favourable to allow storage and prevent migration of plumes of CO_2.

There are four core means of trapping; structural, stratigraphic, geochemical and hydrodynamic.

Structural trapping, alongside stratigraphic trapping is the initial and most basic form of trapping. The caprock – typically a layer of shale or rock salt – has low permeability, and thus traps the CO_2 beneath it. These types of trap can either occur as anticlines, or at faults – where a permeable rock meets an impermeable one [6].

Stratigraphic traps will arise based on the way in which the rock has been deposited, and its varying porosity, thickness and texture [6].

In practice, it is essential that the volume of CO_2 injected does not cause an overpressure, which could lead to a cracking of the caprock and thus escape of CO_2.

Over time, physical trapping becomes less important, and solubility trapping becomes more prevalent as CO_2 begins to dissolve in the formation water. This leads to the CO_2 infused formation water becoming denser, and thus sinking further underground. It also ensures if the caprock does rupture, the CO_2 will not escape in its gas phase [6].

Finally, over the course of thousands of years, mineral trapping can occur. This is the result of dissolved CO_2 reacting with the formation rock to form carbonates [6].

If initially there is no structural or stratigraphic trap available, but still a layer of caprock, it can still be possible to inject CO_2 into saline aquifers and take advantage of hydrodynamic trapping. These saline formations move only a matter of centimetres per year, and so if the caprock stretches a significant distance, the CO_2 plume, were it not to all be immobilised, would take a remarkably long time to reach the end of the caprock [6]. However, immobilisation does occur, and so this is not a concern. Once again solubility trapping is essential, as over time the CO_2 dissolves in the formation water. Additionally, as the CO_2 plume migrates, residual trapping can occur as the tail end of the plume is gradually broken away, and the CO_2 becomes trapped in the pores in the rock, due to the pressure of the formation water [6].

As previously stated, the main concern regarding the geological storage of CO_2 is the quality of monitoring. Shell state that in their Athabasca sands project there are noise, temperature and pressure sensors present. These pressure sensors however are at a depth of 1600 m, whereas the injection of CO_2 occurs at 2300 m, and so there would be a significant delay in the sensors being triggered [16].

6. Enhanced Oil Recovery and Sequestration

It is generally possible to extract 5-20% of oil from a well under its own pressure, known as primary recovery. This number rises to approximately 50% when water injection (secondary recovery) is applied. With CO_2 injection, about 40% of the remaining 50% can be recovered, bringing the total to 70% of all oil from the well [17].

Originally, the principle was to use as little CO_2 as possible to save on costs per barrel extracted [17]. Now however, sequestration is being considered alongside EOR, with the new goal being to maximise not only the oil produced, but also the amount of CO_2 sequestered [18].

To maximise the CO_2 sequestered, it is necessary to minimise the mobility of CO_2 to prevent it simply cycling through the EOR process. Previously, the mobility of CO_2 would've been minimised by alternating water and gas flow, however this water would hinder the sequestration of the CO_2. Kovscek and Cakici [18] present a solution. By simulation and modelling they conclude that rather than alternate between gas and water flow, it is an improvement to operate well control and alter the composition of the injection gas periodically. By implementing this, they state it is possible to "recover virtually the same volumes as an optimised water and gas process, while sequestering twice as much CO_2" [18].

As can be seen, there are certainly methods by which EOR can be used to successfully extract oil, while simultaneously sequestering an adequate amount of CO_2.

7. Work to Be Carried Out

For the duration of the Spring Term, the objectives for the thesis will be as follows;

- Perform an energy and exergy analysis of past and present power generation systems, and their respective CO_2 emissions
- Conduct an energy and exergy analysis on the injection of CO_2 used in EOR, for varying degrees of sequestration
- Perform a critical review of the available technologies used in monitoring CO_2 plume movement in geological formations

References

1. The Secretary-General's Advisory Group on Energy and Climate Change (AGECC), 2010. *Energy for a Sustainable Future,* New York. pp. 7-8. relevant? *

2. IPCC, 2014. *Summary for Policymakers. In: Climate Change 2014: Impacts,Adaptation, and Vulnerability.,* Cambridge and New York: Cambridge University Press. pp. 12.

3. IPCC, 2007. *IPCC Fourth Assessment Report: Climate Change ,* Geneva *?

4. Department of Energy, 2008. *Climate Change Act (c. 27).* USA, UK, EU, ??*

5. ec.europa.eu, 2014. *The EU Emissions Trading System (EU ETS).* [Online]
Available at: http://ec.europa.eu/clima/policies/ets/index_en.html
[Accessed 17 December 2014].

6. IPCC, 2005. *IPCC Special Report on Carbon Dioxide Capture and Storage,* Cambridge and New York: Cambridge University Press. pp. 108-115, 122, 130, 181, 197, 208, 214-216.

FULL LIST OF AUTHORS!

7. Wang, M., Lawal, A., *et al.*, 2011. Post-combustion CO2 Capture with Chemical Absorption: A State-of-the-Art Review. *Chemical Engineering Research and Design* , 89(9), pp. 1609-1624.

8. British Geological Survey, 2014. *Precombustion integrated gasification combined cycle (IGCC).* [Online] Available at: http://www.bgs.ac.uk/discoveringGeology/climateChange/CCS/PrecombustionIntegratedGasificationCombinedCycle.html [Accessed 15 November 2014].

9. Padurean, A., Cormos, C. & Agachi, P., 2012. Pre-combustion carbon dioxide capture by gas–liquid absorption for Integrated Gasification Combined Cycle power plants. *International Journal of Greenhouse Gas Control,* Volume 7, pp. 1-11.

10. Chiesa, P. & Lozza, G., 2005. Using Hydrogen as Gas Turbine Fuel. *Journal of Engineering for Gas Turbines and Power,* Volume 127, p. 78.

11. IEA, 2003. *CO2 Emission From Fuel Combustion 1971-2001,* Paris

12. Kenarsari, S., Yang, D., *et al.*, 2013. Review of recent advances in carbon dioxide separation. *RSC Advances,* Volume 3, p. 22766.

13. Global CCS Institute, 2012. *CO2 capture technologies: oxy combustion with CO2 capture.*

14. Boot-Hanford, M. & al, e., 2013. Carbon Capture and Storage Update. *Energy & Environmental Science,* Volume 7, p. 159.

15. IEA, 2014. *CO2 Capture.* [Online] Available at: http://www.iea.org/etp/tracking/ccs/ [Accessed 27 December 2014].

16. *Shell's Quest Carbon Capture and Storage project.* 2011. [Film] Canada

17. Blunt, M., Fayers, F. & Orr Jr, F., 1993. Carbon dioxide in enhanced oil recovery. *Energy Conversion and Management,* 34(9-11), p. 1197–1204.

18. Kovscek, A. & Cakici, M., 2005. Geologic storage of carbon dioxide and enhanced oil recovery. II. Cooptimization of storage and recovery. *Energy Conversion and Management,* 46(11-12), p. 1941–1956.