Spatial Planning for Underground Carbon Storage and Relative Geo-hazards Assessment

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Abstract

Carbon is known as one of the most effective green house gases on global warming and climate changes. Recently, some developed countries are capturing carbon and pumping it into the earth for long time storage. For instance, pumping CO_2 into reactive rock formation or saline aquifers underground or depleted oil and gas reservoirs or pumping into the deep ocean or onto the sea bed. Geologically, earthquake is able to release carbon from earth to atmosphere. So, underground carbon capturing not only should be paid attention to Greenhouse Gas (GHG) mitigation but also should be considered about geological concepts of carbon storage. Geographically, carbon emission and capturing have spatial concepts and find place for very long carbon storage requires spatial studies. Also, spatial planning feasibility helps us to know and assess current hazards and risks about carbon storage and mapping and characterizing potential geology. This paper describes how spatial planning is useful for carbon captured, injected and stored into earth for long time with the minimum geo-hazards.

1. Introduction

The first world climate conference of 1979 took steps to limit carbon dioxide emission through energy economic modeling and ozone depletion research. In 1979, a report published by the US National Academy of Science stated the doubling of CO_2 concentration would lead to increase of average temperature of the earth's surface between 1.5-4.5°C, which called for global action. After that carbon is known as very serious and influential reasons of climate changes. It is widely accepted that the emission of CO_2 which is formed with the combustion of fossil fuels, contributes to the greenhouse effect and consequently to global warming. In the Dutch 4th National Environmental Policy Plan, the capture of CO_2 and its storage in the underground is considered to be a third option (additional to energy conservation and renewable energy technologies) that may be applied to reduce anthropogenic CO_2 emissions into the atmosphere substantially (VROM, 2001). In the most recent coalition agreement between the parliamentary groups of the Lower House, targets were formulated to reduce Greenhouse Gas (GHG) emissions by 30% in 2020 compared to the level in 1990. This may provide a strong incentive to employ Carbon Capture and Storage in the Netherlands (CDA et al., 2007). Interest in CO_2 storage arose in the early 90s when Dutch researchers began to investigate the feasibility of CO_2 storage. Other advocates like the Dutch Energy Council and the Dutch Environmental Council began to emphasize the beneficial Dutch circumstances for CO_2 storage, arguing that the Dutch should exploit their strong position in the natural gas sector ('Nederland Aardgasland'). In fact, since the discovery of huge amounts of natural gas in the late 1950s an extended natural gas grid was constructed and a large knowledge infrastructure emerged. Both promise to be good starting points for developing CO_2 storage in the Netherlands. Pointing to an increasing number of depleted natural gas fields, the advocates also argue that these fields could be used for storing CO_2. In the 1999 Climate Policy White Paper USA has acknowledged the potential of clean fossil fuels on the long term and again in 2001 in the 4th National Environmental Policy Plan (NMP4) (Van Geel, 2005). Carbon capture and storage (CCS) technology has the potential to dramatically reduce the atmospheric accumulation of CO_2 emitted from human activities. CCS requires a system of interlinked technologies that capture CO_2 from sources and transport it to geologic storage reservoirs into which the captured CO_2 is injected (Ehler, 2008). To significantly mitigate CO_2 emissions, CCS must be deployed at a considerable scale. Each segment of the CCS chain (capture, transport, storage) has a technology with its own characteristic cost structure, and CCS involves the interaction of these technologies and costs in a coupled system. This coupling determines the returns to scale for the entire carbon capture and storage system and suggests how, given the spatial distribution of sources and potential reservoirs, CCS activities should be organized. Given that CCS couples the spatial organization of CO_2-emitting industries to the spatial organization of geology, guidance on locating future CO_2 sources relative to geology is needed (Bielicki, 2009).

2. Spatial Dimensions of CO_2

Spatial planning is an essential tool for managing the development and use of the terrestrial environment in many parts of the world. In North America and Europe, for example, it is commonly used as a central component of economic development and environmental planning. The principal purpose of spatial planning on land is to regulate development and land use in the public interest. Over the past century, the traditional approach of making individual permit decisions on a project-by-project, case-by-case basis—and the unplanned outcome of this approach—has been replaced by a more strategic planning process that lays out a vision—or comprehensive plan—that can guide individual sectoral planning and permitting. This approach has become the standard for terrestrial land-use planning and management. The spatial clustering of sources relative to each other, of injection reservoirs relative to each other, and of sources relative to injection reservoirs can have important ramifications for CCS policy and deployment. The deployment of CCS technology will require large investments in infrastructure, such as dedicated CO_2 pipelines, for example, which can be networked together in order to take advantage of economies of scale with pipeline diameter—from both the physical laws governing fluid flow through pipelines and the empirical costs of building pipelines of marginally larger diameters (Bielicki, 2008a, 2008b). This shows all carbon capturing stages require very accurate spatial studies. Development of the spatial regional inventory requires solving a few specific problems: lack of information on spatial distribution of GHG sources and absence of data necessary for direct estimation of GHG estimation in every important point. Spatial regional levels inventory of GHGs is important for a number of reasons, particularly, it gives local government valuable information on location and magnitude of GHG sources, help to identify cost effective ways of GHG reduction and involve local people into GHG reduction measures (Gómez et al., 2007). The UK regulations also highlight that the use of hazardous substances, such as oxygen, hydrogen and amine solvents will have additional spatial requirements that must be considered when making a planned climate change research (CCR). In particular, the use of these hazardous substances may necessitate that buffer zones are placed around a particular site to avoid land use conflict with neighbouring land uses, and may require consultation with local planning authorities (ERM, 2010).

2.1. Scientific and technical concepts of CO_2 capturing for risk assessment

Technically, CO_2 can be transported and sequestered; carbon capture prefers a relatively pure stream of the gas. Pathways for carbon capture come from three potential sources. First, several industrial processes produce highly concentrated streams of CO_2 as a by-product. Although limited in quantity, they make good initial targets because CO_2 capture is inherent in the existing process, resulting in relatively low incremental costs. Second, power plants emit more than one-third of the CO_2 emissions worldwide, making them a prime candidate for carbon capture. Although the quantity is large, the cost of capture is significant because the CO_2 concentrations are low—typically, 3-5% in gas plants and 13-15% in coal plants. Finally, future opportunities for CO_2 sequestration may arise from producing hydrogen fuels from carbon-rich feed stocks, such as natural gas, coal, and biomass. The CO_2 by-product would be relatively pure, and the incremental costs of carbon capture would be relatively low. The hydrogen could be used in low-temperature fuel cells and other hydrogen fuel-based technologies, but there are major costs ahead for developing a mass market and infrastructure for these new fuels (Herzog, 2001). From a community carbon reduction perspective, we see renewable biomass, or biomethane based community CHP plants playing an important role. Local authorities have a key role in integrating and applying the right mix of low carbon technologies in the community context. The key role of government through the public sector is in providing the anchor thermal loads for these schemes. In turn, this will bring confidences to the developers to increasingly invest in this market (Anonymous, 2009).

2.2. CO_2 transportation and risk assessment

Emissions of CO_2 will not necessarily be at the location of the storage site, so transport of CO_2 is needed. A transport system (via pipelines and/or shipping) is therefore needed to link the CO_2 sources to the CO_2 storage sites (Wildenborg et al., 2005a). CO_2 can be transported via pipeline, by tank wagons and by ship. In practice, because of the huge volumes involved, only pipeline and ships are cost-effective options. Generally, transportation costs are considered to be small compared to the overall capture costs. Successful CO_2 capturing and implementation need appropriate transportation technology to assess environmental and biological hazards. Transportation of CO_2 by ships and sub-sea pipelines, and across national boundaries, is governed by various international legal conventions. Many jurisdictions states have environmental impact assessment legislation that will come into consideration in pipeline building. If a pipeline is constructed across another country's territory, e.g. land-locked states, or if the pipeline is laid in certain zones of the sea, other countries may have the right to participate in the environmental assessment decision-making process or challenges another state's project (Metz, 2005). To keep CO_2 in a compressed, liquid state, CO_2 pipeline pressure must be higher than those used typically in natural gas pipelines. Extra precautions and different designs are therefore necessary for CO_2 pipelines. Nonetheless, CO_2 pipelines have been in operation for many years, and the industry has done well to reduce the risks associated with CO_2 release (Barrie et al., 2004). The most popular hazards in CO_2 pipeline transportation are:

a. Pipeline routing- pipeline construction and maintenance will have impacts on the environment and landscape.

b. Global risk- that the pipeline leaks and the captured CO_2 is re-emitted back to the atmosphere compromising the effectiveness of CCS as mitigation option.

c. Local emission risk that any leaked CO_2 poses to the surrounding local populations and the environment (from asphyxiation of flora and fauna and acidifying effects on soil, surface and ground waters) (Zakkour, 2007).

2.3. Location of CO_2 storage risk assessment

Storage of CO_2 should be such that it remains isolated from the atmosphere for a suitably long period. The options for this are mainly underground, e.g. depleted oil and gas fields, aquifers and deep seated coal bearing layers (Wildenborg et al., 2005_b). The CO_2 capture device can be located at the point of CO_2 end-use or sequestration, eliminating the current need to match CO_2 sources with sinks. For example, the CO_2 originating from all those vehicles in Bangkok can be captured in an oil field in Alberta, Canada, where it could be used on-site for enhanced oil recovery (EOR) operations or it could be captured in South Africa to feed a growing demand in that country for feed stocks for petrochemical production. If the goal is to sequester a given quantity of CO_2 in a specific geological formation, the air capture system could be located at that physical location. Within the United States, formations in Ohio, Oklahoma and Michigan, among other sites, appear to hold promise for long-term underground CO_2 storage. Air extraction could also offer a new window in negotiations between developed and developing countries over how to deploy carbon reducing technologies (UniRazak, 2007). Storage site for short time implementation and long time storage of CO_2 project must be consider for wildlife, human life and biodiversity capacity. CO_2 storage location is very important part of any underground CO_2 storage because amount of carbon is significant and if CO_2 is released from storage sites it would kill people and livestock poisoning the environment for long time. In most of developed countries that have this kind of projects, they do very accurate studies about place for CO_2 capture and storage. For instance, The Dickinson Study Area covers an area extent of approximately 800 km^2 and contains sufficient geologic data for characterization down to a depth of about 3000 m. In this study area, there are several potential CO_2 storage and CO_2 EOR target formations with adequate data for an evaluation of their storage potential. The target formations identified in this area are from the bottom up, the Mississippian Lodgepole carbonate mounds (oil reservoirs), Mississippian Heath carbonates (oil reservoirs), Pennsylvanian Tyler sandstones (oil reservoirs), Pennsylvanian/Permian Broom Creek sandstones and carbonates (saline formation), and the Cretaceous Dakota sandstones (saline formation). The sealing formations for each formation are tight carbonates, evaporates, shale layers and overlying all target formations is approximately 1000 m of Cretaceous Pierre, Greenhorn, and Mowry shale which should act as an additional stratigraphic seal. Initially, the study area appeared to be stratigraphically and structurally simple; however, closer inspection revealed some abrupt changes in some of the structure maps and in the formation of isopach maps. As a result of this study, the methods by which sites are assessed in the PCOR (Plain CO_2 Reduction Partnership) area were modified so that identification of subtle structural and stratigraphic features, including areas that may be faulted or fractured, are more easily identified (Gorecki, 2009).

2.4. CO_2 Injection considerations and hazards mitigation

Deep well injection of liquids has occurred safely for over 20 years and there is less experience with injecting gases like CO_2. While most CO_2 injections for enhanced oil recovery have occurred safely, problems that have occurred illustrate the unique hazard that utilizes and regulators must consider (Gledhill et al., 2009_a). Additional insight is needed for determining the most cost effective injection strategy of CO_2 in a low pressure reservoir. In order to control the CO_2 injection, it might be necessary to place a down whole flow restriction. Furthermore, pre heating of the (decompressed) CO_2 stream might be needed to prevent phase changes in the well tubing and the risk of damaging the lining of the tubing. In this study, it has tacitly been assumed that all wells, that are operational now, will be suited and available for CO_2 injection at reasonable cost and without major modification. However, these wells have not been designed for low temperature CO_2 injection and an extended life time (after a hibernation period of several years). Detailed well design studies on the re-use of former gas wells may point at certain technical or cost barriers (NOGEPA, 2009). Additional insight is needed to optimize the injection strategy of CO_2 in a low pressure reservoir considering safety, costs, capacity, etc. This involves: 1) the mitigation effect on temperature which may occur when CO_2 decompresses whilst being injected into the low pressure reservoir; 2) what is the optimal balance between minimizing the energy consumption for heating the decompressed CO_2 and maximizing the rate of injection. Furthermore, in the pilot, alternative technical solutions to control the injection rate and temperature effects could be tested like the use of orifices or control valves that are positioned in the tubing at the bottom of the well. Apart from additional research, we therefore recommend to test full scale CO_2 injection in practice, especially with respect to the injection of dense phase CO_2 into low pressure reservoirs. This test should include: 1) injection of gasified and heated CO_2, 2) injection of dense phase CO_2 by means of down hole flow control, and 3) injection of unheated CO_2 (both in the dense and gaseous phase) (Cronenberg et al., 2009).

3. Hazard Scenarios for CO_2 Injection and Storage Methods

3.1. *CO_2 injection into rock formation*

Land subsidence and triggered earthquake are common examples of anthropogenic geological hazards caused by or related to the production of subsurface mineral resources and storage of energy residues in the deep subsurface. Geological hazards, either natural or man-made, may cause increased leakage of CO_2 from sequestration site. For public acceptance of geological sequestration of CO_2, it is important to demonstrate the mechanical effects of CO_2 injection and storage will neither cause deterioration of the mechanical stability and the isolation capacity of a sequestration site nor have negative effects on environment (Olric et al., 2005). Technically, we should measure how injection has reaction in term of time. In fact, these kinds of studies are very helpful for finding places for storage and hazards assessment. For instance, the 1D radial reactive transport models represent CO_2 injection in a siliciclastic and carbonate reservoir at 2 km depth and 70^{o}C. CO_2 and other gases were injected in the reservoir at a rate of 1 million ton year^{-1} over a period of 100 years. The reactive transport models simulate the system from 0 to 10,000 years. There are three scenarios of mixed gas injected: CO_2 only, CO_2+H_2S, and CO_2+SO_2 in which CO_2 is injected as gas phase while both H_2S and SO_2 (~5% each) are injected as aqueous solutes. The reservoirs are specified to have an initial porosity of 0.30 and initial permeability of 100 mD. The siliciclastic and carbonate reservoirs were defined by hypothetical mineral assemblages, representing an oligoclase/feldspar-rich sandstone reservoir and a limestone-rich reservoir, respectively (Table 1).

Other primary and secondary minerals are listed in Table 1 as well (Xiao et al., 2009). Conceptual model of CO_2 mineral fixation in Iceland assumes that acidic carbonated waters injected into basaltic rocks will initially cause rock dissolution and release of divalent cations such as Ca_2+, Mg_2+ and Fe_2+. As reactions progress, these elements will combine with CO_3 and precipitate as carbonates due to increasing pH. A large scale experiment with a plug flow reactor imitating chemical and physical conditions within the basaltic rocks after CO_2 injection, gives an opportunity to study the rate of basaltic rock dissolution and solid replacement reactions under controlled CO_2 conditions. The experimental set-up makes it possible to follow changes in pH, Eh and chemical composition of the fluid on different levels along the flow path within the column. Characterization and quantification of secondary minerals (carbonates and clays) enables determination of molar volume and porosity changes with time (Galeczka et al., 2010). But it is not enough for the CO_2 underground storage and we need to have environmental studies as internal and external geomorphology. There is no doubt that we need to take the reactivity between CO_2, pore water, and surrounding rock into account when, considering CO_2 storage in depleted gas fields or aquifers. CO_2 will dissolve in the formation water, which will become more acidic. As the dissolution of CO_2 occurs rapidly after injection of CO_2 in the subsurface, the drop of the pH in the pore water will also be fast. The CO_2 dissolution and change in pH will disturb the existing local chemical equilibria between the solid and liquid gases phases. As this can cause mineral dissolution and precipitation, as well as reactions around the CO_2 injection well, understanding the geochemical reactions that are taking place in the underground is therefore very important. During the lifetime of CO_2storage scheme, various groups of CO_2-rock interactions can be distinguished. Once injection has started, supercritical CO_2 (SC-CO_2) will dissolve and interactions will occur between the injected CO_2 and well materials. If CO_2 is injected as a liquid, either in the well or in the well environment it will become supercritical. In the direct well environment, dry supercritical CO_2 will prevail which might still be at a different temperature than the reservoir. Gradually, CO_2 temperature will adjust to the reservoir temperature and temperature driven CO_2-rock interactions will disappear. Longer-term interactions between host rock and cap rock are the subsequent group of interactions assuming that CO_2 remains contained in the target host rock. Leakage scenarios need to be investigated for each site. Depending on the specific circumstances, CO_2-rock interactions might occur whereby the coupling between the interaction and the flow regime is of crucial importance. If CO_2 has escaped along these leakage pathways, it might enter potable aquifers and cause unwanted indirect impacts on the quality of the water which might be used for human consumption. Also because of the induced pressure built-up during many years of injection, displacement of brine in adjacent layers might occur, again with potential deleterious effects on potable aquifers. A last type of interactions that are enhanced or induced through engineering practices with the objective to immobilize CO_2 faster, prohibit CO_2 induced reactions or maximize dissolution (and then chemical reactions) for enhancing storage capacity (Gaus, 2010).

3.2. *CO_2 injection into saline aquifers underground*

CO_2 sequestration in deep saline aquifers is considered a promising mitigation option for the reduction of CO_2 emissions to the atmosphere. Injecting CO_2 into aquifers at depths greater than 800 m brings CO_2 to a supercritical state where its density is large enough to ensure an efficient use of pore space (Hitchon et al., 1999). Although the density of CO_2 can reach

Table 1: Initial mineral compositions of the siliciclastic reservoirs, carbonate reservoirs and secondary minerals considered in the Simulation

Mineral	Chemical formula	Volume %	
Primary		SR	CR
Quartz	SiO_2	40.6	1.0
Kaolinite	$Al_2Si_2O_5(OH)_4$	1.41	1.5
Calcite	$CaCO_3$	1.35	63.0
Illite	$K_{0.6}Mg_{0.25}Al_{1.8}(Al_{0.5}Si_{3.5}O_{10}(OH)_2$	0.7	0.6
Oligoclase	$Ca_{0.2}Na_{0.8}Al_{1.2}Si_{2.8}O_8$	13.86	0.5
K-feldspar	$KAlSi_3O_8$	5.74	1.2
Na-smectite	$Na_{0.290}Mg_{0.26}Al_{1.77}Si_{3.97}O_{10}(OH)_2$	4.8	0.6
Chlorite	$Mg_{2.5}Fe_{2.5}Al_2Si_3O_{10}(OH)_8$	1.19	1.6
Hematite	Fe_2O_3	0.35	0.00
Porosity		30	30
Secondary			
Anhydrite	$CaSO_4$		
Magnesite	$MgCO_3$		
Dolomite	$CaMg(CO_3)_2$		
Low-albite	$NaAlSi_3O_8$		
Siderite	$FeCO_3$		
Ankerite	$CaMg_{0.3}Fe_{0.7}(CO_3)_2$		
Dawsonite	$NaAlCO_3(OH)_2$		
Ca-smectite	$Na_{0.145}Mg_{0.26}Al_{1.77}Si_{3.97}O_{10}OH)_2$		
Alunite	$KAl_3(OH)_6(SO_4)_2$		
Pyrite	FeS_2		
Opal-A	SiO_2		

SR: Siliciclastic reservoir; CR: Carbonate reservoir

Source: Xu et al. (2007)

values as high as 900 kg m^{-3}, it will always be lighter than the resident brine. Consequently, it will flow along the top of the aquifer because of buoyancy. Thus, suitable aquifers should be capped by a low permeability rock to avoid CO_2 migration to upper aquifers and the surface. Caprock discontinuities, such as fractured zones, may favor upwards CO_2 migration. Additionally, CO_2 injection can result in significant pressure buildup, which affects the stress field and may induce large deformations. These can eventually damage the cap rock and open up new flow paths. These interactions between fluid flow and rock mechanics are known as hydromechanical (HM) coupling. HM processes generally play an important role in geological media and in particular during CO_2 injection into deep saline aquifers. These formations are usually fluid-saturated fractured rock masses. Therefore, they can deform either as a result of changes in external loads or internal pore pressures. This can be explained with direct and indirect HM coupling mechanisms (Rutqvist and Stephansson, 2003). Injection into saline aquifers need special monitoring with high technology:

a) Continuous monitoring for pressure in the aquifer located directly above the injection zone;

b) Other site specific data to include information on the position of the waste front within the injection zone or water quality;

c) Monitoring of ground water quality of the aquifer located directly above the injection zone;

d) Monitoring of ground water quality in the lowest underground source of drinking water;

e) Any additional monitoring to determine if there is fluid movement into underground sources of drinking water (Gledhill et al., 2009).

3.3. *CO_2 injection into depleted oil and gas reservoirs*

Currently, depleted or nearly depleted oil and gas reservoirs are the most appealing geological storage sites for CO_2 sequestration for the following reasons. First, the depleted oil and gas reservoirs have been extensively investigated during the oil exploitation stage. Second, the underground and surface infrastructure (wells, equipment and pipelines) is already available and could be used for CO_2 storage injection with minor or even without modifications (Bachu, 2000; Voormeij et al., 2004). Third, the injection of different gases, including CO_2, into oil and gas reservoirs as a technique to enhance oil or gas recovery has been widely practiced in the oil and gas industry. The experience gained can be adapted to guide the CO_2 sequestration injection. The sequestration of CO_2 in nearly depleted or even developing oil and gas reservoirs can simultaneously reduce greenhouse gas emissions and increase oil recovery (Li et al., 2006). For instance, the UK has numerous oil and gas fields, many of which are becoming emptied of hydrocarbons. These are perhaps the best places to store CO_2. In 1996, it was estimated that there is space for about 5.3 Gt CO_2 in depleted oilfields, i.e. 5,300,000,000 t, and about 11-15 Gt CO_2 in depleted gas fields. This is about 10 years of total UK CO_2 emissions in oil fields, and a further 30 years in gas fields. UK has the technical expertise to plan the storage (gained from extracting the oil and gas) and an established industry base that could undertake the work (CCSC, 2010). Totally, depleted oil and gas reservoirs have very good capacity and space for CO_2 storage because of depth and available facilities too. During oil production, oil, water and CO_2 are being removed from the reservoir through the production wells throughout the productive life of the field, precluding the pressure build-up that characterizes injections in a non-oil producing sequestration project. In addition, because the oil producing wells create a zone of lower pressure into which the mix of oil, water and CO_2 will flow, the movement of the CO_2 in the subsurface from injection to production well is far more predictable than where the CO_2 has to be injected into the rock formation at pressures sufficient to continuously push the CO_2 plume away from the injection well (because there is no zone of lower pressure into which it is drawn). And of course an oil-producing formation will almost by definition have structural or stratigraphic traps that held the oil in place for millions of years and similarly provide natural bounds for CO_2storage (Marston, 2011).

4. Determination and Assessment of CO_2 Geological Hazards

4.1. Seismicity, fault and rocks movements

Underground carbon storage is very sensitive to seismicity because this hazard at the same time is moving rocks melted and solid. Also, seismicity can release storage CO_2. So, seismicity without strong scientific bases and experiences is very dangerous. Cameroon and USA are very good examples in carbon capturing. On 21 August 1986, Lake Nyos, a volcanic lake in Cameroon, western Africa, suddenly released approximately 80 million m^3 of CO_2, which asphyxiated approximately 1,800 people on the flanks of the volcano at distances up to 25 km (Krajick, 2003; Service, 2004). Two years earlier in Cameroon, CO_2 killed 37 people nearby at Lake Monoun. In the United States, volcanic CO_2 is the cause of massive tree kills near Mammoth Lakes, first noticed in 1990 (Sorey et al., 1996). The Cameroon incidents may be worst-case scenarios for the type of accident that could occur at a large CO_2 injection facility. For comparison, one moderate-size (1,000-megawatt) coal-fired electrical power plant that burns 2.5 million metric tons of carbon per year will generate 4.7 billion m^3 of CO_2 $year^{-1}$. Although a catastrophic release of CO_2 could be devastating to anyone nearby, there is sufficient industrial experience in transporting CO_2 by pipeline and injecting it for enhanced oil recovery that the US Department of Energy is seriously investigating the potential for large-scale disposal by geological sequestration (Price et al., 2005). Deep well injection usually triggers activity in a seismically unstable area rather than causing an earthquake in a seismically stable area. Conceptually, the fluid in a fault is pressurized and assumes the stress of the overlying rock and water. Since the fluid has little shear strength, the frictional resistance along the fault declines and the fault blocks slip, causing a seismic event. These processes are best represented by a stress/strain relationship at very high pressures. Other processes involved in the triggering of seismic activity may include transfer of stress to a weaker fault, hydraulic fracture, contraction of rocks due to the extraction of fluids, subsidence due to the saturation of a rock formation, mineral precipitation along a fault, and density-driven stress loading (Wesson and Nicholson, 1987). Seismic hazards can be assessed by testing and monitoring of well and place where we want to inject the CO_2. Many types of tests are available to detect faulting or fractures that could lead to induced seismic activity including down-hole geophysical tests as well as more traditional testing methods that may be performed within the borehole. Another type of testing is pressure fall-off/shut-in testing that involves monitoring pressure buildup in the well. Testing methods are summarized below:

- 2-D or 3-D seismic surveys
- Core sample collection from major units during drilling
- Down-hole caliper logging to detect fractures
- Down-hole resistivity logging to detect fractures and lithologic changes
- Down-hole spontaneous potential logs
- Down-hole gamma ray logging to detect formation changes
- Down-hole density testing
- Fracture-finder logs to detect fractures
- Compression tests on formation samples to determine rock strength
- Geotechnical tests on formation samples (porosity, density, permeability)
- Compatibility test of injection fluids with formation unit and confining unit
- Pressure fall-off/shut-in tests
- Radioactive tracer survey (Sminchak et al., 2002)

4.2. Ground movement and dissolution

A key factor affecting the implementation of CCS are the risks associated with underground CO_2 storage. Gaining a better understanding and quantification of these risks is needed to ensure that they will comply with safety standards (also after injection has been completed). Risk assessment is a first step in a strategy to set up management and control measures to minimize risks of underground CO_2 storage. Also, it helps to facilitate the formulation of standards and regulatory frameworks required for large-scale application of CCS. To date, a wide variety of activities studying the risks of underground CO_2 storage has been completed and is being performed. The risks associated with underground CO_2 storage have been discussed extensively in an EU study on underground disposal of CO_2 (Holloway, 1996). It is possible that earth surface will sink or rise because of man-made pressure changes, which might cause damage to buildings and infrastructure and might also trigger seismicity. Several cases of subsidence in history (mainly during exploitation of oil and gas fields) are known and well documented. For these cases, the mechanism is well understood, but prediction of subsidence is found to be difficult (Holloway, 1996). The primary uncertainties for CO_2 disposal in geologic formations relate to the rate at which CO_2 can be buried underground, the available storage capacity, the utilization of subsurface space and available storage capacity, the presence of a cap rock of low permeability and the potential for CO_2 leakage through imperfect confinement, which may be natural or induced (Gulf Coast Carbon Center, 2005). The uncertainties vary depending on the type and characteristics of the projects. The probabilities of physical leakage are estimated to be small and risks are mainly associated with leakage from casings of abandoned wells. CO_2 injected into a formation can escape through abandoned well bores, faults, and fractures. The possibility of failure exists due to incomplete knowledge of subsurface conditions or corrosion resistance of materials used in injection wells. The limited industry experience regarding the rate of physical leakage from different storage media means that accidental releases could occur over decades or even centuries. The uncertainties are the reason why the verification process is so essential to the integrity of carbon capture and storage and why so much research focuses in this area. Standard protocols and regulatory oversight are a prerequisite to legitimacy and safety in the carbon capture and storage industry (Eaton et al., 2003).

4.3. Displacement of brine and water contamination

Fear of CO_2 leakage and water contaminate is always under threatened the geo CO_2 storage. CO_2 storage will leak slowly and finds way to other water sources or to the atmosphere. Geological storage ('sequestration') of CO_2 emissions in deep saline aquifers is a doomed idea, although billions are being spent to study it. It seems that the proponents are under the impression that there is a lot of empty space underground, when in reality the 'pore space' is presently occupied by very salty water. So in order to put the CO_2 where the water is now, that water will have to be pumped out, and then what becomes of it? You can not just dump the brine, and it is too salty for economical reverse osmosis. The often-mentioned 25 years of experience with underground CO_2 injection for EOR is irrelevant because the reservoirs they are dealing with are open systems, with CO_2 going in and oil coming out in steady state flow. Such depleted reservoirs are empty tanks underground, but deep saline aquifers are full tanks. Trying to hammer supercritical, buoyant CO_2 into them might fracture the sealing formation intended for storage. The CO_2 bubbles trapped underground will migrate and eventually erupt at the surface, with fatal consequences to the inhabitants above (Cr4, 2010). Latest research by Duke University has found that underground storage of injected CO_2 could potentially increase contamination levels in water aquifers as much as tenfold. Core samples were gathered from freshwater aquifers around America that provide potable water supplies and which also lie over the top of sites identified as suitable for potential CCS projects. Scientists put the samples through a range of tests and found that in some cases the CO_2 leaking into the water increased the contaminant loads above that set by the US Environmental Protection Agency's levels for drinking water (Brake, 2010). Fundamental understandings of various processes gained at small spatial scales will eventually be integrated and up-scaled to develop models to understand, quantify and predict multiphase flow and reactive transport processes at reservoir scales and to evaluate CO_2 injectivity, reservoir storage capacity, leakage possibility and impacts of CO_2 leakage. In general, the major risks associated with the operation of an underground CO_2 storage project are related to leakage from the formation. CO_2 leakage from the formation may migrate into potable aquifers or even to the surface, which could result in a significant safety risk. To evaluate this risk requires an improved understanding of formation properties and how the injected CO_2 spreads and interacts with the rock matrix and reservoir fluids. Geologic formations typically consist of layers of rock with different porosities, thicknesses and chemical compositions. All of these factors affect the suitability of the formation as a site for CO_2 sequestration. Porosity and thickness determine the storage capacity of the formation and chemical composition determines the interaction of CO_2 with the minerals in place. Also, an impervious cap rock is necessary to prevent the sequestered CO_2 from migrating to the surface. Finally, if the formation consists of a series of aquifers, it is necessary to ensure that CO_2 stored in a saline formation does not migrate to a potable aquifer. For geologic sequestration to be a viable technical option for climate change mitigation, the risks associated with this activity must be evaluated, including environmental, health, safety and economic risks. By identifying which aspects of geologic sequestration present potential risks, appropriate actions can be taken prior to the commencement of injection activities to obviate the occurrence of problems (Deel et al., 2006).

4.4. Sudden and gradual leakage hazard

Geologic structures constitute one of the key factors that determine the spatial patterns of hydraulic pressures in deep formations. Since any change of hydraulic pressure pattern is also a function of human activities, the effect of prominent geologic features such as those of big fault zones must be evaluated before assessing the impact of human activities on them. In this perspective, techniques to separate out the natural effects are needed for more detailed study on hydraulic pressure change in deep formations (Gautam et al., 2002). Two classes of risk must be addressed for every candidate storage reservoir: gradual and sudden leakage. Gradual release of carbon dioxide merely returns some of the greenhouse gas to the air. Rapid escape of large amounts, in contrast, could have worse consequences than not storing it at all. For a storage operation to earn a license, regulators will have to be satisfied that gradual leakage can occur only at a very slow rate and that sudden leakage is extremely unlikely. Although carbon dioxide is usually harmless, a large, rapid release of the gas is worrisome because high concentrations can kill. Planners are well aware of the terrible natural disaster that occurred in 1986 at Lake Nyos in Cameroon: carbon dioxide of volcanic origin slowly seeped into the bottom of the lake, which sits in a crater. One night an abrupt overturning of the lake bed let loose between 100,000 and 300,000 t of CO_2 in a few hours. The gas, which is heavier than air, fl owed down through two valleys, asphyxiating 1,700 nearby villagers and thousands of cattle. Scientists are studying this tragedy to ensure that no similar man-made event will ever take place. Regulators of storage permits will want assurance that leaks cannot migrate to belowground confined spaces that are vulnerable to sudden release (Socolow, 2005). Some new experiences in underground CO_2 storage are focusing on capacity of environment. Adsorption capacity measuring is what they do in USA for CO_2 storage. Carbonaceous (black) Devonian gas shales underlie approximately two-thirds of Kentucky. In these shales, natural gas occurs in the inter-granular and fracture porosity and is adsorbed on clay and kerogen surfaces. This is analogous to methane storage in coal beds, where CO_2 is preferentially adsorbed, and displacing methane. Black shales may similarly desorb methane in the presence of CO_2. Drill cuttings from the Kentucky Geological Survey Well Sample and Core Library were sampled to determine both CO_2 and CH_4 adsorption isotherms. Sidewall core samples were acquired to investigate CO_2 displacement of methane. An elemental capture spectroscopy log was acquired to investigate possible correlations between adsorption capacity and mineralogy. Average random vitrinite reflectance data range from 0.78 to 1.59 (upper oil to wet gas and condensate hydrocarbon maturity range). Total organic content determined from acid-washed samples ranges from 0.69 to 14% CO_2 adsorption capacities at 400 psi range from a low of 14 scf t^{-1} in less organic-rich zones to more than 136 scf t^{-1} in the more organic-rich zones. There is a direct linear correlation between measured total organic carbon content and the adsorptive capacity of the shale; CO_2 adsorption capacity increases with increasing organic carbon content (Nuttall et al., 2005).

5. Identifying Spatial Planning and Approaches for Underground CO_2 Hazards Assessment

We know climate is changing and CO_2 emissions and other green house gases have significant role on climate change. Impacts of climate changes are extended in different sectors and levels in the world. For instance, health, economy, sociology, environment and too many other sectors are being affected by direct and indirect climate change impacts. Underground CO_2 storage is one of the ways for CO_2 that is found by developed countries for mitigation policies. Planning for climate change mitigation and adaptation and any other acts should be win-win. By the better words, CO_2 capturing and storage should not be implemented successfully because we can face water contamination or geo hazards. Spatial planning, which is charged with making long-term decisions for specific geographic areas, has to consider all spatially relevant sectoral hazards and cannot reduce its focus to only one or two hazards like flood or potentially dangerous industrial facilities. This is so because spatial planning is responsible for a particular spatial area (where the sum of hazards and vulnerabilities defines the overall spatial risk) and not for a particular object, e.g. sectoral engineering sciences. Therefore spatial planning must adopt a multi-hazard approach in order to deal appropriately with risks and hazards in a spatial context (Greiving, 2002; Schmidt, 2005). Briefly, the Integrated Risk Assessment of Multi-hazards consists of four components:

a. Hazard maps: for each spatially relevant hazard a separate hazard map is produced showing in which regions and with which intensity this hazard occurs.

b. Integrated hazard map: the data on all individual hazards are integrated into one map showing for each region the combined overall hazards potential.

c. Vulnerability map: information on the economic and social vulnerability with regard to potential hazards is combined to create a map showing the overall vulnerability of each region.

d. Integrated risk map: the information from the integrated hazard map and the integrated vulnerability map is combined thus producing a map that shows the integrated risk each region is exposed to (Greiving et al., 2006).

Spatial planning and spatial considerations can be assessed and tackle current and future risks by taking into account both environmental hazards and climate changes. At last, by summarizing the underground CO_2 risk assessment the major findings of the current analysis were:

- Risks caused by failures in surface installations are well understood and can be minimized by applying risk abatement technologies and safety measures.
- The risk associated with the storage of CO_2 underground itself (CO_2 and methane linkage, seismicity, ground movements and displacements) is less well understood.
- The lack of knowledge and data to properly quantify the processes controlling/causing risks is partially due to the fact that this mitigation option is relatively new. Another complicating factor is that underground storage has long-term effects that are difficult to assess by means of injection operations or laboratory experiments.
- One of the main issues to be further studied is the leakage of CO_2 from the geological reservoir. In particular the processes that control leakage through wells, faults and fractures need to be objectives for future research projects in order to assess leakage rates for various geological reservoirs.
- The effects of elevated concentrations of CO_2 on terrestrial animals and plants are well known, but the possible impacts on marine ecosystems need further research.
- Risks are strongly dependant on specific reservoir and site conditions (ecosystems, onshore/offshore, presence of water resources, etc.). This makes recommendable the assessment and monitoring of a variety of pilot and demonstration storage projects in order to better understand the site specific nature of risks (EU Commission, 2006).

6. Conclusion

Climate change has started affecting our live recently. Most of the scientists found climate change hazards could be assessed by adaptation and mitigation policies. Mitigation policies are related to GHG emission such as CO_2, methane, sulphur and so on. Most of the developed countries are practicing to capture, pipe, and store the CO_2 as one of the most hazardous GHGs and injecting that for long time into the earth. But, this hazard assessment and mitigation minimize the consequences of natural hazard superficially and in time we will face the impact of such actions on environment. Spatial planning can guide us to take into account not only mitigation policies but also assessment of current and future hazards and how we can strengthen our planning and policies by spatial notion.

7. References

Anonymous, 2009. Low carbon technologies in a green economy: fourth report of session 2009-10. By Great Britain: Parliament: House of Commons: Energy and Climate Change Committee. Vol ii, 8.

Bachu, S., 2000. Sequestration of CO_2 in geological media: criteria and approach for site selection in response to climate change. Energy Conversion and Management 41, 953-970.

Barrie, J., Brown, K., Hatcher, P.R., Schellhase, H.U., 2004. Carbon dioxide pipelines: a preliminary review of design and risk. In: 7th International Conference on Greenhouse Gases Control Technologies, Vancouver, British Columbia. Available from http://uregina.ca/ghg17/PDF/papers/peer/126.pdf.

Bielicki, J.M., 2008a. Returns to scale for carbon capture and storage infrastructure and deployment. BCSIA Discussion Paper 2008-04. Available from http://belfercenter.ksg.harvard.edu/files/Bielicki_CCSReturns ToScale.pdf.

Bielicki, J.M., 2008b. Returns to scale for the integrated carbon capture and storage system. In preparation for Environmental Science & Technology.

Bielicki, J.M., 2009. GHGT9 spatial clustering and carbon capture and storage deployment. Energy Procedia 1, 1691-1698.

Brake, L., 2010. Study finds underground CO_2 storage has potential to contaminate drinking water. Available from http://www.earthtimes.org/health/underground-co2-storage-contaminate-drinking-water/39/.

CCSC, 2010. UK Carbon Capture and Storage Community. Available from http://www.co2storage.org.uk/.

CDA, PvdA, ChristenUnie. Coalitieakkoord tussen de Tweede Kamerfracties van CDA, PvdA en ChristenUnie. 2007. Available from www.regering.nl/Het_kabinet/Beleidsprogramma_2007_2011.html (Dutch). Accessed in 23rd December 2009.

Cr4, 2010. CO2 Storage In Deep Saline Formations Can't Work. Available from http://cr4.Globalspec.com/thread /59653/CO2-storage-in-deep-saline-formations-can-t-work.

Deel, D., Mahaja, K., Mahoney, R.C., McIlvried, G.H., Srivastav, D.R., 2007. Risk assessment and management for long-term storage of CO_2 in geologic formations- United States Department of Energy R&D. Systemics, Cybernetics and Informatics 5(1), 79-84.

Eaton, D., Duncan, I., 2006. Creating a Carbon Capture and Storage Industry in Texas. Policy Research Project on Texas Energy Policy February 2007. University of Texas, Austin.

Ehler, C., 2008. Conclusions: benefits, lessons learned, and future challenges of marine spatial planning. Marine Policy 32, 840-843.

ERM, 2010. Update on selected regulatory issues for CO_2 capture and geological storage focusing on the EU, US, Canada and Australia. Available from http://www.co2-captureproject.org/reports/regulatory_report.pdf.

EU Commission, 2006. Potential risks of underground CO_2 storage. Available from http://ec.europa.eu/ environment /integration/re search/newsalert /pdf/28na2.pdf.

Galeczka, D., Wolff-Boenisch, Gislason, S.R., 2010. Experimental studies on CO_2 sequestration in basaltic rocks with a plug flow reactor. JGGC 4, 537-545.

Gaus, I., 2010. Role and impact of CO_2-rock interactions during CO_2 storage in sedimentary rocks. International Journal of Greenhouse Gas Control 4, 73-89.

Gautam, R.M., Watanabe, K., Saegusa, H., 2003. Analysis of hydraulic pressure fluctuation in deep geologic formations in Tono area, Japan using artificial neural networks. Journal of Hydrology 284, 174-192.

Geel, P.V., 2005. Speech staatssecretaris op Nationaal symposium Schoon Fossiel. November 23.

Gledhill, J., Rollins, J., Pugh, T., 2009. Will water issues/regulatory capacity allow or prevent geologic sequestration for new power plants? A review of the Underground Injection Control Program and Carbon Capture and Storage. America Public Power Association.

Gómez, J.M., Sonnenschein, M., Müller, M., 2007. Information technologies in environmental engineering: ITEE. In: 3rd International ICSCS Symposium, Springer, 271.

Gorecki, C.D., Sorensen, J.A., Steadman, E., Harju, J.A., 2009. CO_2 storage risk minimization through systematic identification and assessment of faults: a Williston Basin case study. Energy Procedia 1(1), 2887-2894.

Greiving, S., 2002. Ra¨umliche Planung und Risiko (Mu¨nchen: Gerling Akademie Verlag).

Greiving, S., fleischhauer, M., ckenkötte, J., 2006. A Methodology for an Integrated Risk Assessment of Spatially Relevant Hazards. Journal of Environmental Planning and Management 49(1), 1-19.

Gulf Coast Carbon Center, Bureau of Economic Geology. 2009. Carbon Dioxide Sequestration in Geologic Media, Regional Evaluation and Modeling of Opportunities in the Gulf Coast. Available from http://www.beg.utexas.edu/environqlty/co2seq/ fieldexperiment. htm. Accessed in October 5, 2005.

Herzog, H.J., 2001. What future for carbon capture and sequestration? New technologies could reduce carbon dioxide emissions to the atmosphere while still allowing the use of fossil fuels. Environmental Science & Technology 35(7), 148A-153A.

Hitchon, B., Gunter, W.D., Gentzis, T., Bailey, R.T., 1999. Sedimentary basins and greenhouse gases: a serendipitous association. Energy Conversion and Management 40, 825-843.

Holloway, S., 1996. The underground disposal of carbon dioxide. Final Report JOULE II Project no. CT92-0031, British Geological Survey, Keyworth, Nottingham, 355.

Krajick, K., 2003. Killer lakes: Smithsonian, v. 34, p. 46–50. Langenheim, V.E., and Schmidt, K.M., 1996, Thickness and storage capacity of basin fill of the northern part of the Eldorado Valley, Nevada and the extent of the Boulder City pluton: U.S. Geological Survey Open-File Report 96- 512, 35.

Li, Z., Dong, M., Li, S., Huang, S., 2006. CO_2 sequestration in depleted oil and gas reservoirs—caprock characterization and storage capacity. Energy Conversion and Management 47, 1372-1382.

Marston, M.P., 2011. From EOR to 'E2R': Sequestering CO_2 while reducing dependence on imported oil. Available from http://www.ucl.ac.uk/cclp/pdf/Marston_thinkpiece_2011.pdf.

Metz, B., 2005. IPCC special report on carbon dioxide capture and storage. Intergovernmental Panel on Climate Change, Working Group III, 189.

NOGEPA, 2009. Potential for CO_2 storage in depleted gas fieldsat the Dutch Continental Shelf Phase 2: Costs of transport and storage Environment and Sustainability Safety and Environment– Industry.

Nuttall, C.B., Eble, F.C., Drahovzal, A.J., Bustin, R.M., 2005. Analysis of Devonian black shales in Kentucky for potential carbon dioxide sequestration and enhanced natural gas production. Report issued, December 30, Kentucky Geological Survey, University of Kentucky.

Olric, B., Schroot, B.M.,Wenassa, L., Hehhland, R., Hatziyannis, G., Nikolaous, N., Poyatzi, E., 2005. Predicting ground deformation due to CO_2 injection: examples from Montmiral, France, Sleipner, Norway, Florina, Greece. Greenhouse Gas Control Technologies 7, 1993-1996.

Price, G.J., Hess, H.R., Fitch, S.E., Faulds, J.J., Garside, L., Shevenell, L., Warren, S., 2005. Preliminary assessment of the potential for carbon dioxide disposal by sequestration in geological settings in Nevada. Nevada Bureau of Mines and Geology Report 51. Mackay School of Earth Sciences and Engineering, University of Nevada, Reno.

Rutqvist, J., Stephansson, O., 2003. The role of hydromechanical coupling in fractures rock engineering. Hydrogeology Journal 11, 7-40.

Schmidt-Thome, P. (Ed.), 2006. (Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions. Espoo: Geological Survey of Finland. Special Paper 42, 167.

Service, R.F., 2004. The carbon conundrum. Science 305, 962-963.

Sminchak, J., Gupta, N., Byrer, C., Bergman, P., 2002. Issues related to seismic activity induced by the injection of CO_2 in deep saline aquifers. Available from http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/p37.pdf.

Socolow, H.R., 2005. Can we bury global warming? Pumping carbon dioxide underground to avoid warming the atmosphere is feasible, but only if several key challenges are met. Available from http://cmi.princeton.edu/resources/pdfs/bury_globalwarming.pdf.

Sorey, M.L., Farrar, C.D., Gerlach, T.M., McGee, K.A., Evans, W.C., Colvard, E.M., Hill, D.P., Bailey, R.A., Rogie, J.D., Hendley, J.W., Stauffer, P.H., 1996. Invisible CO_2 gas killing trees at Mammoth Mountain, California. US Geological Survey Fact Sheet 172-96, version 2.0. Available from http://pubs.usgs.gov/fs/fs172-96/.

Unirazak, 2007. Available from http://www.physorg.com/news96732819.html.

Voormeij, D.A., Simandl, G.J., 2004. Geological, ocean and mineral CO_2 sequestration options: a technical review. Geoscience Canada 31, 11-22.

VROM. Nationaal Milieubeleidsplan 4- Een wereld en een wil werken aan duurzaamheid. Den Haag, Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer. Juni; 2001.(Dutch).

Wesson, R.L., Nicholson, C., 1987. Earthquake hazard associated with deep well injection. US Geological Survey Open-File Report 87-331.

Xiao, Y., Xu, T., Pruess, K., 2009. The effects of gas-fluid-rock interactions on CO_2 injection and storage: insights from reactive transport modeling. Energy Procedia 1, 1783-1790.

Xu, T., Apps, J.A., Pruess, K., Yamamoto, H., 2007. Numerical modeling of injection and mineral trapping of CO_2 with H_2S and SO_2 in a sandstone formation. Chemical Geology 242(3-4), 319-346.

Zakkour, P., 2007. Technical support for an enabling policy framework for carbon dioxide capture and geological storage Task 2: Discussion paper Choices for regulating CO_2 capture and storage in the EU. Task 2 - Policy Options paper v FINAL 27_04_07.