What does CO_2 geological storage really mean?

A responsible use of fossil fuels

Removing the main source of greenhouse gases

Returning the carbon back into the ground

Giving us the time needed to develop climate-friendly energy sources

CO_2GeoNet European Network of Excellence

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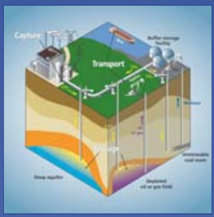

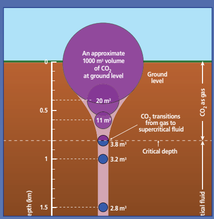

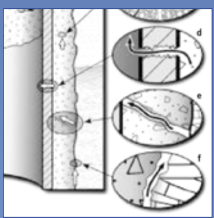
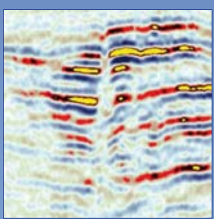

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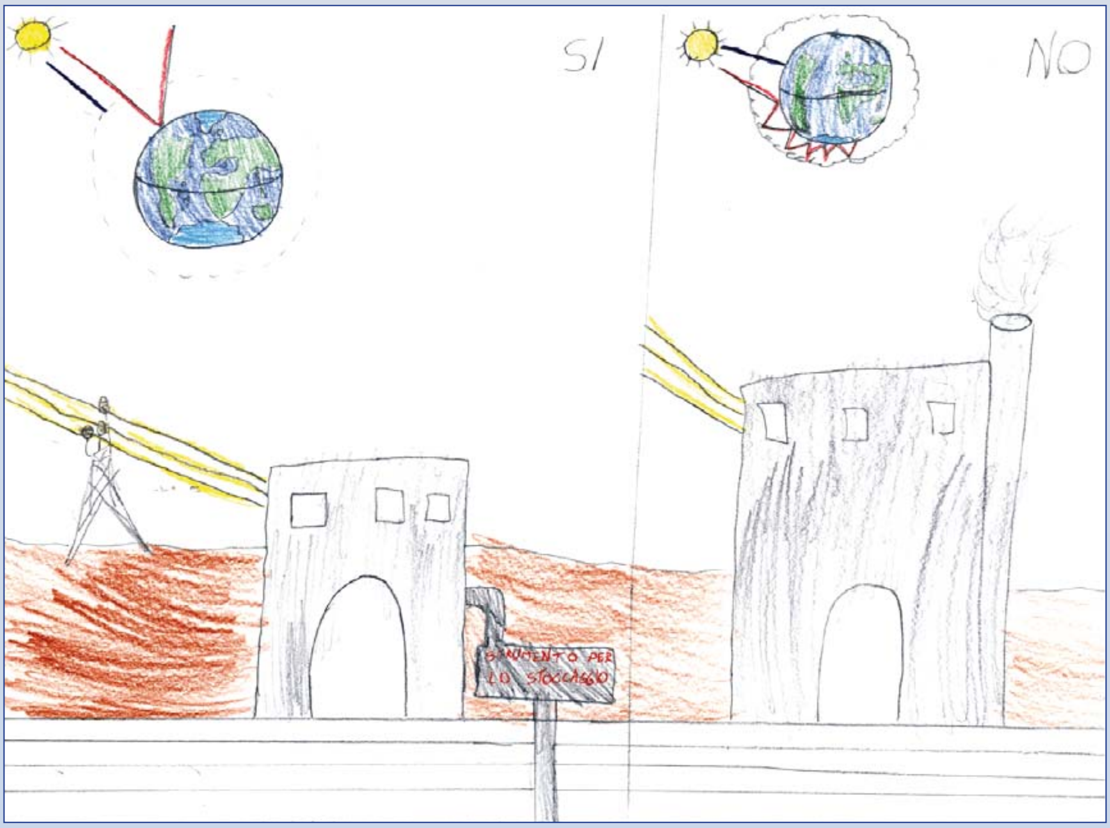
A vision of the future

No more smoking chimneys
A pipeline brings CO_2 and puts it in the ground
This is good for the Earth

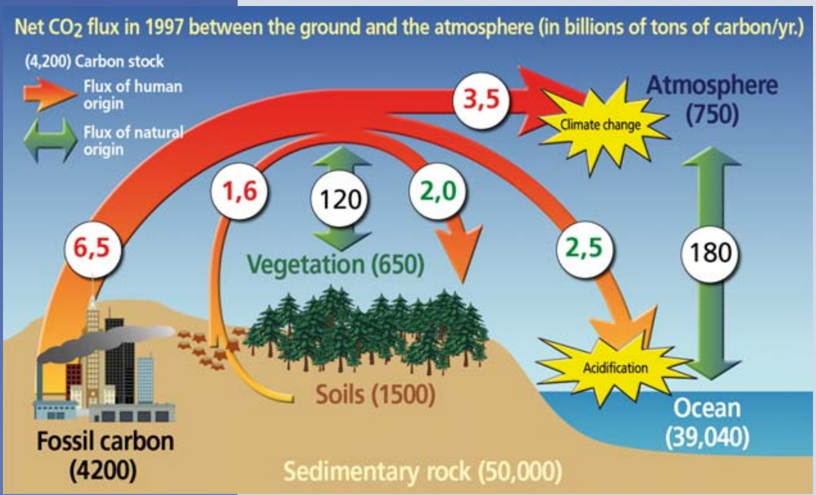


Massimo, age 10, Rome - Italy

For our children
CO_2 geological storage makes sense

Climate change and the need for CO_2 geological storage

Figure 1
Global CO_2 emissions linked to man's activities amount to 30 billion tons (Gt) per year, corresponding to 8.1 Gt of carbon: 6.5 Gt from burning fossil fuels and 1.6 Gt from deforestation and agricultural practices.



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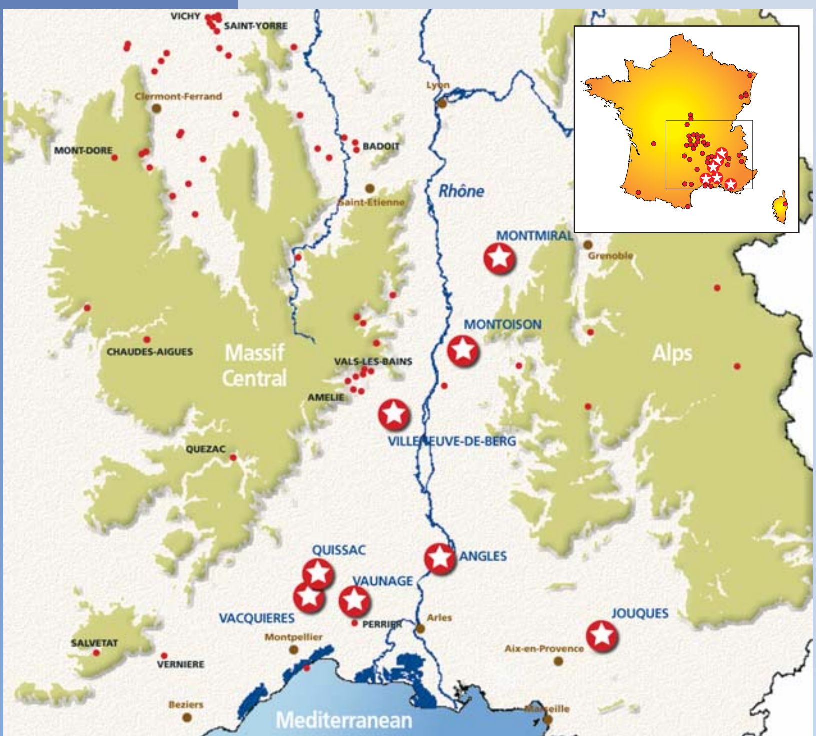
Mankind is releasing excess CO_2 into the atmosphere

It is now accepted that human activities are disturbing the carbon cycle of our planet. Prior to the industrial revolution and extending back some 10,000 years, this finely balanced cycle, involving the natural exchange of carbon between the geosphere, the biosphere, the oceans and the atmosphere, resulted in a low range of CO_2 concentrations in the atmosphere (around 280 ppm, i.e. 0.028%). However, over the past 250 years, our prolific burning of fossil fuels (coal, oil, gas) for power production, heating, industry and transportation, has incessantly raised the amount of CO_2 emitted into the atmosphere (***Fig. 1***). About half of this human-induced excess has been reabsorbed by vegetation and dissolved in the oceans, the latter causing acidification and its associated potentially negative impacts on marine plants and animals. The remainder has accumulated in the atmosphere where it contributes to climate change, because CO_2 is a greenhouse gas that traps part of the sun's heat, causing the earth's surface to warm. Immediate radical action is needed to stop today's atmospheric CO_2 concentration of 387 ppm (already a +38% increase compared to pre-industrial levels) from rising beyond the critical level of 450 ppm in the coming decades. Experts worldwide agree that above this level, it may no longer be possible to avert the most drastic consequences.

Returning the carbon back into the ground

Our world has been heavily dependent on fossil fuels since the start of the Industrial Age in the 1750s, so it is not surprising that the transformation of our society into one based on climate-friendly energy sources will take both time and money. What we need is a short-term solution that will help reduce our dependence on fossil fuels by using them in a non-polluting way as a first step, thus giving us the time needed to develop technologies and infrastructure for a renewable-energy future. One such option is to create a closed loop in the energy production system, whereby the carbon extracted from the ground originally in the form of gas, oil, and coal is returned back again in the form of CO_2. Interestingly, underground storage of CO_2 is not a human invention, but a totally natural, widespread phenomenon manifested by CO_2 reservoirs that have existed for thousands to millions of years. One such example is the series of eight natural CO_2 reservoirs in south-eastern France discovered during oil exploration in the 1960s (***Fig. 2***). These and many other natural sites throughout the world prove that geological formations are able to store CO_2 efficiently and safely for extremely long periods of time.

Figure 2
France's carbogaseous province.



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CO_2 Capture and Storage: a promising mitigation pathway

Amongst the spectrum of measures that need to be urgently implemented to mitigate climate change and ocean acidification, CO_2 Capture and Storage (CCS*)

* See glossary at the end.

can play a decisive role as it could contribute 33% of the CO_2 reduction needed by 2050. CCS involves capturing CO_2 at coal- or gas-fired power stations and industrial facilities (steel mills, cement plants, refineries, etc.), transporting it by pipeline or ship to a storage location, and injecting it via a well* into a suitable geological formation for long-term storage (***Fig. 3***). In view of the growing world population and rising energy demand in developing countries, as well as the current lack of large-scale alternative 'clean' energy sources, the continued use of fossil fuels is inevitable in the short term. Hand in hand with CCS, however, humanity could progress in an environmentally friendly way while at the same time creating a bridge to a worldwide economy based on sustainable energy production.

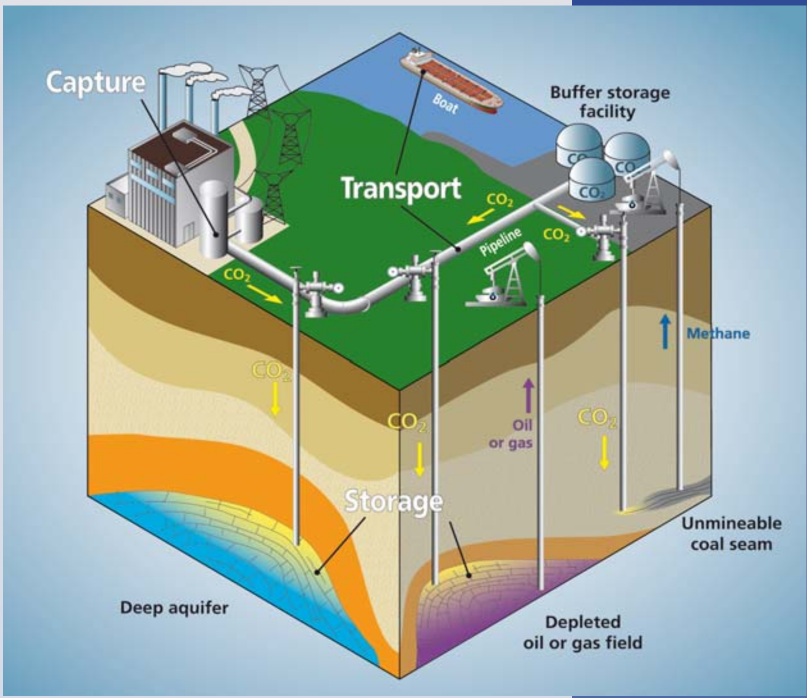


Figure 3
At power plants, the CO_2 is captured by separating it out from the other gases. It is then compressed and transported via pipeline or ship to its geological storage site: deep saline aquifers, depleted oil and gas fields, unmineable coal seams.

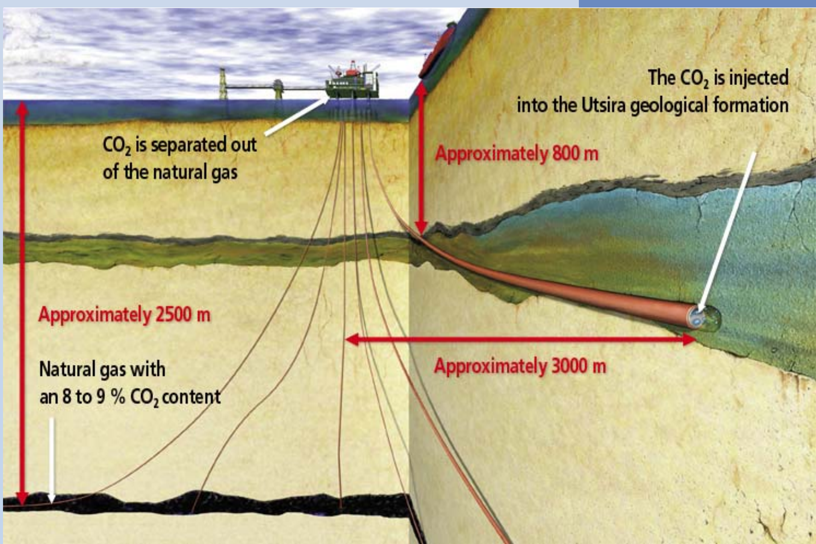
Worldwide development of CCS is flourishing

Major research programmes on CCS have been conducted in Europe, the United States, Canada, Australia and Japan since the 1990's. Much knowledge has already been acquired at the world's first large-scale demonstration projects, where CO_2 has been injected deep underground for several years: Sleipner in Norway (about 1Mt/year since 1996) (***Fig. 4***), Weyburn in Canada (about 1.8Mt/year since 2000), and In Salah in Algeria (about 1Mt/year since 2004). International collaboration on CO_2 storage research, fostered by IEA-GHG* and CSLF*, at these and other sites has been particularly important in extending our understanding and developing a worldwide scientific community that is addressing this issue. An excellent example is the IPCC* special report on CO_2 capture and storage (2005), which describes the current state of knowledge and the obstacles that must be overcome to allow the widespread implementation of this technology. Robust technical expertise already exists, and the world is now confidently moving into the demonstration phase. In addition to technical developments, legislative, regulatory, economic and political frameworks are being drawn up, and social perception and support are being assessed. In Europe, the goal is to have as many as 12 large-scale demonstration projects up-and-running by 2015 to enable widespread commercial deployment by 2020. For this purpose, in January 2008, the European Commission issued the "Climate action and renewable energy package", which proposes a Directive on CO_2 geological storage and other measures to promote the development and safe use of CCS.

Key questions on CO_2 geological storage

CO_2GeoNet Network of Excellence was created under the auspices of the European Commission as a group of research institutions capable of maintaining Europe at the forefront of large-scale international research. One of CO_2GeoNet's goals is the communication of clear scientific information on the technical aspects of CO_2 geological storage. To encourage dialogue on the essential aspects of this vitally important technology, CO_2GeoNet researchers have prepared basic answers to several frequently asked questions. In the following pages, you will find explanations as to how CO_2 geological storage can be carried out, under what circumstances it is possible, and what the criteria are for its safe and efficient implementation.

Figure 4
A vertical cross-section of the Sleipner site, Norway. The natural gas, extracted at a depth of 2500 m, contains several percent of CO_2 that needs to be removed to comply with commercial standards. Instead of releasing it into the atmosphere, the captured CO_2 is injected at approximately 1000-m depth into the sandy Utsira aquifer*.



Where and how much CO_2 can we store underground?

CO_2 cannot be injected just anywhere underground, suitable host rock formations must first be identified. Potential reservoirs for CO_2 geological storage exist throughout the world and offer sufficient capacity to make a significant contribution to mitigating human-induced climate change.

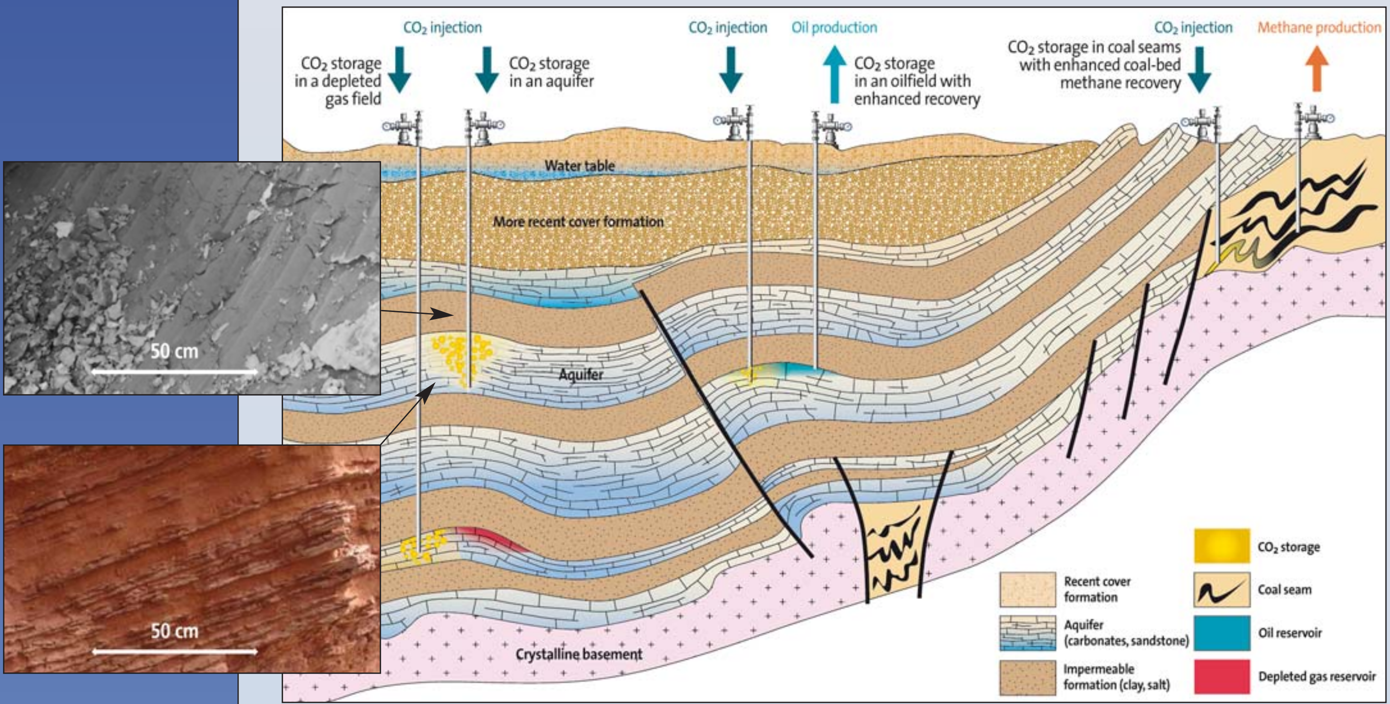


Figure 1
CO_2 is injected into deep geological layers of porous and permeable rocks (cf. sandstone in bottom inset), overlain by impermeable rocks (cf. claystone in top inset) that prevent the CO_2 from escaping to the surface. The main storage options include:
1. Depleted oil/gas reservoirs with enhanced recovery where possible;
2. Aquifers bearing salty water unfit for human consumption;
3. Deep unmineable coal seams locally associated with enhanced methane recovery.

Three main storage options exist for CO_2 (***Fig. 1***):

1. Depleted natural gas and oil fields – well known due to hydrocarbon exploration and exploitation, offer immediate opportunities for CO_2 storage;
2. Saline aquifers – offer a larger storage potential, but are generally not as well known;
3. Unmineable coal seams – an option for the future, once the problem of how to inject large volumes of CO_2 into low-permeability* coal has been solved.

The reservoirs

Once injected underground into a suitable reservoir rock, the CO_2 accumulates in the pores between grains and in fractures, thus displacing and replacing any existing fluid such as gas, water or oil. Suitable host rocks for CO_2 geological storage should therefore have a high porosity* and permeability. Such rock formations, the result of the deposition of sediments in the geological past, are commonly located in so-called "sedimentary basins". In places, these permeable formations alternate with impermeable rocks, which can act as an impervious seal. Sedimentary basins often host hydrocarbon reservoirs and natural CO_2 fields, which proves their ability to retain fluids for long periods of time, having naturally trapped oil, gas and even pure CO_2 for millions of years.

The subsurface is often depicted as an over-simplified, homogeneous, layer-cake structure in illustrations showing the possible storage options for CO_2. In reality, however, it is composed of unevenly distributed and locally faulted rock formations, reservoirs and cap rocks forming complex, heterogeneous structures. In-depth knowledge of the site and geoscientific experience are required to assess the suitability of underground structures that are proposed for long-term CO_2 storage.

Potential CO_2 storage reservoirs must fulfil many criteria, the essential ones being:

- sufficient porosity, permeability and storage capacity;
- the presence of overlying impermeable rock – the so-called "cap rock" (e.g. clay, clay stone, marl, salt rock), which prevents the CO_2 from migrating upwards;
- the presence of "trapping structures" – in other words features, such as a dome-shaped cap rock,

that can control the extent of CO_2 migration within the storage formation;
- location deeper than 800 m, where pressures and temperatures are high enough to enable the storage of CO_2 in a compressed fluid phase and thus maximize the quantity stored;
- the absence of drinking water: CO_2 will not be injected into waters fit for human consumption and activities.

Where to find storage sites in Europe

Sedimentary basins are widespread throughout Europe, for example offshore in the North Sea or onshore surrounding the Alpine mountain chains (***Fig. 2***). Many formations in the European basins fulfil the criteria for geological storage, and are currently being mapped and characterized by researchers. Other European areas are composed of ancient consolidated crust, such as much of Scandinavia, and thus do not host rocks suitable for CO_2 storage.
One example of an area with potential for storage is the Southern Permian Basin, which extends from England to Poland (represented on Figure 2 by the largest ellipse). The sediments have been affected by rock-forming processes that left some of the pore space filled with saline water, oil or natural gas. The clay layers that exist between the porous sandstones have been compacted to low-permeability strata, which prevent fluid ascent. Much of the sandstone formations are located at depths between 1 and 4 km, where pressure is high enough to store CO_2 as a dense phase. The salt content in the formation waters increases in this depth interval from about 100 g/l to 400 g/l, in other words, much saltier than seawater (35 g/l). Movements in the basin have caused plastic deformation of the rock salt, creating hundreds of dome-shaped structures that subsequently trapped natural gas. It is these traps that are being studied for eventual CO_2 storage sites and pilot projects.

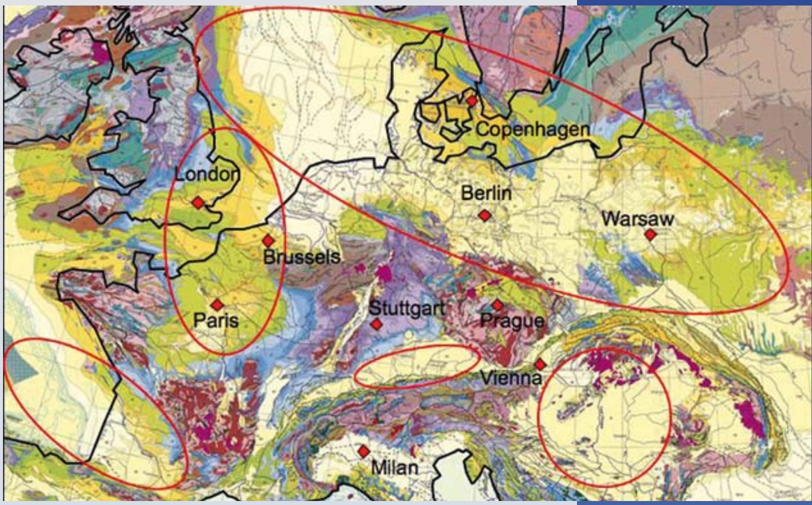


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Figure 2
Geological Map of Europe showing the location of the main sedimentary basins (red ellipses) where suitable reservoirs for CO_2 storage can be found (based on the Geological Map of Europe at 1:5,000,000 scale).

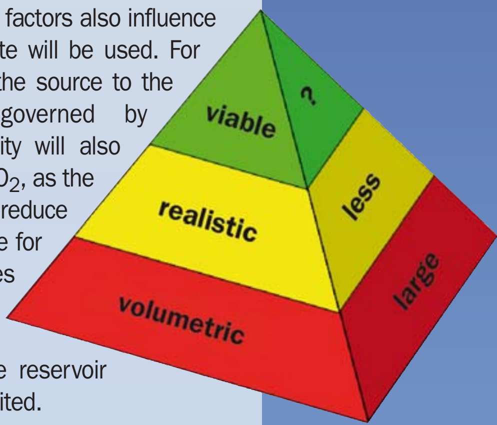
Storage capacity

Knowledge of CO_2 storage capacity is needed by politicians, regulatory authorities and storage operators. Storage capacity estimates are usually highly approximate and based on the spatial extent of potentially suitable formations. Capacity can be assessed on different scales, from national scale for rough estimates, through to basin and reservoir scale for more precise calculations that take into account the heterogeneity and complexity of the real geological structure.

Volumetric Capacity: Published national storage capacities are generally based on calculations of the formations' pore volume. In theory, the storage capacity of a given formation can be calculated by multiplying its area by its thickness, its average porosity and the average density of CO_2 at reservoir depth conditions. However, because the pore space is already occupied by water, only a small part can be used for storage, generally assumed to be about 1-3%. This storage capacity coefficient is then applied when assessing the volumetric capacity.

Realistic Capacity: More realistic capacity estimates can be made on single storage sites through detailed investigations. Formation thickness is not constant, and reservoir properties can vary over short distances. Knowledge of the size, shape and geological properties of structures allows us to reduce the uncertainties in the volume calculations. Based on this information, computer simulations can then be used to predict CO_2 injection and movement within the reservoir in order to estimate a realistic storage capacity.

Viable Capacity: Capacity is not merely a question of rock physics. Socio-economic factors also influence whether or not a suitable site will be used. For example, moving CO_2 from the source to the storage site will be governed by transportation costs. Capacity will also depend on the purity of the CO_2, as the presence of other gases will reduce the reservoir volume available for CO_2. Finally, political choices and public acceptance will have the last say as to whether or not the available reservoir capacity will actually be exploited.



In conclusion, we know that the capacity for CO_2 storage in Europe is high, even if uncertainties exist related to reservoir complexity, heterogeneity and socioeconomic factors. The EU project GESTCO* estimated the CO_2 storage capacity in hydrocarbon fields in and around the North Sea at 37 Gt, which would enable large installations in this region to inject CO_2 for several decades. Updating and further mapping of storage capacities in Europe is a matter of ongoing research, in individual member states and through the EU Geocapacity* project for Europe at large.

How can we transport and inject large quantities of CO_2?

After its capture at the industrial facility, the CO_2 is compressed, transported, and then injected into the reservoir formation through one or several wells. The whole chain has to be optimized to enable the storage of several millions of tons of CO_2 per year.

Compression

CO_2 is compressed into a dense fluid form that occupies significantly less space than a gas.
Once the CO_2 has been separated from the flue gas in the power plant or industrial facility, the resulting highly concentrated CO_2 stream is dehydrated and compressed, making transport and storage more efficient (***Fig. 1***). Dehydration is necessary to avoid corrosion of equipment and infrastructure and, under high pressure, the formation of hydrates (solid ice-like crystals that can plug equipment and pipes). Compression is carried out together with dehydration by a multistage process: repeated cycles of compression, cooling and water separation. Pressure, temperature and water content all need to be adapted to the mode of transport and to the pressure requirements at the storage site. Key factors for the design of the compressor installation are gas flow rate, suction and discharge pressures, heat capacity of the gas, and efficiency of the compressor. The technology for compression is available and already widely used in many industrial fields.

Transportation

CO_2 can be transported by either ship or pipeline.
Ship transportation of CO_2 is currently only operated at very small scales (10,000-15,000 m^3) for industrial uses, but this could become an attractive option in the future for CCS projects where a near-coast source is very far from a suitable reservoir. The vessels used for transporting liquefied petroleum gas (LPG) are suitable for CO_2 transportation. In particular, the semi-refrigerated systems are both pressurized and cooled, and thus the CO_2 can be transported in the liquid phase. The newest LPG ships have volumes of up to 200,000 m^3 and are capable of transporting 230,000 t of CO_2. However, ship transport does not provide continuous flow logistics, and intermediate storage facilities are required at the port to handle the reloading of CO_2.
Pipeline transportation is currently employed for large quantities of CO_2 used by oil companies in Enhanced Oil Recovery* (approximately 3000 km of CO_2 pipelines in the world, most in the United States). This is more cost-effective than ship transportation and also offers the advantage of providing a continuous flow from the capture plant to the storage site. Existing CO_2 pipelines all operate at high pressures under supercritical conditions for CO_2 under which it behaves like a gas but has a liquid density. Three important factors determine the quantity that a pipeline can handle: its diameter, the pressure along its length and, consequently, its wall thickness.

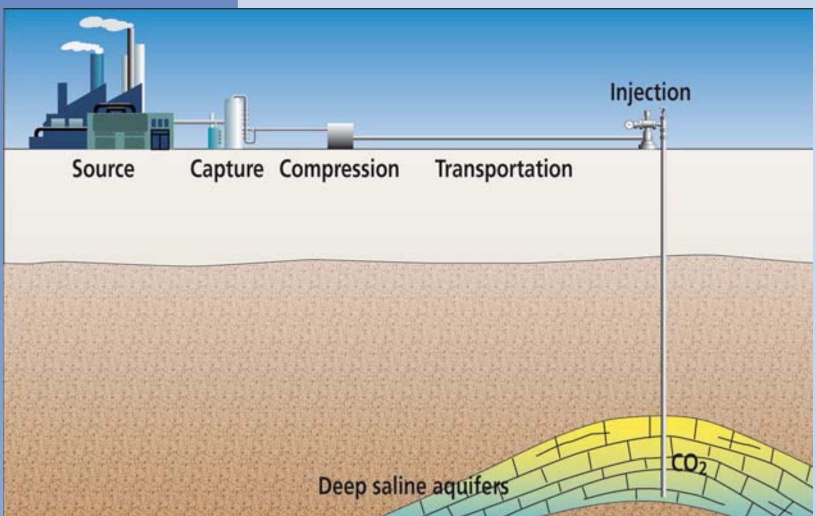


Figure 1
Stages of geological storage of CO_2. In order to bring CO_2 from its emission point towards its safe and durable storage, it has to go through a whole chain of operations including capture, compression, transportation and injection.

Injection

When the CO_2 arrives at the storage site, it is injected under pressure into the reservoir (***Fig. 2***).
Injection pressure must be sufficiently greater than reservoir pressure to move the reservoir fluid away from the injection point. The number of injection wells depends on the quantity of CO_2 to be stored, the injection rate (volume of CO_2 injected per hour), the permeability and thickness of the reservoir, the maximum safe injection pressure, and the type of well. As the main objective is the long-term containment of CO_2, we must be certain of the hydraulic integrity of the formation. High injection rates can cause pressure increases at the point of injection, particularly in low-permeability formations. Injection pressure usually should not exceed the fracture pressure of the rock as this may damage the reservoir or the overlying seal. Geomechanical analysis and models are used to identify the maximum injection pressure that will avoid fracturing the formation.

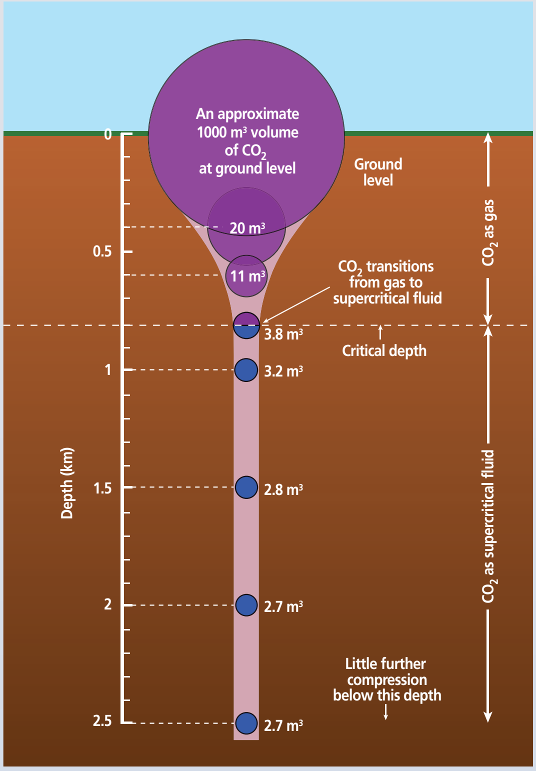


Figure 2
When injected underground, CO_2 becomes a dense supercritical* fluid at around 0.8 km depth. Its volume is dramatically reduced from 1000 m³ at the surface to 2.7 m³ at 2-km depth. This is one of the factors that makes the geological storage of large quantities of CO_2 so attractive.

Chemical processes might affect the rate at which CO_2 can be injected into the formation. Depending on the reservoir rock type, the composition of the fluids, and the reservoir conditions (such as temperature, pressure, volume, concentration, etc.), mineral dissolution and precipitation processes can occur near the well. This can lead to increased or decreased injection rates. As soon as CO_2 is injected, part of it dissolves in the salty reservoir water and the pH* slightly decreases, buffered by the dissolution of carbonate minerals present in the host rock. Carbonates are the first minerals to dissolve as their reaction rate is very high and dissolution starts as soon as injection begins. This dissolution process can increase the porosity of the rock and the injectivity*. However, following dissolution, carbonate minerals can re-precipitate and cement the formation around the well. High flow rates can be used to limit permeability reduction near the well, thus displacing the geochemical equilibrium area of precipitation farther away.
Drying is another phenomenon induced by injection. After the acidification phase, the residual water that has remained around the injection well dissolves in the injected dry gas, which in turn concentrates chemical species in the brine*. Minerals (such as salts) can then precipitate when the brine is sufficiently concentrated, thus reducing permeability around the well.
These injectivity issues depend on complex interacting processes that occur locally around the injection well, but that are also highly dependent on time and distance to the injection well. Numerical simulations are used to assess such effects. Injection flow rates need to be carefully handled to overcome processes that might limit the injection of the desired quantities of CO_2.

CO_2 stream composition

The composition and purity of the CO_2 stream, which are a result of the capture process, have a significant influence on all subsequent aspects of a CO_2 storage project. The presence of a few percent of other substances, such as water, hydrogen sulphide (H_2S), sulphur and nitrogen oxides (SOx, NOx), nitrogen (N_2) and oxygen (O_2), will affect the physical and chemical properties of the CO_2 and its associated behaviour and impacts. The presence of such substances must therefore be carefully considered when designing the compression, transportation and injection phases and also when adjusting the operating conditions and equipment.

In conclusion, the transportation and injection of large quantities of CO_2 is already feasible. However, if the geological storage of CO_2 is to be widely deployed, all the stages involved need to be tailored to each storage project. The key parameters are the thermodynamic properties of the CO_2 stream (***Fig.3***), flow rates, and upstream and reservoir conditions.

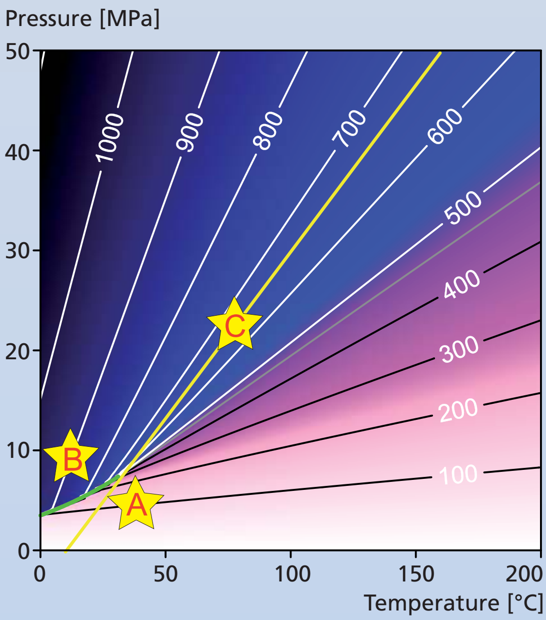


Figure 3
Density of pure CO_2 (in kg/m³) as a function of temperature and pressure. The yellow line corresponds to a typical pressure and temperature gradient in a sedimentary basin. At depths greater than 800 m (~8 MPa), reservoir conditions facilitate high densities (blue shading). The green curve is the phase boundary between gaseous and liquid CO_2. Typical pressure and temperature conditions for capture, transport and storage are indicated respectively by A, B and C.

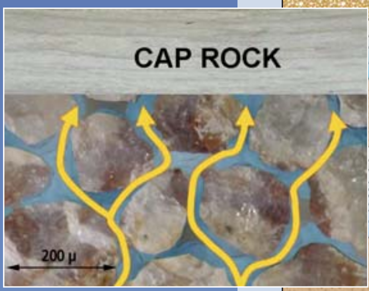
What happens to the CO_2 once in the storage reservoir?

Once injected in the reservoir, the CO_2 will rise buoyantly filling the pore spaces below the cap rock. Over time, part of the CO_2 will dissolve and eventually be transformed into minerals. These processes take place at different time scales and contribute to permanent trapping.

Trapping mechanisms

When injected in a reservoir, the CO_2 fills the rock's pore spaces, which in most cases are already filled with brine i.e. salty water.
As the CO_2 is injected, the following mechanisms begin to come into play. The first is considered the most important and prevents the CO_2 from rising to the surface. The other three tend to increase the efficiency and security of storage with time.

Microscopic view.



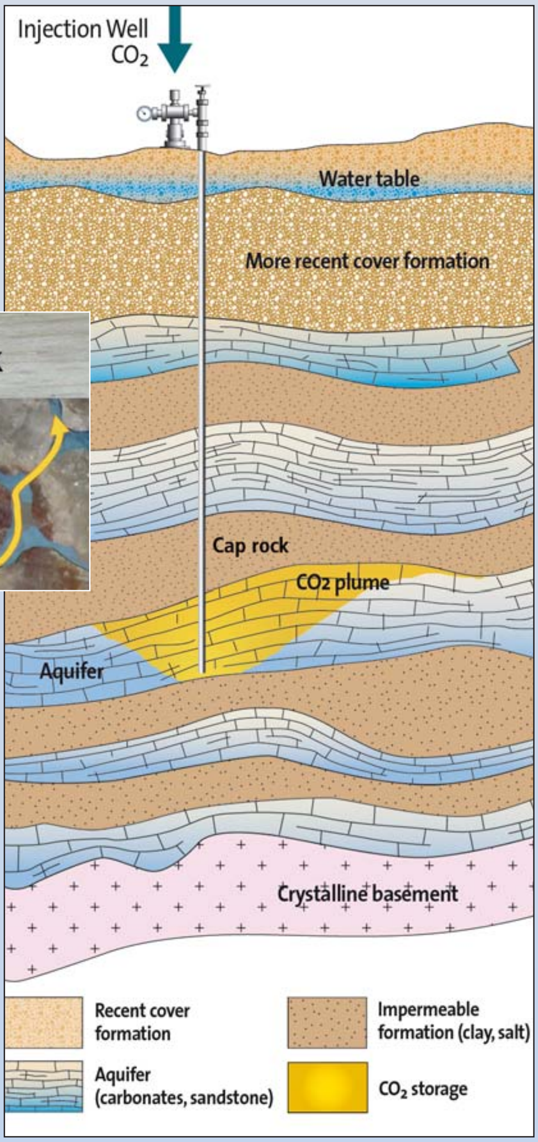


Figure 1
The injected CO_2, which is lighter than water, tends to rise and is stopped by overlying impermeable rocks.

1. **Accumulation below the cap rock (Structural trapping)**
   As dense CO_2 is 'lighter' than water, it begins to rise upwards. This movement is stopped when the CO_2 encounters a rock layer that is impermeable, the so-called 'cap rock'. Commonly composed of clay or salt, this cap rock acts as a trap, preventing the CO_2 from rising any farther, and leading to its accumulation directly beneath. ***Figure 1*** illustrates the upward movement of the CO_2 through the pore spaces of the rock (in blue) until it reaches the cap rock.

2. **Immobilization in small pores (Residual trapping)**
   Residual immobilization occurs when the pore spaces in the reservoir rock are so narrow that the CO_2 can no longer move upwards, despite the difference in density with the surrounding water. This process occurs mainly during the migration of CO_2 and can typically immobilize a few percent of the injected CO_2, depending on the properties of the reservoir rock.

3. **Dissolution (Dissolution trapping)**
   A small proportion of the injected CO_2 is dissolved, or brought into solution, by the brine already present in the reservoir pore spaces. A consequence of dissolution is that the water with dissolved CO_2 is heavier than the water without, and it tends to move downwards to the bottom of the reservoir. The dissolution rate depends on the contact between the CO_2 and the brine. The amount of CO_2 that can dissolve is limited by a maximum concentration. However, due to the movement of injected CO_2 upwards and the water with dissolved CO_2 downwards, there is a continuous renewal of the contact between brine and CO_2, thus increasing the quantity that can be dissolved. These processes are relatively slow because they take place within narrow pore spaces. Rough estimates at the Sleipner project indicate that about 15% of the injected CO_2 is dissolved after 10 years of injection.

4. **Mineralization (Mineral trapping)**
   The CO_2, especially in combination with the brine in the reservoir, can react with the minerals

Figure 2
Dense CO_2 migrating upwards (light blue bubbles), dissolving and reacting with the grains of the rock, leading to precipitation of carbonate minerals on the grain boundaries (white).

actually forming the rock. Certain minerals can dissolve, whereas others can precipitate, depending on the pH and the minerals constituting the reservoir rock (***Fig. 2***). Estimations at Sleipner indicate that only a relatively small fraction of the CO_2 will be immobilized through mineralization after a very long period of time. After 10,000 years, only 5% of the injected CO_2 should be mineralized while 95% would be dissolved, with no CO_2 remaining as a separate dense phase.

The relative importance of these trapping mechanisms is site specific, i.e. it depends on the characteristics of each individual site. For instance, in dome-shaped reservoirs, CO_2 should remain mostly in a dense phase even over very long timescales, while in flat reservoirs such as Sleipner, most of the injected CO_2 will be dissolved or mineralized.
The evolution of the proportion of CO_2 in the different trapping mechanisms for the Sleipner case is illustrated in ***Figure 3***.

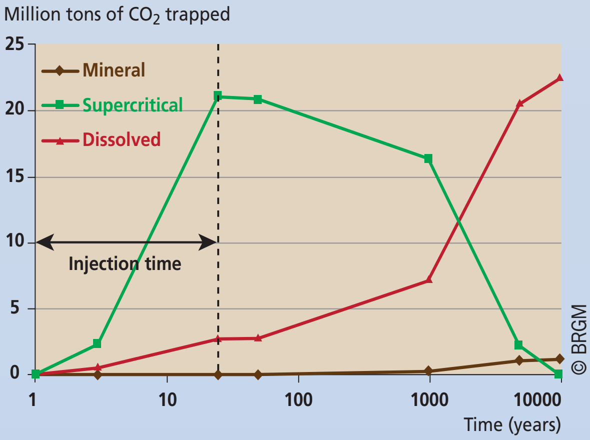


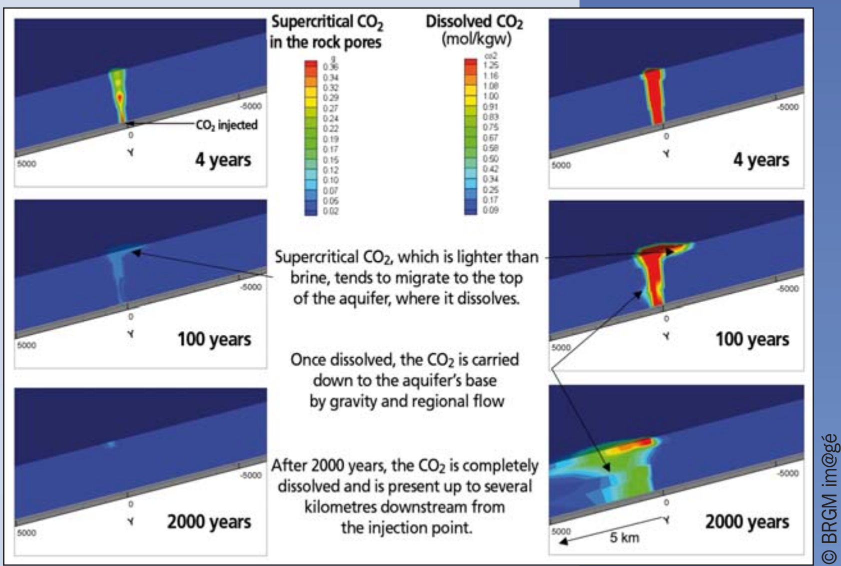
Figure 3
Evolution of the CO_2 in its different forms in the Sleipner reservoir according to flow simulations. CO_2 is trapped in supercritical form by mechanisms 1 and 2, in dissolved form by mechanism 3, and in mineral form by mechanism 4.

How do we know all this?

The knowledge of these processes comes from four main sources of information:

- **Laboratory measurements**: small-scale experiments for mineralization, flow and dissolution can be conducted on rock samples, giving insight into short-term and small-scale processes.
- **Numerical simulations**: computing codes have been developed that can be used to predict CO_2 behaviour over much longer timescales (***Fig. 4***). Laboratory experiments are used to calibrate numerical simulations.
- **The study of natural CO_2 reservoirs**, where the CO_2 (generally of volcanic origin) has been trapped underground for long periods of time, often millions of years. Such a setting is referred to as a 'natural analogue'*. These sites provide us with information on gas behaviour and the very long term consequences of the presence of CO_2 in the underground.
- **Monitoring of existing CO_2 geological storage demonstration projects**, such as Sleipner (offshore Norway), Weyburn (Canada), In Salah (Algeria) and K12-B (offshore The Netherlands). The results of the simulations in the short term can be compared with real field data and help refine the models.

Figure 4
3D modelling of CO_2 migration in an aquifer, after the injection of 150,000 tons over 4 years in the Dogger aquifer in France. Depicted here is the supercritical CO_2 (left) and the dissolved CO_2 in brine (right) 4, 100 and 2000 years after injection began. The simulation is based on field data and experiments.



Only by constantly cross-referencing and cross-checking these four sources of information is it possible to acquire reliable knowledge on all the processes occurring some 1000 m below our feet.

In conclusion, we know that the safety of a CO_2 storage site tends to increase with time. The most critical point is to find a reservoir with a suitable cap rock above it that can withhold the CO_2 (structural trapping). The processes related to dissolution, mineralization and residual trapping all work in favour of preventing CO_2 from migrating to the surface.

Could CO_2 leak from the reservoir and, if so, what might be the consequences?

Based on the study of natural systems, carefully chosen storage sites are not expected to show any significant leakage. Natural reservoirs containing gas help us understand the conditions under which gas is trapped or released. In addition, leaking sites help us understand what the possible impacts of CO_2 leakage could be.

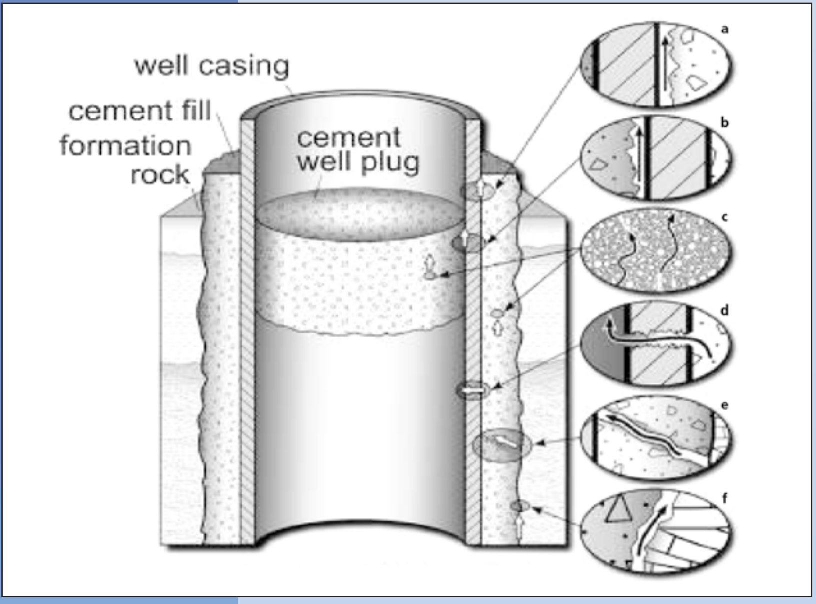
Leakage pathways

In general, potential leakage pathways are either man-made (such as deep wells) or natural (such as fracture systems and faults).

Both active and abandoned wells could constitute migration pathways because firstly, they form a direct connection between the surface and the reservoir, and secondly, they are composed of man-made materials that may corrode over long periods of time (***Fig. 1***). An added complication is that not all wells are created using the same techniques, and thus newer wells are generally more secure than older ones. In any case, the risk due to leakage through wells is expected to be low because both new and old wells can be monitored very effectively using sensitive geochemical and geophysical methods, and because technology already exists in the petroleum industry for any remedial action that may be needed.

Flow along natural faults and fractures that could exist in the cap rock or the overburden* is more complex because we are dealing with irregular, planar features with variable permeability. A good scientific and technical understanding of both leaking and non-leaking natural systems will allow us to design CO_2 storage projects that have the same characteristics of naturally occurring reservoirs that have trapped CO_2 and methane for thousands to millions of years.

Figure 1
Possible pathways for CO_2 in a well. Escape via altered material (c, d, e) or along interfaces (a, b, f).



after Nordbotten et al. 2005

Natural analogues: lessons learned

Natural systems (so-called "analogues") are invaluable sources of information for improving our understanding of deep gas migration and the natural exchange of gases between the earth and the atmosphere. The main findings derived from the study of numerous leaking and non-leaking natural gas reservoirs are:

- under favourable geological conditions, naturally produced gas can be trapped for hundreds of thousands to millions of years;
- isolated gas reservoirs and pockets even exist in the least-favourable geological settings (volcanic areas);
- the migration of any significant amount of gas requires advection (i.e. pressure-driven flow) because diffusion is a very slow process;
- for advection to occur, the fluid conditions in the reservoir need to be close to lithostatic pressure* to keep faults and fractures open or to mechanically create new pathways;
- areas where naturally produced gas leaks to the surface are situated almost exclusively in highly fractured volcanic and seismic regions, with gas vents lying along active or recently activated faults;
- significant gas leaks exist only rarely and tend to be restricted to highly faulted volcanic and geothermal areas where CO_2 is continuously produced by natural processes;
- gas anomalies at the surface usually occur as localized spots that have a limited spatial impact on the near-surface environment.

Therefore, the combination of a number of specific conditions are needed before leakage can occur. Consequently, it is highly unlikely that a well-chosen and carefully engineered CO_2 geological storage site will leak. Although the potential for leakage is small, the associated processes and potential effects must be fully understood in order to choose, design and operate the safest possible CO_2 geological storage sites.

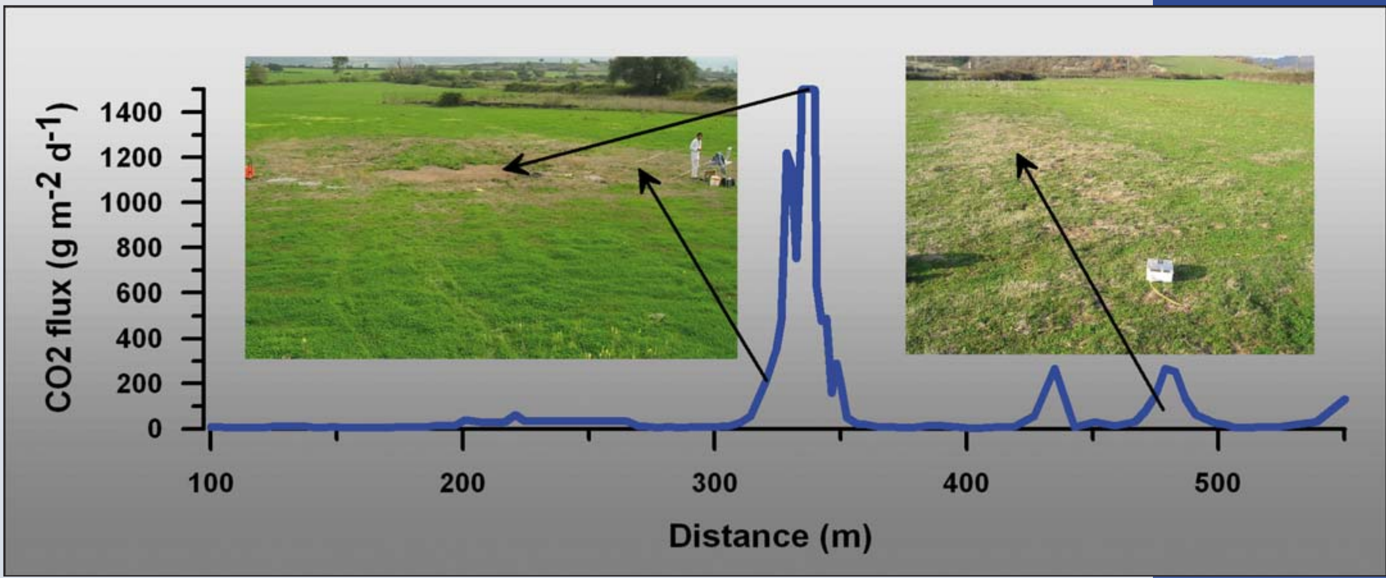


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Figure 2
Impact of CO_2 leakage on vegetation with a high (left) and reduced (right) flux.
Impact is limited to the area where CO_2 escapes.

Impact on humans

We breathe CO_2 all the time. CO_2 is only dangerous for human health at very high concentrations, with values up to 50,000 ppm (5%) causing headaches, dizziness, and nausea. Values above this level can cause death if exposure is too long, especially by asphyxia when the concentration of oxygen in the air falls below the 16% level required to sustain human life. However, if CO_2 leaks in an open or flat-lying area, it quickly becomes dispersed into the air, even with low winds. The potential risk to populations is thus restricted to leakage in enclosed environments or topographical depressions, where concentrations may rise because CO_2 is denser than air and tends to accumulate close to the ground. The knowledge of the characteristics of degassing areas is useful in risk prevention and management. In reality, many people live in areas characterized by daily natural gas emanations. For example, in Italy at Ciampino, near Rome, houses are located only 30 metres from gas vents, where CO_2 concentrations in the soil reach 90% and about 7 tons of CO_2 are released daily into the atmosphere. The local inhabitants avoid any danger by following simple precautions, such as not sleeping in the basement and keeping the houses well ventilated.

Impact on the environment

Potential impacts on the ecosystems would vary depending on whether the storage site is located offshore or onshore.

In marine ecosystems, the main effect of CO_2 leakage is local lowering of the pH and its associated impact, primarily on animals that live on the seafloor and can not move away. However, the consequences are spatially limited and the ecosystem soon shows signs of recovery after the leakage subsides.

In terrestrial ecosystems, impact can be broadly summarized as follows:

- **vegetation** – Although soil gas CO_2 concentrations of up to about 20-30% can actually favour plant fertilization and increase the growth rate for certain species, values above this threshold can be lethal to some, but not all plants. This effect is extremely localized around the gas vent, however, and the vegetation remains robust and healthy only a few metres away (***Fig. 2***).
- **groundwater quality** – The chemical composition of groundwater could be altered by the addition of CO_2, as the water becomes more acidic and elements may be released from the aquifer's rocks and minerals. Even if CO_2 should leak into a drinking-water aquifer, the effects would remain localized and quantification of the impacts is currently being investigated by researchers. Interestingly, many aquifers throughout Europe are enriched in natural CO_2, and this water is actually bottled and sold as "sparkling mineral water".
- **rock integrity** – The acidification of groundwater can result in rock dissolution, decreased structural integrity, and the formation of sinkholes. However, this type of impact only occurs under very specific geological and hydrogeological conditions (tectonically active, high flow rate aquifers, carbonate-rich mineralogy), which are not likely to occur above a man-made geological storage site.

In conclusion, as the impacts of any hypothetical CO_2 leakage will depend on the specific site, a thorough knowledge of the underlying geological and structural setting will allow us to identify any potential gas migration pathways, choose sites with the lowest potential of CO_2 leakage, predict gas behaviour and thus evaluate, and prevent, any significant impact on humans and the ecosystem.

How can we monitor the storage site at depth and at the surface?

All CO_2 storage sites will need to be monitored for operational, safety, environmental, societal and economic reasons. A strategy has to be drawn up to define what exactly will be monitored and how.

Why do we need monitoring?

Monitoring site performance will be critical to ensure that the principal goal of CO_2 geological storage is attained, namely the long-term isolation from the atmosphere of anthropic CO_2. The reasons for monitoring storage sites are numerous, including:

- **Operational**: to control and optimize the injection process.
- **Safety and environmental**: to minimize or prevent any impact on people, wildlife and ecosystems in the vicinity of a storage site, and to ensure the mitigation of global climate change.
- **Societal**: to provide the public with the information needed to understand the safety of the storage site and to help gain public confidence.
- **Financial**: to build market confidence in CCS technology and to verify the stored volumes of CO_2 so that they are credited as 'avoided emissions' in future phases of the European Union's Emission Trading Scheme (ETS).

Monitoring of both the initial state of the environment (so-called "baseline") and the subsequent site performance is an important regulatory requirement in the EC Directive on CCS, published in draft form on 23rd January 2008. Operators need to be able to demonstrate that the storage performance conforms to regulations and will continue to do so over the long term. Monitoring is an important component that will reduce uncertainties in site performance, and thus it should be strongly linked to safety management activities.

What are the monitoring targets?

Monitoring can be focused on various targets and processes in different parts of the site, such as:

- Plume imaging – tracking of the CO_2 as it migrates from the injection point. This provides key data for calibrating models that predict the future distribution of CO_2 at the site. Many mature techniques are available, most notably repeat seismic surveys, which have been successfully applied at several demonstration and pilot-scale projects (***Fig. 1***).
- Cap-rock integrity – necessary to evaluate if the CO_2 is isolated within the storage reservoir and to enable early warning of any unexpected upward CO_2 migration. This can be especially important during the injection phase of a project, when reservoir pressures are significantly, but temporarily, increased.
- Well integrity. This is an important issue as deep wells could potentially provide a direct pathway for CO_2 migration to the surface. CO_2 injection wells plus any observation wells or pre-existing abandoned wells must be carefully monitored during the injection phase and beyond to prevent sudden escape of CO_2. Monitoring is also used to verify that all wells have been efficiently sealed once they are no longer required. Existing geophysical and geochemical monitoring systems, which are standard practice in the oil and gas industry, can be installed within or above wells to provide early warning and ensure safety.
- Migration in the overburden. At storage sites where additional, shallower rock units have properties that are similar to those of the cap rock, the overburden may form a key component in reducing the risk of CO_2 escape into the sea or the atmosphere. If monitoring in the reservoir or around the cap rock indicates an unexpected migration through the cap rock, monitoring of the overburden will be necessary. Many of the techniques used in plume imaging or monitoring cap-rock integrity can be used within the overburden.
- Surface leakage and atmospheric detection and measurement. To ensure that the injected CO_2 has not migrated to the surface, a range of geochemical, biochemical and remote sensing techniques is available to locate leaks, assess and monitor CO_2 distribution in the soil and its dispersion in the atmosphere or the marine environment (***Fig. 2***).
- Quantity of stored CO_2 for regulatory and fiscal

Pre-injection (1994) **2.35 Mt CO_2 (1999)** **4.36 Mt CO_2 (2001)**

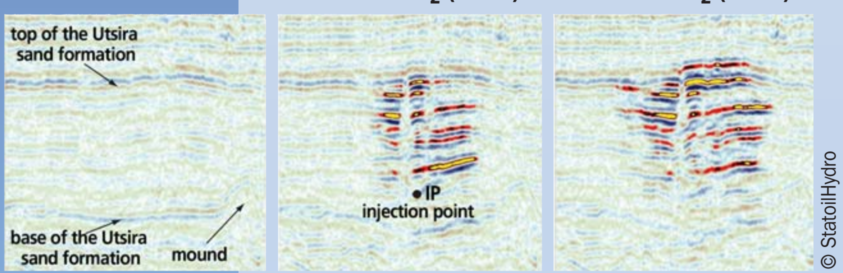


Figure 1
Seismic imaging to monitor the CO_2 plume* at the Sleipner pilot before injection (which began in 1996) and after injection (respectively 3 and 5 years later).

purposes. Although the amount of CO_2 injected can be readily measured at the wellhead, quantification in the reservoir is technically very challenging. If leakage to the near-surface occurs, then the amounts being released will have to be quantified for accounting purposes within national greenhouse gas inventories and future ETS schemes.

- Ground movements and microseismicity*. The increased reservoir pressure due to CO_2 injection could, in specific cases, increase the potential for microseismicity and small-scale ground movements. Microseismic monitoring techniques and remote methods (surveys from aircraft or satellites) able to measure even tiny ground distortion are available.

How is monitoring done?

A wide range of monitoring techniques has already been applied at existing demonstration and research projects. These include methods that directly monitor the CO_2, and those that indirectly measure its effects on rocks, fluids and the environment. Direct measurements include the analysis of fluids from deep wells or the measurement of gas concentrations in the soil or atmosphere. Indirect methods include geophysical surveys, and monitoring pressure changes in wells or pH changes in groundwater.

Monitoring will be required for storage sites whether they are offshore or onshore. The selection of appropriate monitoring techniques will depend on the technical and geological characteristics of the site and the monitoring aims. A wide range of monitoring techniques is already available (***Fig. 3***), many of which are well established in the oil and gas industries; these techniques are being adapted to a CO_2 context. Research into optimization of existing methods or the development of innovative techniques is also underway with the goal of improving resolution and reliability, reducing costs, automating operation, and demonstrating effectiveness.

Monitoring strategy

When designing a monitoring strategy, many decisions must be made that depend on the geological and engineering conditions specific to each individual site, such as reservoir geometry and depth, expected spread of the CO_2 plume, potential leakage pathways, overburden geology, injection time and flow rate, and surface characteristics, such as topography, population density, infrastructure and ecosystems. Once decisions have been made regarding the most appropriate measurement techniques and locations, baseline surveys must be conducted prior to injection operations to serve as a reference for all future measurements. Finally, each monitoring programme must be flexible so that it can evolve as the storage project itself evolves. A monitoring strategy capable of integrating all these issues, while at the same time improving cost effectiveness, will form a critical component in risk analysis and the verification of site safety and efficiency.

In conclusion, we know that the monitoring of a CO_2 storage site is already feasible with the many techniques that are available on the market or under development. Research is currently underway, not only to develop new tools (particularly for sea-floor use), but also to optimize monitoring performance and reduce the costs.

Figure 2
Monitoring buoy with solar panels for energy supply, floats and device to sample gas at the bottom of the sea.

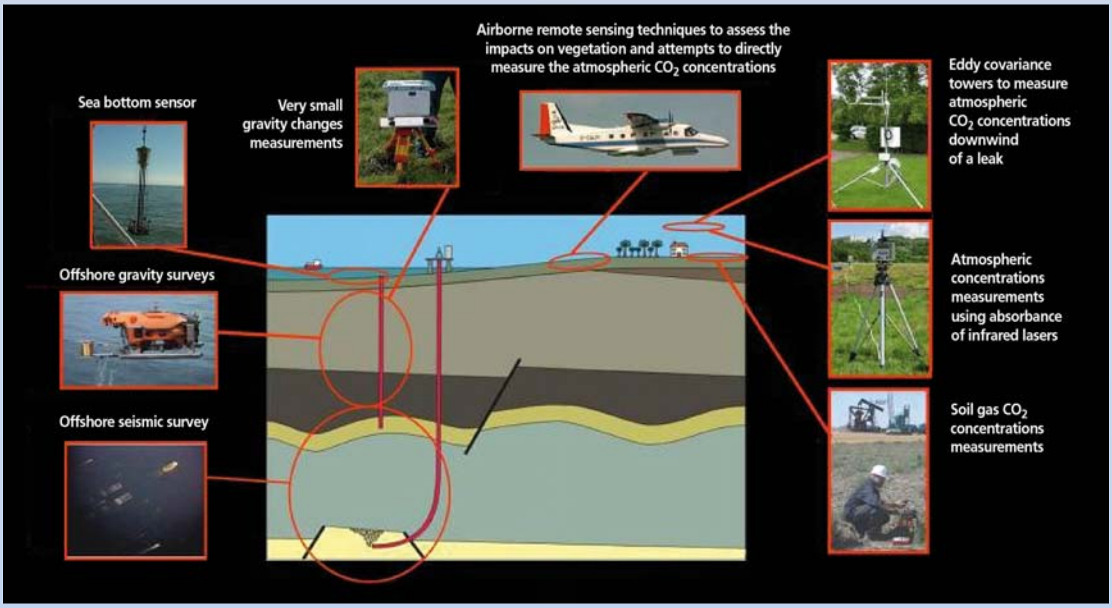


Figure 3
A small selection illustrating the range of techniques available to monitor different components of a CO_2 storage system.

What safety criteria need to be imposed and respected?

In order to ensure storage security and efficiency, conditions for project design and operation must be imposed by the regulating authorities and respected by the operators.

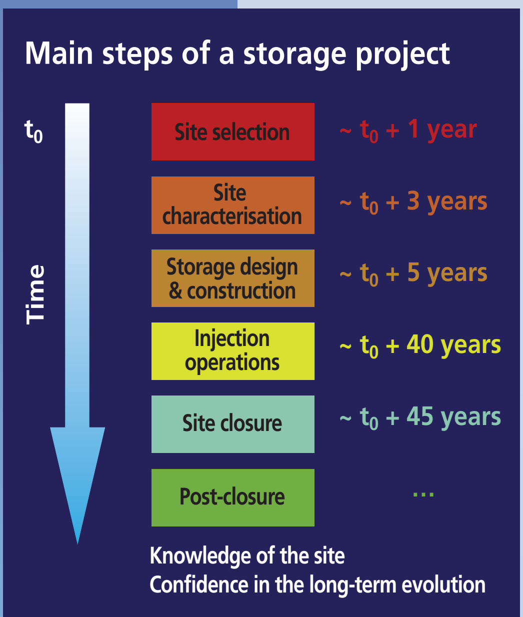
Although CO_2 geological storage is now broadly accepted as one of the credible options for mitigating climate change, the safety criteria with respect to human health and the local environment remain to be established before industrial-scale operations can be widely deployed. Such criteria can be defined as the requirements imposed upon the operators by the regulating authorities to ensure that impacts on local health, safety and the environment (including groundwater resources) are negligible in the short, medium and long term.

One key issue of CO_2 geological storage is that it should be permanent, and consequently, storage sites are not expected to leak. However, the 'what if?' scenario means that the risks must be assessed and the operators required to respect measures that prevent any leakage or anomalous behaviour of the sites. According to the IPCC, the injected CO_2 needs to remain underground for at least 1000 years, which would allow atmospheric CO_2 concentrations to stabilize or decline by natural exchange with ocean waters, thereby minimizing surface temperature rise due to global warming. However, local impacts need to be assessed on a time scale ranging from days to many thousands of years.

Several main steps can be identified during the lifetime of a CO_2 storage project (***Fig. 1***). Safety will be ensured throughout by:

- careful site selection and characterization;
- safety assessment;
- correct operation;
- an appropriate monitoring plan;
- an adequate remediation plan.

Figure 1
The different steps of a storage project.



The associated critical aims are to:

- ensure that the CO_2 remains in the reservoir;
- maintain well integrity;
- preserve the physical properties of the reservoir (including porosity, permeability, injectivity), and the impermeable nature of the cap rock;
- take into consideration the composition of the CO_2 stream, paying particular attention to any impurities not eliminated during the capture process. This is important to avoid any adverse interaction with the well, reservoir, cap rock and, in case of leakage, any overlying groundwater.

Safety criteria for project design

Safety must be demonstrated before operations begin.

With respect to site selection, the main components that must be examined include:

- the reservoir and cap rock;
- the overburden and particularly the impermeable layers that could act as secondary seals;
- the presence of permeable faults or wells that could act as pathways to the surface;
- the drinking-water aquifers;
- the population and environmental constraints at the surface.

Oil and gas exploration techniques are used to assess the geology and geometry of the storage site. Fluid flow, chemical and geomechanical modelling of the CO_2 within the reservoir allows predictions of CO_2 behaviour and long-term outcome, and definition of the parameters for efficient injection. As a result, careful site characterization should enable the definition of a 'normal' storage behaviour scenario, corresponding to a site suitable for storage where we are confident that the CO_2 will remain in the reservoir. Risk assessment then needs to consider less plausible scenarios for future states of the storage, including occurrences of unexpected events. In particular, it is important to envisage any potential leakage pathways, exposure and effects (***Fig. 2***). Each leakage scenario should be analysed by experts and, where possible, numerical modelling applied, in order to evaluate the probability of occurrence and potential severity. As an example, the evolution of the CO_2 plume extent should be mapped carefully to detect any connection with a faulted zone. Sensitivity to variations in the input parameters and uncertainties should be evaluated carefully in risk assessment. Estimating potential effects of CO_2 on human beings and the environment should be addressed through impact assessment studies, which is usual practice in any licensing process of an industrial facility. In this process, both normal and leaking scenarios will be examined to assess any

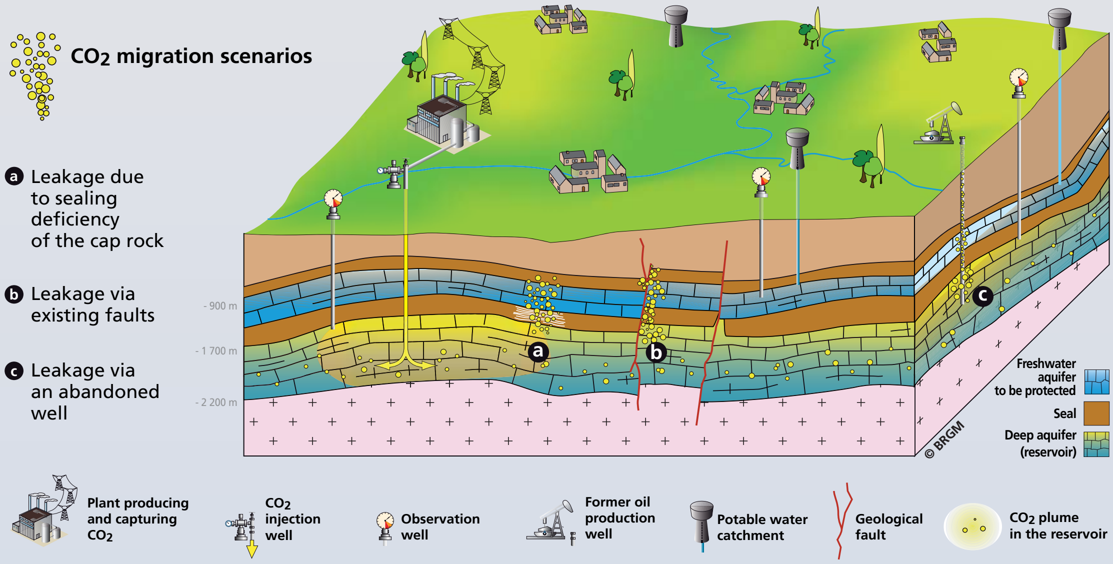


Figure 2
Example of potential leakage scenarios.

potential risk linked to the facility.
The monitoring programme, from short to long term, should be established according to the risk-assessment analysis and should control the critical parameters defined within the different scenarios. Its main objectives are to image CO_2 plume migration, check well and cap-rock integrity, detect any leakage of CO_2, assess groundwater quality and ensure that no CO_2 has reached the surface. The remediation and mitigation plan is the last component of safety assessment and aims at detailing the list of corrective actions to be deployed in the event of leakage or anomalous behaviour. It covers cap-rock integrity and well failure, during injection and post-injection periods and considers extreme remediation solutions, such as storage reversibility. Existing know-how encompasses standard oil and gas techniques, such as workover completion, decreasing injection pressure, partial or complete gas withdrawal, water extraction to relieve pressure, shallow gas extraction, etc.

Safety criteria during operation and post-closure

The main safety concern is associated with the operational phase: after injection stops, the decrease in pressure will make the site safer.
Confidence in the ability to inject and store CO_2 in a safe way relies on experience of industrial companies. CO_2 is a fairly common product used in various industries, so the handling of this substance does not raise any new problems. The design and control of operations will be based mainly on oil and gas industry know-how, in particular seasonal natural gas storage or enhanced oil recovery (EOR). The main parameters to be controlled are:

- injection pressure and flow rate – the former should be maintained below fracturing pressure, i.e. the pressure above which fractures are induced within the cap rock;
- injected volume, in order to meet predictions defined by modelling;
- composition of the injected CO_2 stream;
- integrity of the injection well(s) and any well located within or nearby the extension of the CO_2 plume;
- extension of the CO_2 plume and detection of any leakage;
- ground stability.

During injection, the actual behaviour of the injected CO_2 will need to be repeatedly compared against predictions. This constantly improves our knowledge of the site. If any anomalous behaviour is detected, the monitoring programme should be updated and corrective actions taken if necessary. In the case of suspected leakage, appropriate monitoring tools could be focused on a specific area of the storage site, from the reservoir up to the surface. This would detect the ascent of CO_2 and, moreover, any adverse impact that could be harmful to drinking-water aquifers, the environment and, ultimately, human beings.
When injection is completed, the closure phase starts: wells should be properly closed and abandoned, the modelling and the monitoring programme updated, and, if necessary, corrective measures taken to reduce risks. Once the level of risk is considered to be sufficiently low, the liability of storage will be transferred to national authorities and the monitoring plan can be stopped or minimized.

The proposed European Directive establishes a legal framework to ensure that CO_2 capture and storage is an available mitigation option, and that it can be done safely and responsibly.

In conclusion, safety criteria are essential for the successful industrial deployment of CO_2 storage. They have to be adapted to each specific storage site. These criteria will be particularly important for public acceptance, and essential in the licensing process for which regulatory bodies must decide the level of detail for safety requirements.

Glossary

Aquifer: permeable body of rock containing water. The most superficial aquifers contain fresh water used for human consumption. The ones at greater depth are filled with salty water that is unsuitable for any human needs. These are called saline aquifers.

Brine: very salty water, i.e. containing high concentration of dissolved salts.

Caprock: impermeable layer of rocks that acts as a barrier to the movement of liquids and gases and which forms a trap when overlying a reservoir.

CCS: CO_2 Capture and Storage.

CO_2 plume: spatial distribution of the supercritical CO_2 within the rock units.

CSLF: Carbon Sequestration Leadership Forum. An international climate change initiative that is focused on the development of improved, cost-effective technologies for the separation and capture of carbon dioxide and its transport and long-term safe storage.

Enhanced Oil Recovery (EOR): a technique that improves oil production by injecting fluids (like steam or CO_2) that help mobilize the oil in the reservoir.

EU Geocapacity: an on-going European research project that is assessing the total geological storage capacity that exists in Europe for anthropic CO_2 emissions.

GESTCO: a completed European research project that assessed the geological storage possibilities of CO_2 in 8 countries (Norway, Denmark, UK, Belgium, Netherlands, Germany, France and Greece).

IEA-GHG: International Energy Agency – Greenhouse Gas R&D programme. An international collaboration which aims to: evaluate technologies for reducing emissions of greenhouse gases, disseminate the results of these studies, and identify targets for research, development and demonstration and promote the appropriate work.

Injectivity: characterizes the ease with which a fluid (like CO_2) can be injected into a geological formation. It is defined as the injection rate divided by the pressure difference between the injection point inside at the well base and the formation.

IPCC: International Panel on Climate Change. This organization was established in 1988 by WMO (World Meteorological Organization) and UNEP (United Nations Environment Programme) to assess the scientific, technical and socio-economic information relevant for the understanding of climate change, its potential impacts and options for adaptation and mitigation. IPCC and Al Gore were awarded the Nobel Peace Prize for 2007.

Lithostatic pressure: the force exerted on a rock below ground surface by the overlying rocks. Lithostatic pressure increases with depth.

Microseismicity: slight tremor or vibration in the earth's crust, unrelated to earthquakes, which can be caused by a variety of natural and artificial agents.

Natural analogue: naturally occurring CO_2 reservoir. Both leaking and non-leaking sites exist, and their study can improve our understanding of the long-term fate of CO_2 in deep geological systems.

Overburden: the geological strata lying between the reservoir cap rock and the land surface (or seabed).

Permeability: property or capacity of a porous rock to transmit a fluid; it is a measure of the relative ease of fluid flow under a pressure gradient.

pH: measure of the acidity of a solution, where pH 7 corresponds to neutral.

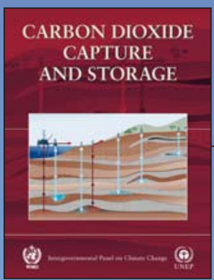
Porosity: percentage of the bulk volume of a rock that is not occupied by minerals. These gaps are called pores and they can be filled by various fluids; typically in deep rocks this fluid is salty water but it can also be oil or gas like methane or also naturally formed CO_2.

Reservoir: body of rock or sediment that is sufficiently porous and permeable to host and store CO_2. Sandstone and limestone are the most common reservoir rocks.

Supercritical: the state of a fluid at pressures and temperatures above critical values (31.03 °C and 7.38 MPa for CO_2). Properties of such fluids are continuously variable, from more gas-like at low pressure to more liquid-like at high pressure.

Well (or borehole): a circular hole made by drilling, especially a deep hole of small diameter, such as an oil well.

Going further:



The Intergovernmental Panel on Climate Change (IPCC) Special Report on CCS:
http://www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf

The European Commission's webpage on CCS:
http://ec.europa.eu/environment/climat/ccs/

The EC Directive:
http://ec.europa.eu/environment/climat/ccs/eccp1_en.htm

The ETS system:
http://ec.europa.eu/environment/climat/emission.htm

IEA GHG monitoring tools webpage:
http://www.co2captureandstorage.info/co2tool_v2.1beta/introduction.html

What CO_2GeoNet can do for you

CO_2GeoNet is a European Network of Excellence that is engaged in providing unbiased and scientifically sound information about the safety and efficiency of CO_2 geological storage. The partnership consists of more than 150 scientists at 13 public research institutes, with each partner having a high international profile in all aspects of CO_2 geological storage research. The Network is sponsored by the European Commission under the 6th Framework Programme.

The institutes involved in the network are:
BGR, BGS, BRGM, GEUS, Heriot Watt University, IFP, Imperial College, NIVA, OGS, IRIS, SINTEF, TNO, Sapienza University of Rome.

Activities of the Network

The Network researchers work together to constantly improve our knowledge about geological storage of CO_2 and the tools needed for its safe deployment. They are involved in several high-priority research projects that address every level of the issue: the reservoir, the cap rock, potential passageways for CO_2 migration up to the ground surface, potential impacts on humans and local ecosystems in the event of leakage, and public outreach and communication.
CO_2GeoNet's strength lies in its ability to create multi-disciplinary teams of highly experienced specialists, thereby allowing it to better understand the individual facets of geological storage and how they are linked together within a larger and more complex system.
In addition to its research activities, CO_2GeoNet can also:

- offer training & capacity building for the scientists and engineers who will be needed to enable CO_2 storage;
- provide scientific advice and project proposal audits (geotechnical quality, environmental protection, risk management, planning and regulatory issues, etc.);
- disseminate independent, unbiased information based on its research results;
- engage with stakeholders and help address their concerns and needs.

In order to raise public awareness about the geological storage of CO_2 as a viable option for mitigating climate change, CO_2GeoNet has tackled the basic question "What does CO_2 geological storage really mean?". A panel of eminent scientists from CO_2GeoNet has prepared state-of-the art answers to six pertinent questions, based on more than a decade of European research and the experience of demonstration projects worldwide. The goal of this endeavour is to deliver clear and unbiased scientific information to a broad audience, and to encourage dialogue on essential questions concerning the technical aspects of CO_2 geological storage.
This work, summarized in this booklet, was presented during the Network's first Training and Dialogue workshop held in Paris on 3rd October 2007. The wide audience included stakeholders, industrialists, engineers and scientists, policymakers, journalists, NGOs, sociologists, teachers, and students. In total, 170 people from 21 different countries attended, during which they had the opportunity to share their views and gain a more complete understanding of CO_2 geological storage.

For further information, or enquiries regarding the possibility of a similar tailored training course on geological storage, please contact the CO_2GeoNet Secretariat at info@co2geonet.com or visit our website at www.co2geonet.eu.

CO_2GeoNet
The European Network of Excellence on the geological storage of CO_2

www.co2geonet.eu

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BGS Natural Environment Research Council-British Geological Survey, **BGR** Bundesanstalt für Geowissenschaften und Rohstoffe, **BRGM** Bureau de Recherches Géologiques et Minières, **GEUS** Geological Survey of Denmark and Greenland, **HWU** Heriot-Watt University, **IFP**, **IMPERIAL** Imperial College of Science, Technology and Medicine, **NIVA** Norwegian Institute for Water Research, **OGS** Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, **IRIS** International Research Institute of Stavanger, **SPR SINTEF** Petroleumsforskning AS, **TNO** Netherlands Organisation for Applied Scientific Research, **URS** Sapienza University of Rome Dip. Scienze della Terra.

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