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A Review of Carbon Capture and Sequestration Technology

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Abstract

Carbon capture and sequestration is a viable option to reduce the effect of anthropogenic activities before the complete transition to renewable energy. This review paper is directed towards understanding the concept behind CCS, highlighting each of the processes involved and where the process has been deployed around the world. The implementation of CCS is imperative if we must continue to burn fossil fuel.

1. Introduction

There has been an increase in the level of carbon dioxide contained in the atmosphere. This is as a result of direct burning of fossil fuel (coal, oil and natural gas) in response to meet the rising demand of the world's energy supply. Reports around the globe show that the world's average temperature is on the increase which is likely to continue at a steady rate if the emission of Green House Gases (GHGs) is not reduced .In countries like China and India where there is a rapid growth in industrialization, the demand for energy is bound to increase which subsequently will result in an increase in the use of fossil fuel of about 70 percent [1]. In this case, emission of CO_2 into the atmosphere is inevitable. The most feasible way to prevent CO_2 emission is the use of Carbon Capture and Storage (CCS) technology. However, numbers of factors serve as hurdles that have to be overcome before CCS technology gains its ground as an option to mitigate the release of CO_2 into the atmosphere. According to [1] the acceptance of geological storage option as a safe means of storage, creation of factors that will facilitate the development of feasible CCS projects and lastly, identifying regulatory and legal issues needs to be tackled. In other to achieve the capturing of about 6Gt of CO_2 per year, contributions from government, private bodies, research institutions and the energy industry is important [2]. CCS technology will help reduce the emissions of CO_2 to the minimum level (zero emission) by the year 2050. There are strict laws governing the emission of CO_2 by power producing plants which has forced countries like UK to cut down itsCO_2 emission to about 80 per cent similar to CO_2 emission level in the year 1990 [3].CCS technology will remain the best option among other options such as renewable energy and energy efficiencies techniques, to tackle the emission of CO_2 before a complete transition is achieved. Improvements in policies surrounding CCS technology and the development of the technology as time goes on will encourage investors. However, the current prices of carbon in the market is low when compared to the cost of

CCS technology and also the demand of captured CO_2 to be used for Enhanced Oil Recovery (EOR) is at a minimal level [4]. CCS technology is required to grow since fossil fuel will continue to be the dominant source of energy supply and before we start experiencing a substantial growth in the use of renewable energy, also to completely incorporate energy efficiency techniques. To fill up the gap between this present time and 2050, CCS technology should fully be utilized. However, CCS technology offers too expensive an option and steps are needed to be taken to lower the cost of building a CCS plant [4].

2. Climate Change

25 years ago, the issues of climate change in relations to greenhouse effects were taken likely and not treated with seriousness. Now, the masses are aware of their immediate environment and are concerned about the devastating effect human activities such as burning of fossil fuel has caused on climate and if this problem is not tackled could lead to more challenges in the future. With advancement in technologies, scientist have been able to prove the consequences of global warming which include the increase in temperature of about 5°C and rising in sea level of about 10 to 80cm over the next century [5].[5]also explained how the use of biogeochemical and physical models were used to model and predict the impact of the GHGs on the environment and future climate change in other to find means of mitigation. The best option suggested for mitigating GHGs particularlyCO_2 is sequestration.

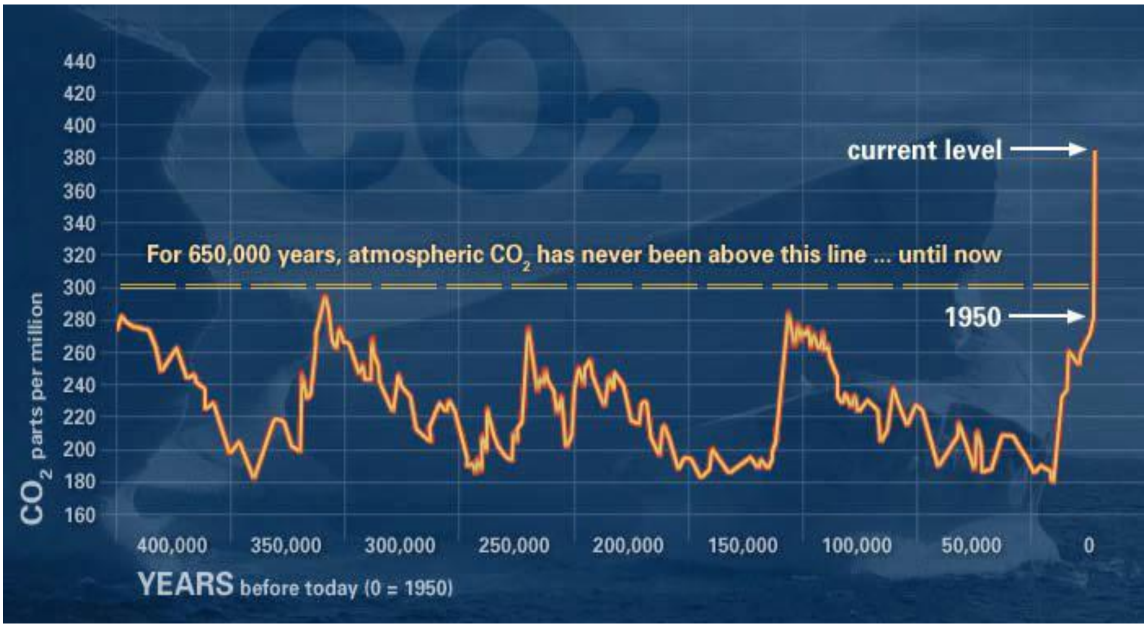

Figure 1 - The varying CO_2 concentration in the atmosphere (in parts per million) [6]

Figure 1 shows atmospheric concentration of carbon dioxide for the past 650 000 years. It is noted from the figure that the level of CO_2 in the atmosphere for the past 650000 years has never exceeded 300 parts per million. However this has changed tremendously due to the emission of GHGs into the atmosphere. The current level of CO_2 emissions is set to be around 380 parts per million which has raised serious environmental concerns all over the world.

3. Greenhouse Gases (GHGs)

GHGs include Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), CCF-12 and HCFC-22, with CO_2 being the most important GHG. GHGs are known to cause global warming. The ability of these gases to trap heat energy is referred to as Global Warming Potentials (GWP) and each of the gases differ in their GWP. Carbon dioxide is known to have the least Global Warming Potentials [5]. As seen in the Table 1, USA has the highest emission of Co_2.

Table 1. Top GHG emitting countries (extracted from original table)

Country	Mt CO_2	% of World GHGS
USA	6928	20.6
China	4938	14.7
Russia	1915	5.7
Germany	1009	3.0
Canada	680	2.0
United Kingdom	654	1.9
Australia	491	1.5
Developed	17,355	17
Developing	16,310	48

Source: ***Global Climate Change and U.S. Law.***

Economic development and industrialization are the major factor responsible for high emissions in the United States and china as seen from the table.

3.1 Possible Ways to Mitigate GHGs Emissions

Three possible ways to combat climate change includes; the use of energy efficient technologies and conversion, focusing on other energy sources (Renewable and Green Technology) and thirdly, carbon capture and sequestration technology [7].

a. Energy Efficiencies

This is simply achieved by eliminating energy waste. It is the cheapest way to reduce greenhouse gas emission. The application of energy efficient techniques can be seen in buildings, transportation, energy generation and distribution, vehicles and the way we design our neighborhood.

b. Renewable Energy

Usage of renewable energies such as hydrothermal, wind, hydro and solar should be encouraged, low carbon emission should be adopted i.e. the recent trends for natural gas to replace coal in power generation. Another area of focus is the use of nuclear energy for power generation however, environmental concerns is hindering the full establishment of nuclear energy as a source of power.

c. Carbon Capture and Sequestration

CCS offers the best option to reduce GHGs emission. It is a process where carbon dioxide from large stationary source is captured before it's released into the atmosphere. However lots of people argue about the feasibility of the process. CCS technology involves three main stages i.e. Capture, Transport and Geological storage.

4. Brief Overview of CCS Technology

CCS popularly known as carbon capture and storage or carbon capture and sequestration is a process where GHGs emissions from industrial or large power plants is captured, transported and stored in geological formations. [8] Described CCS technology as a four way process i.e. capture, transportation, storage in geological formation sand continuous monitoring. CO_2 captured from stationary sources can be transported to where it can be stored without posing any danger to the environment and can also be used for EOR as seen in Figure 2. The various formations where CO_2 can be stored include; saline formation, depleted oil/gas and coal seam.

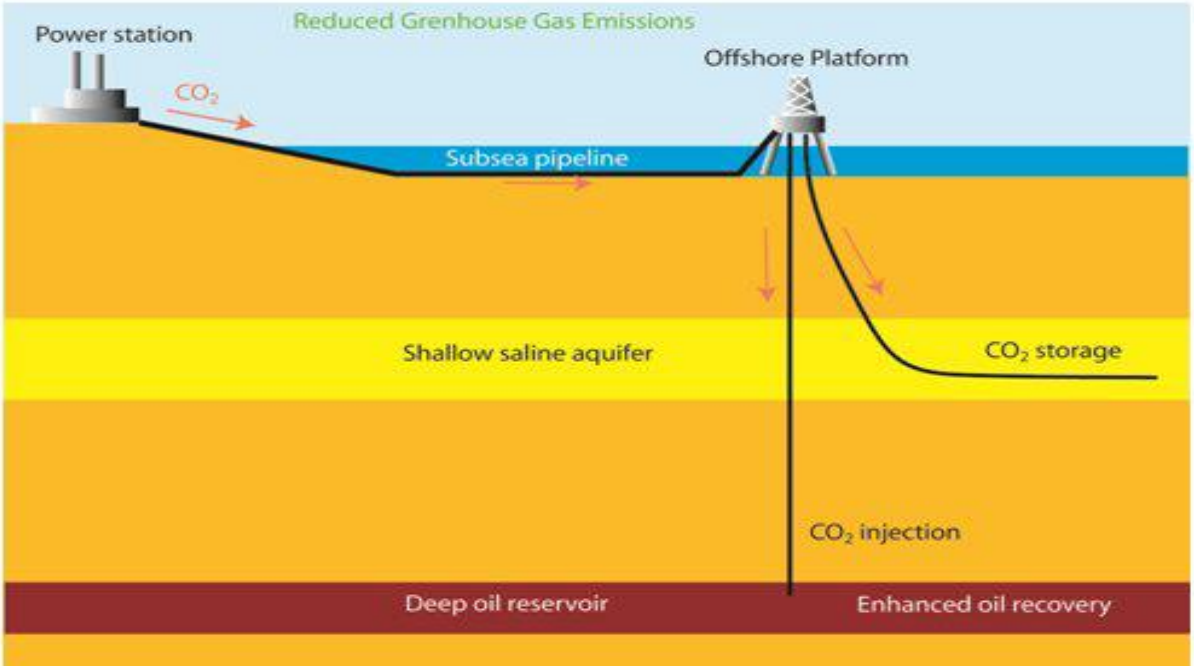

Figure 2. - The concept of CCS technology [16]

4.1 CO_2 Capturing

It is an important factor to capture CO_2 from a highly concentrated source since this gives an advantage of low capture cost. CO_2 capture from generated source (coal plants or gas powered plants) can be accomplished with any of these three (3) methods.

1. Post-Combustion
2. Pre-Combustion and
3. Oxy Fuel Combustion

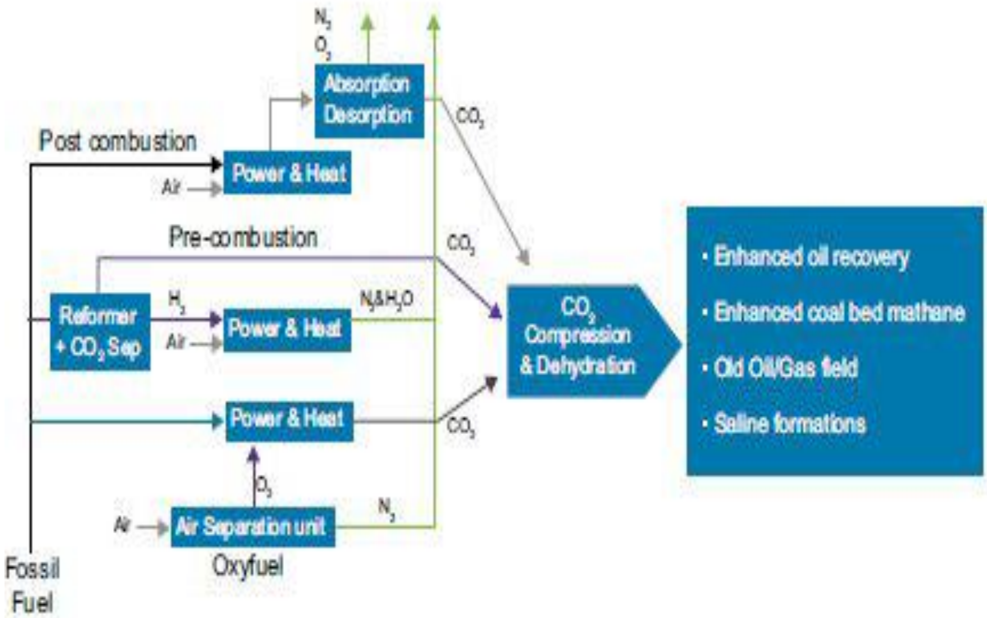

Figure 3- Schematic overview of the three processes of CO_2 capture technologies [17].

Figure 3 shows the final deposition of CO_2 one of which can serve as revenue when used for Enhanced Oil Recovery.

(i) Post-Combustion Method

Post-combustion CO_2 capture refers to the removal of CO_2 from flue gases prior to the final discharge into the atmosphere and it can be mostly applied to PC power plants. The major challenges of this process are as follows:

1. Large power is required for the compression of the captured CO_2, since the captured CO_2 must be compressed from atmospheric pressure to pipeline pressure (about 2000 pounds per square inch absolute).
2. The flue gas is at low pressure (near atmospheric pressure); hence trace impurities such as PM, sulphur oxides (SOx), nitrogen oxides (NOx) can degraded CO_2 capture materials.
3. High volume of gas must be treated because CO_2 is dilute (13 to 15 per cent by volume in coal fired systems, 3 to 4 per cent in natural gas fired system.PCC is the splitting of CO_2 from flue gas resulting from combustion of fossil fuels (oil, coal or natural gas). Coal based power plant burn coal in air and the generated heat is converted by steam turbines connected to a generator into electricity. The burning of coal creates a flue gas in a mixture of CO_2, N_2, O_2, H_2O and other compounds such as NOx, SOx as well as small amounts of heavy metals as seen in Figure 4. Some of these compounds are removed with the aid of existing technologies such as Electrostatic Precipitation (ESP), Selective Catalytic Reduction (SCR) and Flue Gas Desulphurization (FGD). However, a PCC procedure is aimed to selectively pick out CO_2 from the remaining gas mixture [9].

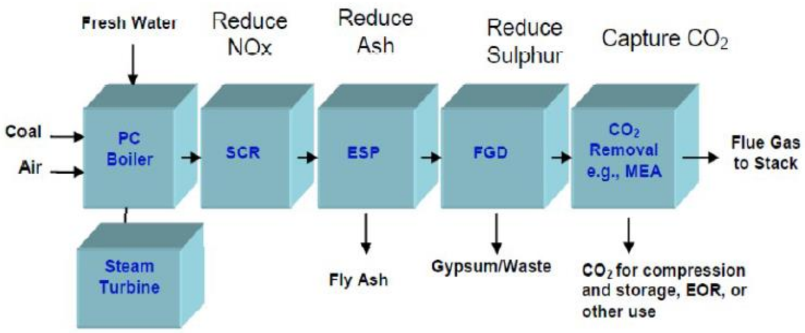

Figure 4. The PCC process. [18]

(ii) Pre-Combustion Method

In the pre-combustion process, fossil fuels are oxidized partially or gasified to produce CO and H_2 which is referred to as syngas. Syngas is further oxidized to produce CO_2 and H_2O during power generation in a gas turbine. More hydrogen can be produced by sending the syngas to a shift reactor and addition of steam and removing CO_2 from the gas stream coming out of the reactor. A chemical solvent is used to produce pure CO_2 just like the post-combustion process. A characteristic implementation for pre-combustion capture is an integrated gasification combined cycle (IGCC) plant. The main benefit of pre-combustion carbon capture as opposed to post-combustion capture is that the syngas is at a higher pressure and a higher concentration of CO_2 gas.

(iii) Oxy-Fuel Combustion

In an oxy-fuel combustion process, combustion of fossil fuel is carried out using Oxygen in contrary to using air. As shown in Figure 5, the removal of Nitrogen is achieved in the air separation chamber supplying pure oxygen for the combustion process. The flue gas composition is mostly CO_2 and H_2O with minute amounts of impurities such as argon, oxygen, oxides of sulphur and nitrous oxides.

As a result, physical gas separation and compression process can be effectively used to capture most of the impurities and a high purity CO_2 is obtained out of the flue gas. The Oxy-fuel combustion procedure eliminates the need for solvent based capture process. However, it is a high energy consumption process. Air separation unit (ASU) which supplies O_2 is needed.

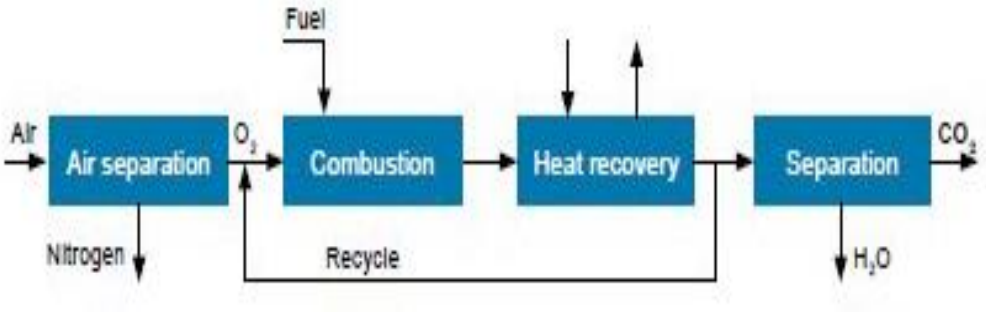

Figure 5: An oxy-fuel unit [19]

4.2. CO_2/Gas Transport

Over the years, USA has demonstrated the use of pipeline for the transportation of oil and gas products. With experience in pipeline transportation, they have been able to prove that transporting CO_2 through pipeline is possible and it is the safest and cheapest method.USA is known to have pipeline infrastructure in place to transport about 50 million tons of CO_2 a year. CO_2 are usually transported to where they can be stored in the sub-surface or for the purpose of EOR. CO_2 also find industrial application which has made the European market to grow continually and sales of 3 million tons of CO_2 was recorded in 2004. In this case, there is need to transport CO_2 by trucks or ship over distance greater than 300km [10]. In the Permian basin region of west Texas and southeast New Mexico, a typical CO_2 pipeline has been constructed for the purpose of EOR, totaling in length of about 3500kmwith maximum capacity of 80000 tons of CO_2 per day. CO_2 pipelines have similarities with oil and gas pipelines in terms of construction and operational features only that CO_2 pipelines require pressures between 2000-3000 psi in contrary to natural gas pipelines with pressures of about 1000psi.

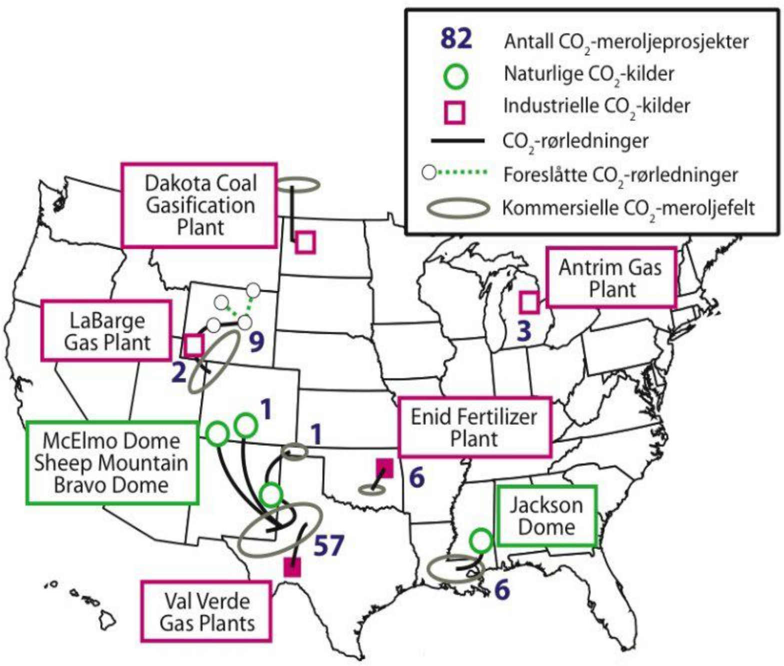

Figure 6 - Pipeline infrastructure for CO_2 transportation in USA. (Source: Transporting CO_2 —ZERO, 2012)

4.3. Gas Transportation as a Proven Technology

A pipeline that transport natural gas from Nigeria gas reserves, Nigeria's Escravos region of Niger Delta to 3 other parts of West Africa i.e. Ghana, Togo and Benin with possibility of further extension to cote d' Ivoire and Senegal in future. The project known as WAGP (West African Gas Pipeline project) begun in 1982 and was proposed by ECOWAS (Economic Communities of West African States) with the primary aim of constructing natural gas pipeline throughout the West African region**.** The pipeline which is 678 kilometre long has a capacity of 12.8mm^3 per day and a total cost of 600 million dollars, it is described as both an onshore and offshore project. The pipeline is used to supply natural gas to the Volta River Authority (VRA) Takoradi power plant in Ghana for power generation.

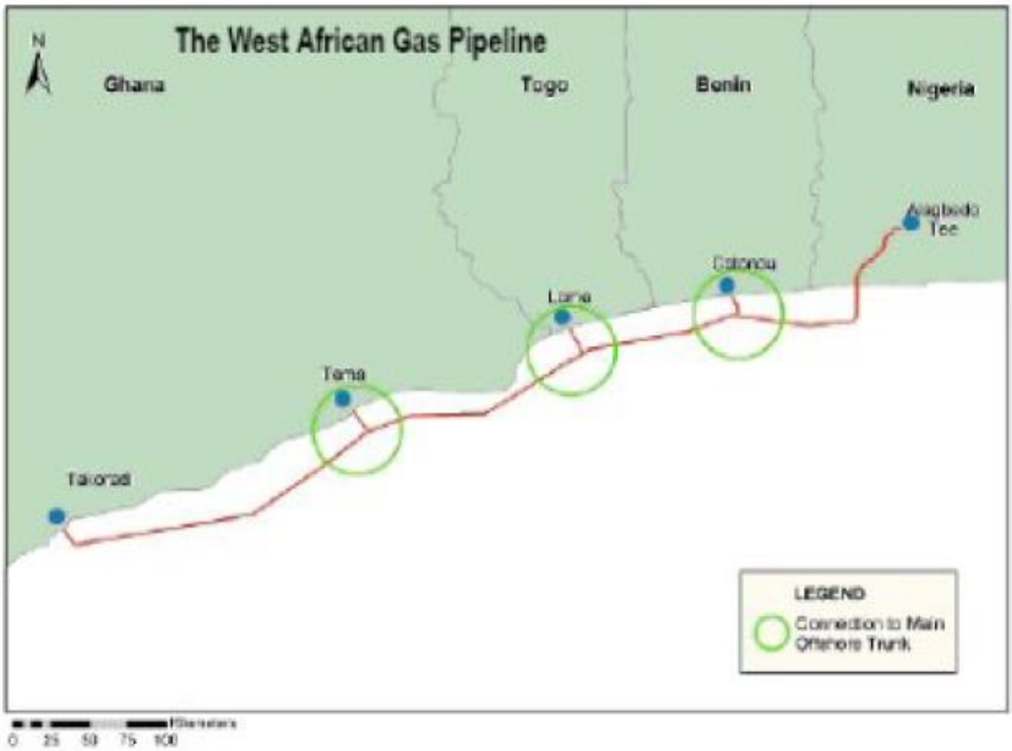

Figure 7 Route of West African Gas pipeline. (Source: Environmental Resource Management ERM, 2008)

Another example of proven gas pipeline technology is the Langeled pipeline which is used to transport natural gas from Norway to the United Kingdom. It is a 1200km pipeline that stretches from Norway via sleipner in the North sea to East England and carries 70million cubic meters of natural gas per day [11].

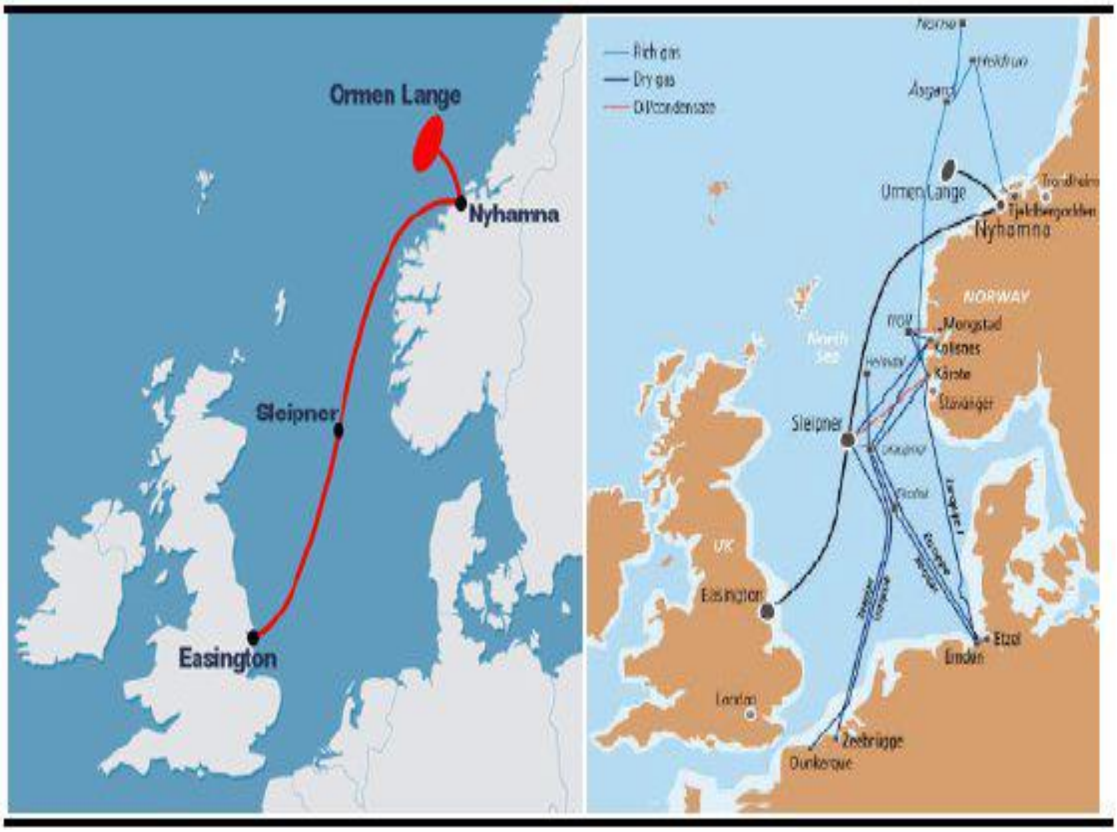

Figure 8. Route of the Langeled pipeline route and integration with existing gas transport infrastructure.
(Source: Environmental Resource Management ERM, 2008)

4.4. CO_2 Storage

Geological formations have proven to be an ideal location for storage of CO_2generated from production in industries. Industries such as petroleum refineries, power plants, cement plants, iron and steel mills as well as various chemical plants release enormous amounts of CO_2 into the atmosphere. Carbon capture and storage technology can be used to capture this carbon dioxide before it is emitted and dispose of it safely into underground formations. CO_2 storage areas should be stable since these areas are prone to cracks due to the movement of the earth crust in other to avoid leakage of CO_2.Geological storage options include depleted oil and gas reservoirs, saline aquifers and un-mineable coal seams. Of the three options saline aquifers have been shown to offer the largest capacity for storage. In the United States, there is an estimated value of 1 billion tons of potential carbon dioxide storage within saline aquifers. Due to the fact that most geological storing capacity options for CO_2 storage can be found in saline aquifers, this thesis therefore confine its analysis and discussion to saline aquifers and comparing with the second most important geological storage option which is the depleted oil and gas reservoirs. Saline aquifers are reservoir rocks with porosity and permeability that contains saline fluid within the pore spaces and in-between the rock grains. They are found at greater depths than portable water containing aquifers. Currently the Sleipner site close to Norway in the North Sea is the worldwide single case of CO_2 storage in a saline aquifer. Sandstones or limestone are the common forms of which saline aquifers may exist but the following properties must also be present for formation to be a viable option for CO_2 it storage.

1. Size: the reservoir must be able to support the lifetime emission of the plant or other planned CO_2 emission source. The reservoirs capacity is determined by the volume of pore spaces available for CO_2 injection.

2. Porosity and permeability plays important role in storing CO_2 in geological formation. There must be high porosity and permeability to accommodate large volume of CO_2 injected. A limiting factor occurs when the rock permeability is low since the injected CO_2 have to displace the *in situ* pore fluids. A direct effect of low permeability is restriction to fluid flow and this can result in concentration of fluid pressure at the point of injection. This will place a limit on the amount of CO_2 that can be injected practically into the formation.
3. Depths: CO_2 storage in aquifers is considered at depths 800m below sea level. CO_2 is present in its dense phase as a liquid and occupy a smaller amount of pore space at temperatures and pressures at depths between 600 to 800m.In addition to the above listed properties of a good geological storage formation, an overlying cap rock must exist which is impermeable to the passage of CO_2. CO_2 is mobile in the pore space and will rise vertically to the top of the reservoir due to its buoyant nature than reservoir fluids. The cap rock which is usually an impermeable low porosity layer will trap the CO_2 and prevent it from migrating vertically in the formation. The main trapping mechanism for the long term security storage of CO_2 is provided by the cap rock and it is usually shale, mudstones or evaporates layers [12].
Although, saline aquifers have the largest volume potential for CO_2 storage but they are not the best choice for CO_2 storage from an economic point of view because of the non-existing surface equipment, injection wells and implementing them appear to be costly. A depleted oil and gas reserve offers the most attractive option for CO_2 storage due to the fact that, during exploitation stage, enough information about the geology of the reservoir has already been known, secondly surface and underground infrastructures are already in place with little or no modification for CO_2 injection and thirdly, CO_2 injection into oil and gas reservoirs to increase oil productivity (Enhance Oil Recovery) has been widely practiced. Experienced gained from previous exploitation work on a reservoir can be applied for successful injection of CO_2 in geological formations. The IEA GHG Weyburn CO_2 monitoring and storage project being conducted in Canada is a prime example of CO_2 storage in depleted oil and gas reserves [13].

4.5. Interactions of CO_2 in geologic formations

In other to predict correctly how CO_2 behaves in geologic formations, it is important to understand the physical properties of CO_2. Temperature and pressure have significant effect on the gas. At ambient conditions (standard temperature and pressure), CO_2 is a gas, but as depth increases it changes to a liquid phase. CO_2 occurs as supercritical fluid at high temperature and pressure. The phase transition of CO_2 depends on the geothermal gradient factor in the formation. In saline aquifers and depleted oil and gas reservoirs, it is important to have an impermeable cap rock in other for CO_2 to be contained since CO_2 has a lower density than the *in situ* fluids and has the tendency to rise and settle below the underlying seal. (Benson and Cole, 2008)

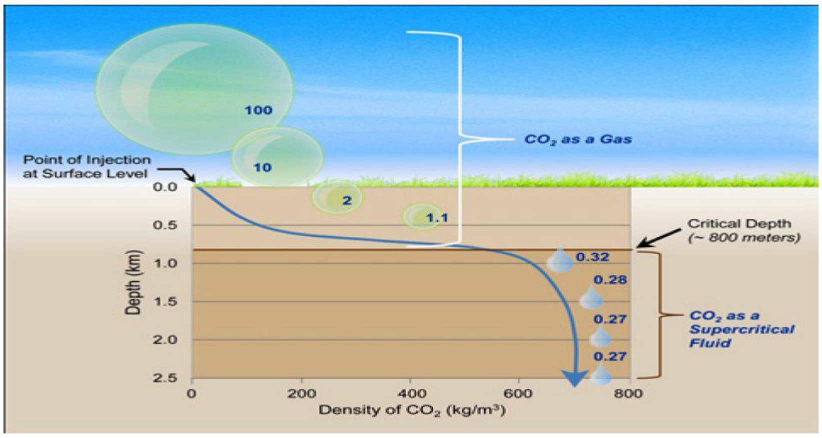

Figure 9. Changes in CO_2 phases at the point of injection. (Source: NETL,Department of Energy (DOE) US).

It can be seen from Figure 9 that the volume of CO_2 from the point of injection reduces as we go deeper and exist as a supercritical fluid. The injection of CO_2 into a porous rock can result into multiple physical phenomena that will allow the injected CO_2 to stay confined within the rock. There are four major trapping mechanisms that assist in the storage of CO_2.

1. Structural trapping
2. Solubility trapping
3. Capillary trapping
4. Mineral trapping.

The relative significance of each of this process will change over time since CO_2 migrates and reacts with the rocks.

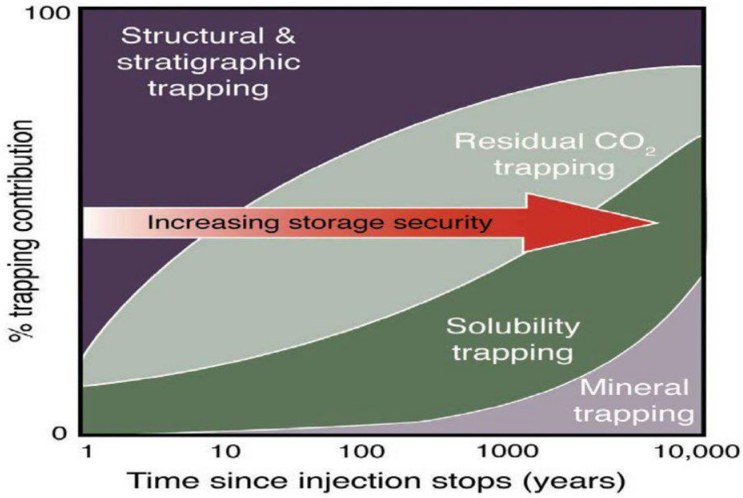

Figure 10. Variation in timeframes for different trapping mechanism. (**Source: CO_2 Sequestration in Deep Sedimentary Formations by Benson and Cole, 2008)**

Structural trapping indicates the occurrence of a dense and fine textured rock that functions as a seal above the sequestration reservoir. It should be able to provide an adequate permeability and capillary hurdle to upward migration of CO_2.

Solubility trapping occurs once CO_2 dissolves into the pore water which is termed trapping by solubility. Several factors such as pressure, temperature and salinity of the brine initiate solubility. At most reservoir conditions (ambient to 150°C and pressure), CO_2 solubility rises with increase in pressure but declines as temperature and salinity increases.

The next trapping mechanism known as capillary trapping traps CO_2 immediately after injection comes to a halt and water starts to imbibe into the CO_2 plume. Capillary trapping is imperative for sequestration in dipping aquifers without a structural closure present. The trailing edge of the CO_2 is restrained therefore slowing up migration. Research works have suggested that the entire CO_2 plume can be immobilized in this manner. Capillary trapping is also referred to as residual phase trapping in mineral trapping, dissolved CO_2 reacts with minerals in geologic formations thus promoting the formation and precipitation of carbonate minerals. Mineral trapping process is comparatively slow but immobilizes CO_2 for very long geologic period of time. Overall impact of this process can take tens to hundreds of years to become evident.

It is a requirement to understand the fundamentals of the geochemical, hydrologic, and geologic, geo-mechanical processes regulating the movement of CO_2 in the subsurface and its long term effect in order to create a means of developing approaches to characterize storage locations, and to choose sites for CO_2 storage with minimal leakage risk. However, it will also be a good practice to validate predictive model to enable for continuous monitoring of storage site by observing the behavior of CO_2 in the subsurface and to ensure reservoir integrity [14].

5. Conclusion

CCS is a proven technology as it has been practiced in some parts of the world. Although, the technology offers an expensive solution to the reduction of CO_2 in the atmosphere however, it remains the only option if anthropogenic activities must continue. Large power plants that emit high source of CO_2 should have CSS technology in place. Interest should be focused on areas with clusters of cement factories because CO_2 emissions from these areas are of high concentrations. Proper survey of weather the geological area of interest will be suitable for CO_2 sequestrationshould also be checked. Continuous monitoring of injected CO_2 is a must in other to ascertain the sustainability of the whole process.

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