Carbon Dioxide Capture and Storage and Hydrology in the GCC and in the EC

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Global Warming

The climate on Earth has been subject to various changes in the past for various reasons. The main reasons include dynamic processes of Earth itself, variations in solar radiation, variation in the Earth's orbit, and variations in the concentration of greenhouse gases. Solar radiation is partly received by the Earth's surface as heat. Due its temperature, the Earth's surface emits energy in the form of infrared radiation. This infrared radiation is partly absorbed by the greenhouse gases naturally present in the atmosphere. The absorption causes a warming of the lower atmosphere and again of the Earth's surface. This process is referred to as the Greenhouse Effect (Arrhenius, 1896). With an increasing concentration of greenhouse gases, the temperature on the Earth's surface may rise. IPCC (2005) states that "most of the observed increase in globally averaged temperatures since the mid-20$^{\text{th}}$ century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations". The panel defines "very likely" as indicating probabilities greater than 90 %. Greenhouse gases include water vapour, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). In the past 160 years, human fossil fuel use increased tremendously (see Figure 1). As a result, the global atmospheric CO_2 concentration has been increasing from a pre-industrial value of about 280 ppm* to 379 ppm in 2005 (IPCC, 2005).

Effects

The severe effects that nature and mankind are facing due to increasing temperature and changing climate include a rise in sea level, failing crop yields in many developing countries, and the extinction of animal and plant species. This ecological and economic interest led to the United Nations Framework Convention on Climate Change (1992), which has been accepted by 189 nations, and whose main objective is to achieve "…stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change …". In 2005, a number of nations approved an addition to this treaty which also includes some legally binding measures, known as the Kyoto Protocol. Nevertheless, due to the complexity of the problem, it is not clear to date what a sustainable level of greenhouse gas concentrations is and what emission reductions are necessary. From model runs, it has become clear that emission reductions in the range of 55–90 % by 2100, compared to the emissions of 2001, might be necessary to stabilise the atmospheric CO_2 concentration at a value of 450 ppm (IPCC,

*parts per million, i.e. ratio of the number of molecules of the considered gas compared to the total number of molecules of dry air.

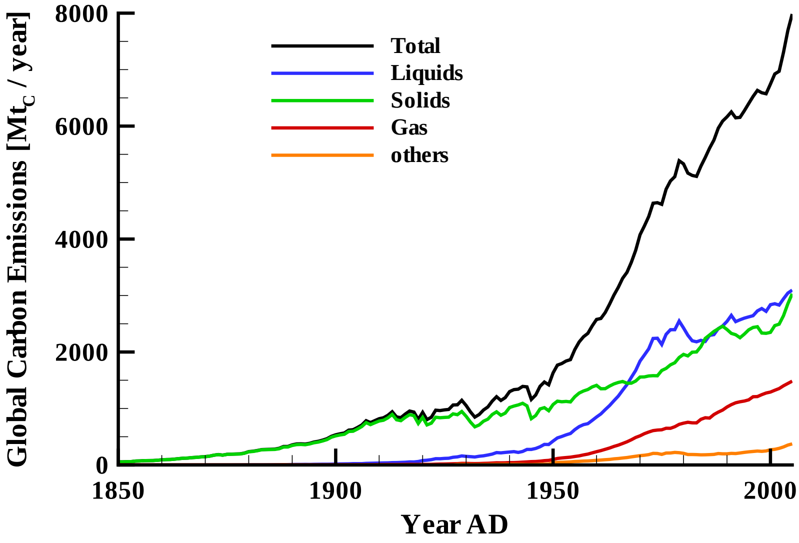

Figure 1: Variation of global annual carbon emissions from burning solids (e.g. coal), liquids (e.g. petroleum), natural gas, and others (i.e. cement production and natural gas lost during oil and gas mining) from 1850 to 2005 (after Marland et al. (2008)). One tonne of carbon compares to $3.\overline{6}$ tonnes of CO_2.

2005). Beside the ecological interest, there is an economic interest. Stern (2007) states that "the benefits of strong, early action on climate change outweigh the costs". "Costs" refers here to a global reduction of the gross domestic product.

Mitigation Options

The options for reducing global CO_2 emissions are manifold, although, considering the magnitude of the problem, one single option is not sufficient. Pacala and Socolow (2004) estimate the magnitude of the problem, discuss possible options for solving it, and state that viable techniques already exist. These authors assume that the current carbon emissions will continue to grow linearly and reach a value of 14000 MtC/year by 2054. To stabilise the CO_2 concentration at 500 ppm, it is assumed sufficient to maintain current emissions (~7000 MtC/year) for the next 50 years and reduce them significantly afterwards. Thus, the total mass of future emissions that need to be avoided in the next 50 years accumulates to 175 GtC. The authors then discuss 15 options for activities that reduce emissions to the atmosphere. All necessary technologies are currently deployed on an industrial scale, but need to be upscaled. In their concept, activities start in 2004 at zero prevented emissions and reach a value of 1000 MtC/year prevented emissions in 2054. If seven of those 15 activities could be scaled up to such a magnitude, this would solve the problem. Options are grouped in different sectors, i.e. energy efficiency and conservation, fuel shift, carbon dioxide capture and storage, nuclear fission, forests and agricultural soils. In conclusion, no single activity can prevent future emissions sufficiently, but there are a number of options which can be scaled up and simultaneously need to be expanded. The focus of this study lies on CO_2 capture and storage (CCS). The special attribute of CCS is the possibility of a fast and large-scale deployment that could outweight time delays in the development of other technologies. The long-term goal, however, should be to achieve a sustainable energy generation and consumption.

Carbon Dioxide Capture and Storage

Carbon dioxide capture and storage is a process that captures CO_2 from the burning of fossil and/or renewable fuels and from processing industries and then stores the CO_2 away from the atmosphere for geological periods of time. Carbon dioxide is primarily captured at point sources such as power plants and other large-scale industrial processes.

To capture the CO_2, there are different approaches, i.e. pre-combustion, post-combustion, and oxyfuel combustion. The process conditions for operation determine the approach to be selected. Each approach requires at some point a separation of CO_2, water, or oxygen from a bulk gas stream. Efficiencies of 80–90 % of captured CO_2 can be reached whereas about 10–40 % more energy is required for the additional operations (IPCC, 2005)

It is preferable to transport the captured CO_2 to feasible storage options in pipelines, but transportation by ship, rail, or road tankers is also possible. Challenges at the transport stage include costs, design, and safety, although experience with the current practice suggests that these problems can be solved.

Carbon dioxide storage can occur in geological formations, in the ocean, or by industrial fixation in inorganic carbonates. In the following, the focus is on storage in geological formations. Feasible reservoir types include deep saline aquifers, oil and gas fields and unminable coal seams. Accordingly, one can distinguish between the exclusive purpose of storing the CO_2 and the use of injected CO_2 to enhance oil recovery (EOR), natural gas (EGR) or methane from coal beds (ECBM). The latter three options are likely to be implemented in the near future because of cost benefits and presumably good knowledge about the site-specific geology as well as the existing infrastructure. However, in the following, the focus of this study is on storage in deep saline aquifers since estimates of the available storage capacity necessary to store the immense amounts of human CO_2 production are promising. In Figure 2, the technology is schematically sketched, including processes occurring in the sub-surface, monitoring devices, and potential leakage pathways.
Carbon dioxide is injected into a saline formation at a depth preferably greater than 800 m below the surface. The CO_2 plume spreads laterally in the aquifer, displacing the resident brine, which results in pressure increase. At the same time, due to the lower CO_2 density than the brine density at these pressures and temperatures, it migrates in an upward direction. To prevent CO_2 from leaving the formation a confining layer above the storage reservoir is necessary. This confining layer is usually called caprock and should provide low permeability, considerable thickness, and no geological weaknesses such as e.g. fractures or faults.

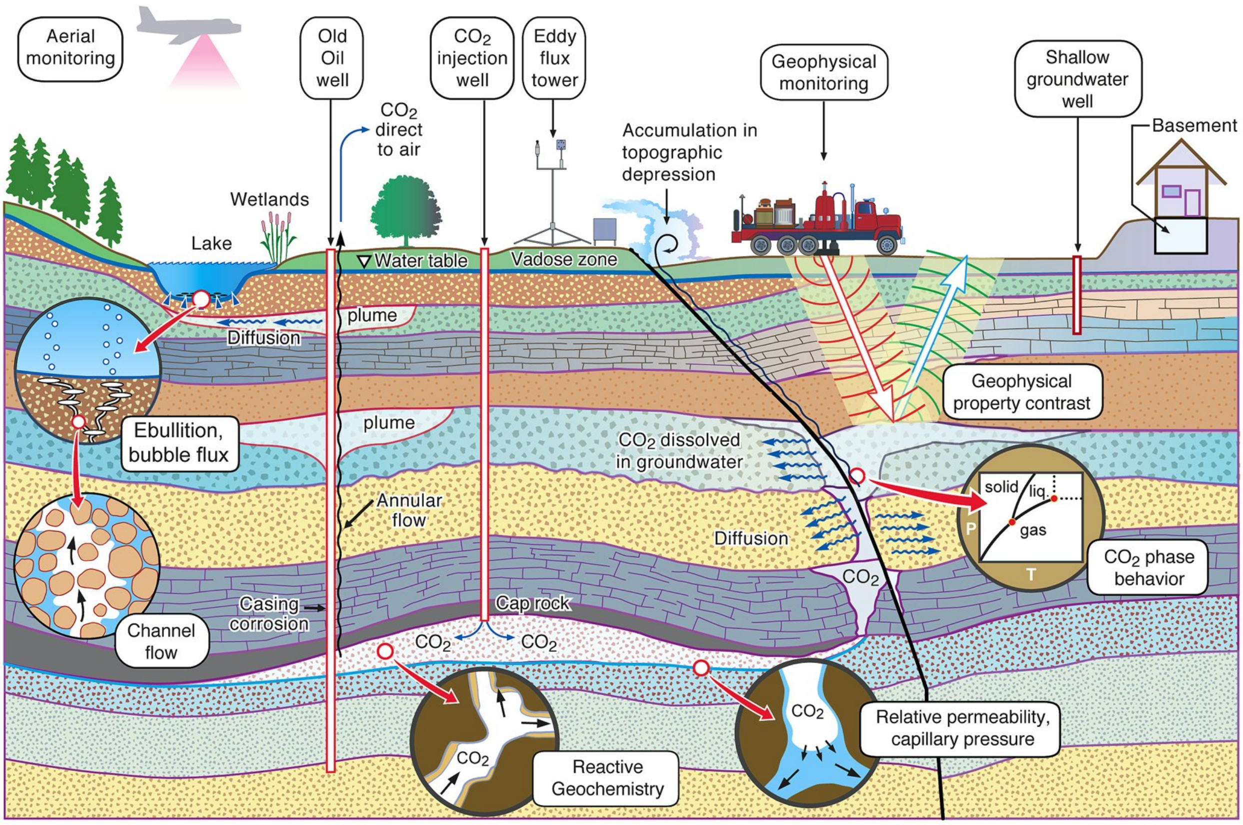

Figure 2: Principal processes, leakage risks, and monitoring techniques associated with CO_2 storage in geological formations (Figure courtesy of Lawrence Berkeley National Laboratory).

However, the risk remains that CO_2 might leak out of the storage reservoir through these natural or man-made pathways. This issue needs to be addressed carefully in every storage attempt. Carbon dioxide leakage is illustrated in Figure 2 through a leaky well (e.g. poorly plugged abandoned well or old oil well) and through a fault. It may then migrate into shallower aquifers (harming potable groundwater) or migrate back to the surface (leading to risk directly associated with exposure to leaked CO_2). To prevent harm to the health of humans and animals as well as to the environment, an efficient and reliable monitoring network is essential. Monitoring leaked CO_2 on the land surface, geophysical (seismic) monitoring, and monitoring from aeroplanes is also sketched in Figure 2.

Existing Projects

Currently, several projects all over the world are injecting CO_2 into saline aquifers for either socio-economic reasons or for research purposes. The first commercial attempt is being made by the Statoil-operated Sleipner project (Torp and Gale, 2004). Since 1996, approximately 1 $MtCO_2$/year has been injected into the 50–250 m-thick Utsira formation in the North Sea at ∼1100 m depth. The CO_2 is extracted from natural gas (containing about 9% CO_2) that is captured from another field and then processed to the supercritical conditions of 80 bar pressure and 40 °C temperature before being re-injected. At another site in Norway, CO_2 has been injected since May 2008 - the Snøhvit field in the Barent Sea. The CO_2 content of the natural gas extracted there is decreased from 5–8 % to less than 50 ppm before the gas can be further processed (converted to liquefied natural gas). The $\sim$0.75 $MtCO_2$ produced per year are re-injected into a deeper formation. Another commercial example is the In-Salah project in the southern Sahara (Algeria), where CO_2 has been injected since 2004. Similar to the Norwegian projects, the natural gas produced initially has a CO_2 content of $\sim$10 %, which has to be decreased to $\sim$0.3 % to meet European market standards. The annually produced $\sim$1.2 $MtCO_2$ are re-injected into a 1800 m-deep sandstone reservoir. The next commercial project in operation may be the Gorgon Joint Venture project (Australia). The natural gas produced there has a CO_2 content of up to 14 %, which is to be reduced. The $\sim$2.7–3.2 $MtCO_2$ produced annually are to be re-injected into a saline formation at $\sim$2300 m depth (IEA Greenhouse Gas R&D Programme, 2008).

Beside that, several pilot sites are currently being investigated for experimental research purposes:
In the Nagaoka project, 10400 tCO_2 were injected in 2003 and 2004 in a $\sim$1100 m deep saline aquifer at the Iwanohara base near Nagaoka (Japan). The purpose of the project was the investigation of the behaviour of CO_2 during and after injection, the long-term stability of CO_2 in the reservoir, and the potential and costs of CO_2 storage (Nagaoka-Project, 2009).
In 2004, the Frio project injected 1600 tCO_2 and 320 tCO_2 in two stages in two saline aquifers at the Frio site, north-east of Houston in the U.S.A. in $\sim$1600 m depth. Extensive monitoring techniques have been tested (Hovorka et al., 2006).
In the CO2SINK project, 8450 tCO_2 were injected until February 8th 2009 into a saline aquifer in the Ketzin anticline close to Berlin (Germany) at a depth of $\sim$500–700 m. It is planned to inject up to 60000 tCO_2 and sophisticated monitoring techniques are to be tested. The project provides an in-situ laboratory for CO_2 storage to fill the gap between the numerous conceptual engineering and scientific studies on geological storage and a fully-fledged on-shore storage demonstration (CO2SINK-Project, 2009).
The Department of Energy in the U.S.A. has initiated a national network of seven regional partnerships to investigate the best approaches for capturing and storing gases that can contribute to global climate change (NETL, 2009). The partnerships aim at injecting CO_2 into 14 formations in the U.S.A. in 2009 and 2010. Injection rates at the sites vary between 3 kt and 10.8 Mt CO_2.

Presentation Objectives
A conception of the life cycle of a CO_2 storage project is shown in Figure 3. Typical steps include the initial estimation of the magnitude of emissions from large stationary sources and the screening of regional storage opportunities for potential reservoirs (sites). A subsequent step includes the site-specific characterisation and assessment of the reservoir by develop-

ing a geological model, performing numerical simulations and performing a risk assessment. Then, a proposal is sent to the regulator and, if approved, CO_2 is injected and monitored for up to several decades. Finally, the site is properly closed.

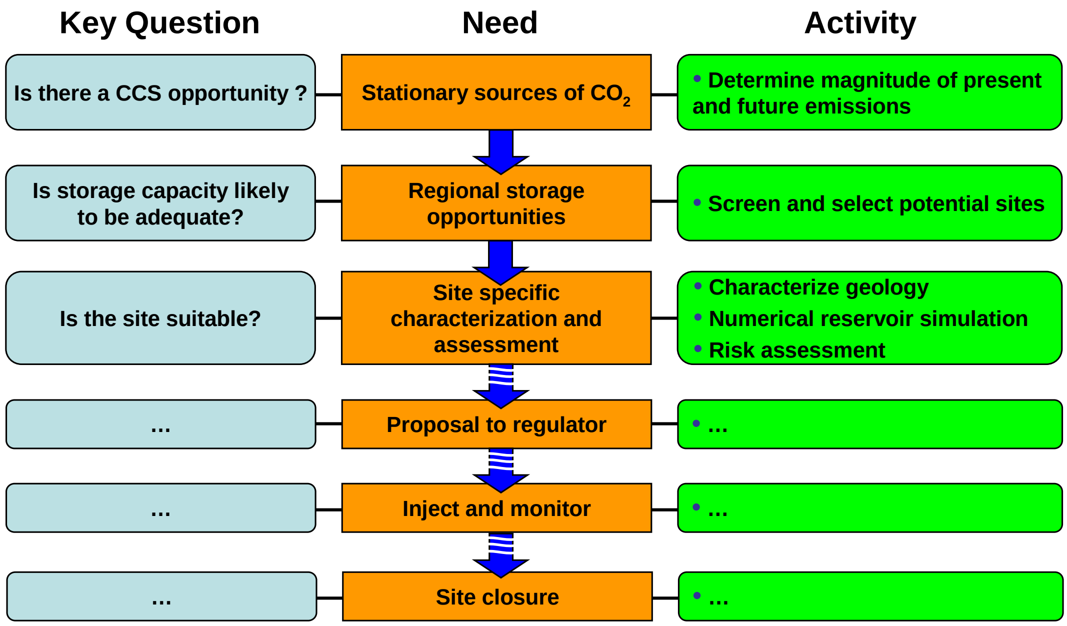

Figure 3: Life cycle of a CO_2 storage project (modified after IPCC (2005)).

This study refers to the key questions in the early phase of site screening and characterisation, i.e. “Is storage capacity likely to be adequate?” (Kopp et al. (2008a), Kopp et al. (2008b)) and “Is the site suitable?”(Kopp et al., 2009). Site screening is the initial step in site characterisation and is aimed towards a pre-selection of potential storage reservoirs. Usually, little information is available on the reservoir properties and geology at this stage of a project. At a later stage, further investigations on the properties of the identified reservoirs will lead to good data availability, which can then be fed into detailed investigation methods, e.g. site-specific numerical models.

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