CO_2 Storage in Saline Aquifers

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Résumé — Stockage du CO_2 dans les aquifères salins — Les aquifères salins représentent une option prometteuse pour la séquestration du CO_2. Leur capacité de stockage est très importante. Le site de Sleipner en mer du Nord est actuellement le seul cas au monde de stockage de CO_2 dans un aquifère salin.

Cet article donne une vue d'ensemble des risques liés à ce type de stockage, ainsi que la distribution régionale des sites potentiels. Pour finir, les limites technologiques et les futurs programmes de recherche dans ce domaine sont présentés.

Abstract — CO_2 Storage in Saline Aquifers — Saline aquifers represent a promising way for CO_2 sequestration. Storage capacities of saline aquifers are very important around the world. The Sleipner site in the North Sea is currently the single case world-wide of CO_2 storage in a saline aquifer.

A general review is given on the specific risks for CO_2 storage in saline aquifer. The regional distribution of CO_2 storage potential is presented. Finally, the knowledge gaps and the future research in this field are defined.

1 GENERAL AND SPECIFIC ASPECTS OF THE STORAGE OPTION

Saline Aquifers are defined as porous and permeable reservoir rocks that contain saline fluid in the pore spaces between the rock grains. They generally occur at depths greater than aquifers that contain potable water. Usually, due to its high saline proportion and its depth, the water contained cannot be technically and economically exploited for surface uses. There is currently only one CO_2 storage site worldwide in a saline aquifer. This is at Sleipner in the North Sea where CO_2 is being injected into the Utsira Sandstone Formation. The amount of CO_2 that could potentially be stored in saline aquifers, for a reasonable amount of time, is very large. The basic criterion for all potential storage sites are as follows.

Potential storage sites should be in a geologically stable area, as tectonic activity could create pathways for the CO_2 to migrate out of the reservoir through the cap rock (low permeability seal) into the overburden and potentially to surface.

Saline aquifers can be sandstones or limestones, but to be a potential storage reservoir for CO_2 they must have the following properties:

– Size: the reservoir must be large enough to be able to store the quantities of CO_2 planned *e.g.* the lifetime emissions of one power plant. The capacity of the storage site is the volume of pore spaces in the aquifer that could be occupied by CO_2.

– Porosity and permeability: These parameters must be sufficiently high to both provide sufficient volume for the CO_2, and to allow injection of the CO_2. As CO_2 is injected into the pore spaces of the reservoir rock, it displaces much of the *in situ* pore fluid. If the permeability of the rock is low, or there are barriers to fluid flow, such as faults, injection will cause a progressive increase in the fluid pressure centred on the injection point. This will limit the rate at which CO_2 can be injected, and may ultimately limit the amount of CO_2 that can be practically stored. Highly structurally compartmentalised reservoirs are likely therefore to be less suited to CO_2 storage than large unfaulted or high permeability reservoirs.

– Depth: Usually only aquifers below 800 m below sea level are considered for CO_2 storage. At temperatures and pressures in the subsurface of around 600 to 800 m CO_2 exists in its dense phase as a liquid and occupies much less pore volume than in its gaseous phase. 1 t of CO_2 occupies 509 m^3 at surface conditions of 0°C and 1 bar. The same amount of CO_2 occupies only 1.39 m^3 at 1000 m subsurface conditions of 35°C and 102 bar. *(see Fig. 1)* CO_2 density at a geothermal gradient of 30ºC/km.

In addition to a reservoir rock, an overlying "cap rock" that is impermeable to the passage of CO_2 is required. When CO_2 is injected into a reservoir it is more buoyant than the reservoir fluid in the porespaces and will rise to the top of the reservoir. The cap rock, an impermeable low porosity layer will prevent the CO_2 migrating vertically and so the CO_2 becomes trapped at the top of the reservoir underneath the cap rock. The cap rock provides the main trapping mechanism for the long-term security of storage. Cap rocks are usually shales, mudstones or evaporite layers. The cap rock should ideally be unfaulted, as unsealed faults would provide migration pathways for the CO_2 out of the reservoir. In some situations, for example in faulted salt layers, faults can become resealed, and therefore do not present a leakage/seepage pathway. However, their sealing nature would need to be confirmed by detailed analysis of the storage site to ensure the integrity of the storage site.
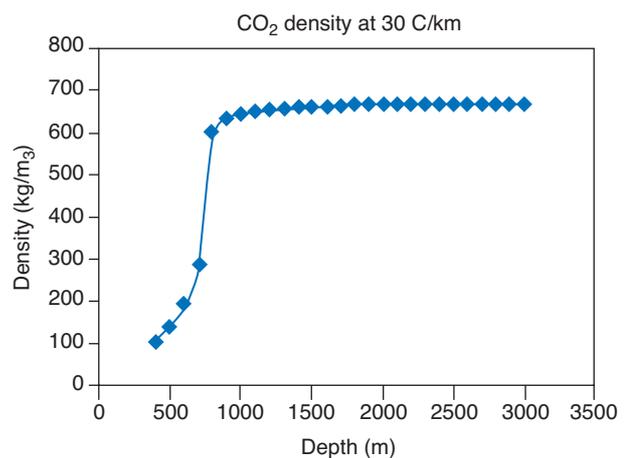

Figure 1

CO_2 density at a geothermal graient of 30°C/km.

Injected CO_2 remains in the reservoir rock by a combination of three main processes, the relative importance of which will vary from site to site, depending on the reservoir characteristics, but which together, under the correct conditions can produce long-term, effectively permanent subsurface storage (Chadwick *et al.*, 2002):

– immobilisation in traps (structural/-stratigraphic);

– dissolution in the saline waters;

– Geochemical reaction and formation of minerals in the pore spaces.

The main storage process, at least initially, is that of trapping. With time, depletion of these accumulations is likely to take place as a consequence of dissolution, an important process capable of sequestering CO_2 more or less permanently. The solubility of CO_2 under typical reservoir conditions at a pore water salinity of 3% is about 49 kg m^{-3}, corresponding to a volume of free CO_2 of about 7% of the pore volume (Lindeberg, 1996). It should be noted that the solubility of CO_2 is sensitive to changes in the pore water

salinity and salinity gradients are know to exist in the Southern North Sea close to the Zechstein evaporite deposits. As formation water becomes saturated with dissolved CO_2 its density increases and it tends to sink in the reservoir, a process that effectively sequesters the CO_2. The rate of dissolution depends on the amount of mixing of CO_2 and formation water. Diffusion of CO_2 into the water is assisted by accumulations with a high surface area to volume ratio, such as in thin but widespread layers. Similarly, the presence of internal permeability barriers such as intra-reservoir shales, will make the migration path of the CO_2 through the reservoir more tortuous and encourage mixing and dissolution. Nevertheless, for many accumulations, dissolution could be slow; in the order of a few thousand years for some injection scenarios (Ennis-King and Paterson, 2001), unless there is some form of active mixing induced by fluid flow or convection within the reservoir (Lindeberg and Wessell-Berg, 1997).

Another process leading to long-term sequestration is chemical 'fixing' by reaction of the injected CO_2 with either the formation water or the reservoir rock. The amount of chemical fixing and the reaction timescales depend on pore water chemistry, rock mineralogy and the length of the migration path (Czernichowski-Lauriol *et al.,* 1996). In some circumstances hydrodynamic trapping of the CO_2 may also have a part to play. Hydrodynamic trapping occurs when the natural flow in the aquifer is very low, reducing the movement of CO_2 allowing diffusion, dispersion and convection to come into play. (Bachu, Gunter and Perkins 1996), though this should perhaps not be relied upon as a primary sequestration mechanism.

In contrast to gas storage schemes in abandoned hydrocarbon fields, the effectiveness of the cap rock as a seal over the length of time required will not have been tested or demonstrated; significant research will normally be required to confirm this.

Storage of CO_2 in saline aquifers can be in both "confined" and "unconfined" aquifers *(see Fig. 2)*. Storage in confined aquifers relies on trapping of the buoyant CO_2 by structural (*e.g.* anticlines) and /or stratigraphic (*e.g.* sandstone pinchout) features, and is closely analogous to gas storage schemes in hydrocarbon fields, or indeed to natural gas storage in subsurface aquifers. In simple structural traps, volumes and migration pathways of the injected CO_2 can be predicted and reservoir models constructed with a higher degree of certainty than in an unconfined aquifer, where the lateral boundaries are not well known. The potential storage volume in such structural traps can be very large *e.g.* in the closed structures of Triassic rocks in the Southern North Sea. Here the Bunter Sandstone Formation has four-way dip closed anticlines formed by movement of the underlying Zechstein Salt into pillows and diapirs. In such cases it may not be necessary to utilise the entire capacity of the regional aquifer but only use the structural closures, therefore retaining large volume of CO_2 in defined areas. This may aid the monitoring of the CO_2 over large time scales. The estimated storage capacity of the Bunter Sandstone Formation (regional extent) is 620 000 Mt. Of that total storage capacity it is estimated 89 404 Mt of CO_2 could be stored in the closures alone.

Storage in unconfined aquifers involves the injection of CO_2 into large regional aquifers with no specific large structural or stratigraphic closures as a target. Once the CO_2 has been injected it migrates upwards along the most permeable pathway until it encounters the impermeable cap rock. This provides a barrier to further vertical movement; the CO_2 then migrates largely laterally, being driven by buoyancy to structurally higher levels along the cap rock-reservoir boundary
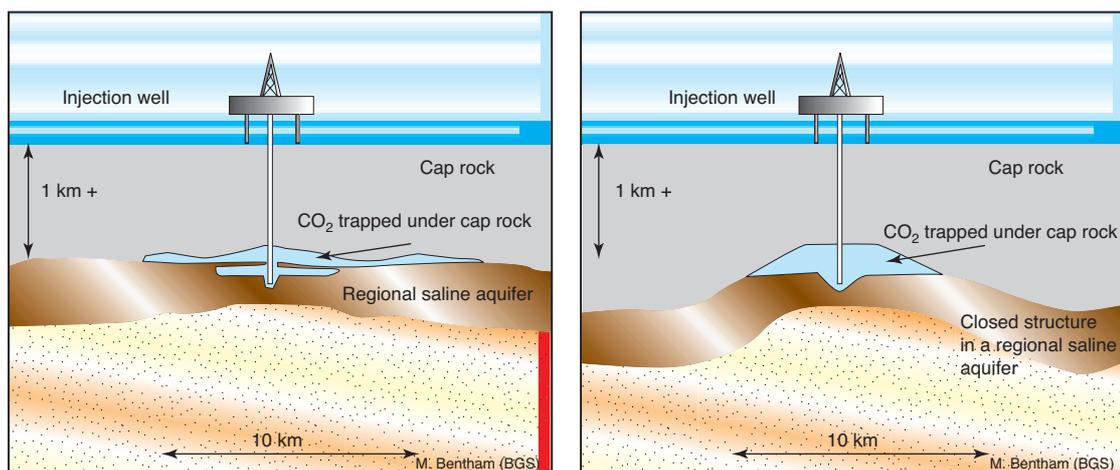

Figure 2

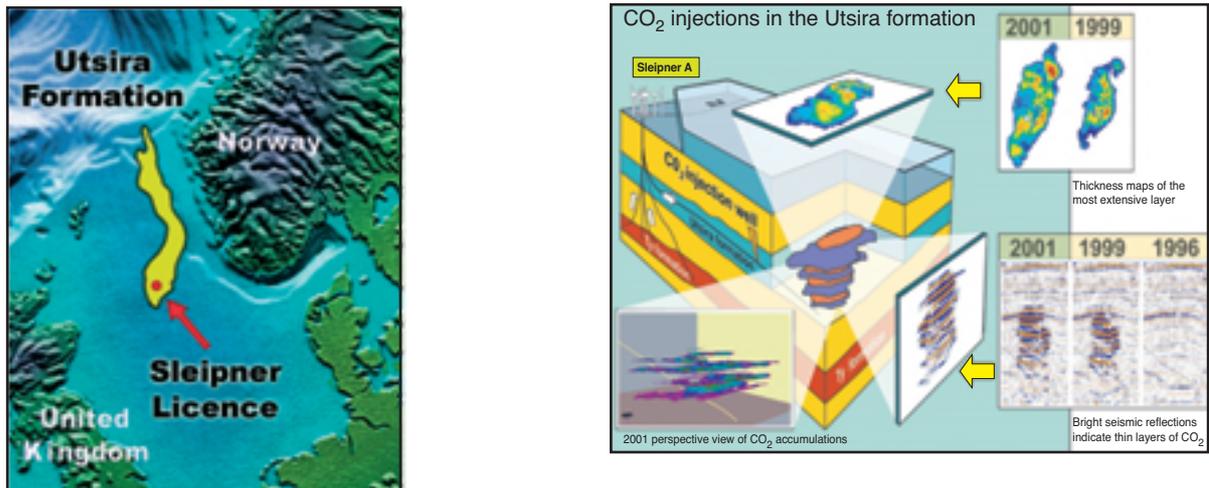Conceptual diagrams of storage in unconfined and confined aquifers.

Figure 3

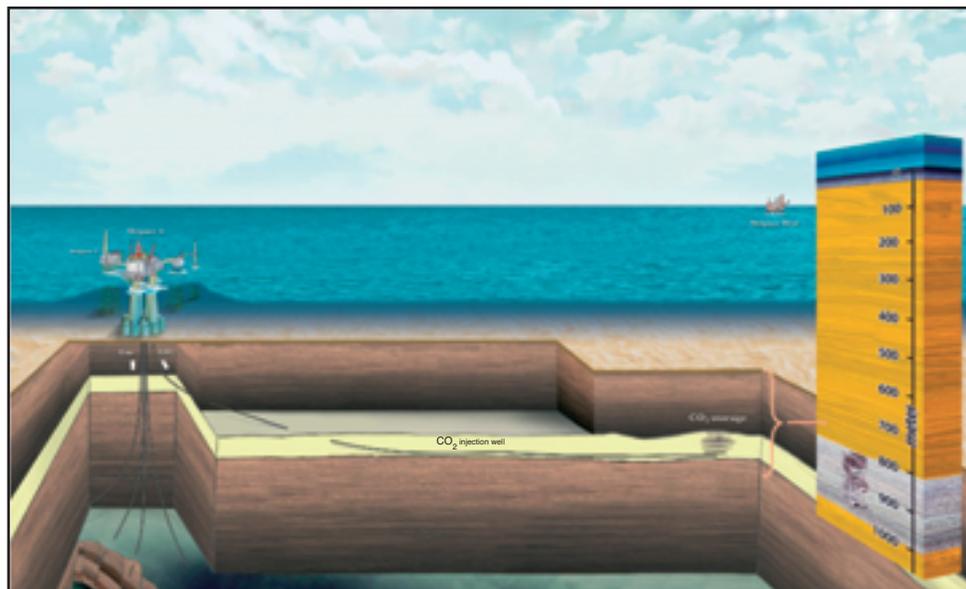Scheme showing the CO_2 injection and monitoring at Sleipner.

Figure 4

The Sleipner CO_2 injection project.

and following the most permeable pathways in the uppermost parts of the aquifer. As it migrates along the high permeability pathways, some of the CO_2 will fill small domes and undulations in the reservoir underneath the cap rock, effectively trapping a proportion of the injected CO_2. As these minor structural closures are filled, the CO_2 spills out and continues to migrate laterally. In unconfined aquifers therefore, it is likely that over time the CO_2 will become distributed over a large area and in low concentrations. The volumes of CO_2 that can be stored in these small perturbations on the top reservoir surface will depend on the average "roughness" (*i.e.* number of these traps per unit area) of this surface, but could be quite large if the CO_2 is distributed across a large area. The large area means that the reservoir model to determine likely migration routes needs to be similarly extensive. Just as with the confined case, these models will need to demonstrate that the aquifer is not juxtaposed with other permeable layers that might provide the CO_2 with a migration route to the surface, but because of the larger area considered, the possibilities of this are increased, and

detailed mapping to define likely migration paths is required. Because of the likely large migration path lengths, the component of storage due to dissolution is increased significantly, making it likely in many cases that in the absence of vertical migration pathways the CO$_2$ is unlikely to reach the surface.

This type of storage has been demonstrated at Sleipner *(see Figs. 3 and 4)*. Here CO$_2$ separated from natural gas produced at the Sleipner field (Baklid *et al.*, 1996) is currently being injected into the Utsira Sand, a major saline aquifer lying within the thick Cenozoic post-rift succession of the North Sea. Injection started in 1996 and is planned to continue for about 20 years, at a rate of about 1 Mt/y. The CO$_2$ injection point is at a depth of 1012 m below sea level with an estimated formation temperature of about 36ºC. Between this and the top of the reservoir at about 800 m, with an estimated formation temperature of 29ºC, the CO$_2$ forms a supercritical fluid with a roughly constant density of around 700 kgm^{-3}.

2 SPECIFIC RISKS FOR STORAGE IN SALINE AQUIFERS

2.1 Potential Conflicts of Interest

2.1.1 Gas Storage

In many European Union countries for example France and Germany, saline aquifers are used for natural gas storage. This may be in direct conflict of interest with CO$_2$ storage, especially for onshore closures.

2.1.2 Water Extraction

Some saline aquifers have both saline and non-saline water zones. For example the Bunter Sandstone Formation in the United Kingdom is saline offshore and onshore is dominantly a fresh water aquifer. The Bunter Sandstone is produced for drinking water supplies. It is unlikely that in such cases CO$_2$ would be allowed to be stored close to or in the potable water zone near water extraction boreholes. Storage of CO$_2$ in such areas may cause the mobilisation of brines or the migration of CO$_2$ into the drinking water supply.

2.1.3 Mining

Storing CO$_2$ in aquifers below mines may allow CO$_2$ to migrate into the mine workings if the storage site leaks.

2.1.4 Geothermal Energy

Some saline aquifers in Europe are also geothermal reservoirs. For Example the Paris Basin in France. Storing CO$_2$ in such aquifers may inhibit the use of the aquifer for geothermal energy, as this requires extraction of pore waters to surface, which would permit the CO$_2$ to revert to a gaseous phase and potentially escape to the atmosphere.

2.1.5 Hydrocarbon Production

Saline aquifers are often the host reservoir rocks for oil and gas fields. Although this is good evidence that they can store buoyant fluids and gas over geological timescales, it may also lead to conflict of interest in the subsurface where storage could interfere with oil and gas production.

2.2 Insufficient Data

2.2.1 Reservoir Properties and Modelling

In contrast to storage in abandoned oil or gas fields, where there is likely to be abundant core, geophysical logs, pressure measurements, both of the reservoir and overburden and seismic data, all of which can help to characterise the reservoir, saline aquifers are not likely to be as well-studied. Therefore reservoir characterisation and the building of a model to test migration paths will most likely require the acquisition of such data, thereby increasing costs significantly.

2.2.2 Cap rock Integrity

In abandoned hydrocarbon fields, the existence of a seal, at least to hydrocarbons, is demonstrated by the very existence of the field. This is not the case for aquifers, and although analogies are likely to be able to be drawn, determination of cap rock properties by testing and modelling is likely to be required

2.3 Aquifer Flow

Aquifer flow from areas of high pressure to areas of lower pressure is common. This will effectively increase the potential for dissolution of CO$_2$. This might be considered a benefit; however, if, as is likely, flow is towards the shallower part of the aquifer, this could provide a route for effective leakage of CO$_2$ either by flow to the surface, or to a position where a phase change to a gas is likely when the buoyancy is increased significantly and the potential for vertical migration through cap rocks is increased.

2.4 Security of Storage

Potential issues associated with the injection of CO$_2$ into a closed structure (*e.g.* a dome) developed in a saline aquifer are common to many different reservoir rocks whether in an abandoned hydrocarbon field or a saline aquifer, and are considered to be as follows.

2.4.1 Geochemical Issues

The chemical interactions with the injected CO$_2$ and the rocks and formation water in place are potentially of importance. The reactions that may occur are highly site

specific, and dependant on the geochemical conditions and on the relative abundance of the various primary minerals in the formation rock, these are likely to vary according to the exact mineralogy and petrography of the reservoir and cap rocks. Prediction of these is best constrained by geochemical experiments using physical samples of the specific rocks.

- Corrosion of the reservoir rock matrix by CO_2/water mixtures, leading to the compaction or collapse of the formation and thus to the development of cracks and new migration paths through the cap rock
- Dissolution of primary (native) minerals and precipitation of secondary minerals may occur; the precipitation of minerals in the pore spaces of the reservoir rock, leading to injection problems. This could mean that injection would have to be abandoned if a safe pore fluid pressure was likely to be exceeded.
- Dissolution of components of the cap rock by CO_2/water mixtures, leading to its collapse or failure as a seal.
- Dehydration of the cap rock by reaction with the dry injected CO_2 (dry to minimise well corrosion issues), leading to shrinkage and the creation of new pathways through it for CO_2.
- Dissolution of CO_2 into the pore fluid and transport out of the structure by natural or induced pore fluid flow.

It should be noted that some of these reactions may take a very long time, this makes simulation and data collection difficult to the relevant time scales difficult.

2.4.2 Pore Fluid Pressure Issues

Again, these problems are likely to be specific to individual situations, and the likelihood of any problems arising is best assessed by simulation in a reservoir model.

- Fracturing of the cap rock, due to increased pore fluid pressures in the reservoir.
- The opening up of pre-existing but previously closed migration paths (*e.g.* faults) through the cap rock, caused by increased pore fluid pressures during injection.
- Gas pressure in the CO_2 accumulation exceeding the capillary entry pressure of the overlying cap rocks, resulting in CO_2 transport through the cap rock (breaching).

2.4.3 Well Issues

It is unlikely that there will be many existing boreholes through the saline aquifer, unless targeted at deeper horizons, certainly far fewer than in an abandoned hydrocarbon field. However, for those that do exist, escape of CO_2 via poorly sealed pre-existing wells or by failure of the injection well is possible.

Escape of CO_2 due to corrosion of cement or steel in wells penetrating the storage structure or cement holding the borehole casing to the surrounding rock is also a possibility.

2.4.4 Other Issues

The presence of unidentified migration paths through the cap rock *e.g.* those below seismic resolution

Escape of CO_2 via a spill point at the base of the closed structure, *e.g.* due to underestimated viscous fingering or incorrect mapping of structural closure.

3 REGIONAL DISTRIBUTION

Saline aquifers occur throughout the geological column and in all sedimentary basins throughout the world, although reservoir properties vary widely, both aerially and stratigraphically. Globally therefore, deep saline aquifers have the largest storage potential of all of the storage options. Although the potential storage capacity is not ubiquitous from country to country, the countries surrounding the North Sea are particularly well endowed with potential capacity. Two large studies, the JOULE, II project (1996) and the GESTCO project (2003) have been undertaken to estimate the CO_2 storage capacities of several EU countries. A summary of the results is provided in the Tables 1 and 2.

Although these studies give a good overview of the size and relative storage capacities in the countries represented, it should be noted that the calculation method for storage capacity is not the same in each study or in each country. The studies do not provide a comprehensive coverage of all the storage potential in Europe. Case studies were used, especially in countries with a large storage capacity. As a result therefore it can be expected that more saline aquifers in Europe may have the potential to store CO_2. For example in the United Kingdom the Bunter Sandstone formation in the Southern North Sea was studied, but there may also be a large potential onshore in the Cheshire Basin, offshore in the Northern North Sea and the Irish Sea Basin.

The site-specific geological characteristics have not been studied in the estimation of overall storage capacity. When sites are identified and studied more closely it is likely that not all of the sites would be suitable for CO_2 storage. Each site has its own geological characteristics and should be investigated separately.

Another problem when calculating the storage capacities of saline aquifers is the amount of information available for saline aquifers is not as comprehensive as for oil and gas fields nor is the data of the same degree of coverage in all of the areas. There is more data in areas where there are hydrocarbons reservoirs or geothermal resources.

4 SPECIFIC COST ASPECTS

Table 1 shows the calculated costs of CO_2 capture and storage (ccs) from three studies. The costs of CO_2 capture and storage in a saline aquifer range from 13 to 100 €/t of CO_2 avoided. This range in values is largely dependant on

TABLE 1

CO$_2$ storage capacities of selected EU countries

Country	Saline aquifer storage (Gt)	Report
United Kingdom Southern North Sea	14.7	GESTCO
Selected Onshore and near shore aquifers Denmark	16	GESTCO
Germany	23-43	GESTCO
Offshore Norway (traps)	13	GESTCO
Offshore Norway (open)	278	GETSCO
The Netherlands	1.6	GESTCO
Greece	2.2	GESTCO
Belgium (Campine Basin)	0.1	GESTCO
Paris Basin:		GESTCO
Dogger aquifer,	0.008-4	
Triassic aquifer (Keuper and Bunter)	0.6-22	
Country	**Saline aquifer storage (Mt)**	**Report**
Denmark (onshore aquifers)	5596	JOULE 11
France (onshore in traps)	1527	JOULE 11
Germany (onshore in traps)	472	JOULE 11
Italy (onshore and offshore traps)	473	JOULE 11
Netherlands (onshore traps)	1014	JOULE 11
Norway (traps)	10852	JOULE 11
Norway (open)	475887	JOULE 11
Spain (traps onshore and offshore)	1466	JOULE 11
United Kingdom (traps)	8808.94	JOULE 11

the sources of CO$_2$ and the cost of capture *e.g.* the cheapest option is from a nearly pure source of CO$_2$ at an ammonia factory, where practically no capture is required. The third study has calculated the costs of CCS in a gas field in the United Kingdom and has been added for comparison.

In all the studies the cost of CO$_2$ capture and storage have been calculated in different ways. The costs are highly dependant on the source of CO$_2$ and the capture technology used. The proximity of the storage to the reservoir and the number of injection wells required are also major factors. When considering storage in saline aquifers it is unlikely there will be any existing infrastructure that can be reused, unlike in the case of using depleted hydrocarbon fields. All the costs of storage have been calculated for a single scheme from an emission source delivering CO$_2$ in a new pipeline to one storage site. Costs would be likely to decrease with an increase in the number of CCS schemes adopted.

Unlike using CO$_2$ for producing more oil in enhanced oil recovery, injecting CO$_2$ for pure storage in saline aquifers at the moment has no economic benefit, unless emitting the CO$_2$ to the atmosphere is taxed, as in the case at Sleipner. The economic viability of storing CO$_2$ in saline aquifers may increase when emissions trading of CO$_2$ commences (European emission trading scheme EU-ETS) in 2005 in Europe. CO$_2$ emissions will have a monetary value and volumes of CO$_2$ will be traded. Even with emission trading for saline aquifer storage to be economic it is likely that the CO$_2$ source would have to be close to the storage site.

5 KNOWLEDGE GAPS AND FUTURE RESEARCH (FROM RTD STRATEGY)

– Insufficient data for input into reservoir models. Stochastic models based on well-sampled examples of reservoir rocks have a significant and largely under-used potential.

– It is clear from the reports that CO$_2$ storage capacity has been calculated in different ways. For example whether the capacity of open and closed structure has been used and what the pore space saturation of CO$_2$ is. There is therefore some uncertainty in storage capacity. This is an area of possible future work to allow all of the separate case studies to be compared.

– Long term integrity of the sites. Unlike for conventional hydrocarbon gas storage, timescales are much longer. A cap rock that might be adequate for gas storage may not be adequate for CO$_2$ storage.

– Different lithologies: most studies have concentrated on sandstone reservoirs. The potential storage capacities, and specific issues related to carbonate reservoirs are largely untested and have not been quantified.

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TABLE 2

Costs of CO$_2$ storage in saline aquifers.

Report	Plant	Costs (€/t) Capture (Ca) Compression (C) Transport (T) Injection (I) Storage (S)	Emissions (t) Yearly/captured/avoided	€/t avioded	Country	Year of study
GESTCO	Coal fired power plant. Postcombustion capture	Ca 21.5 C 7.4 T 1.4 S 1.3	10314/11909/7856	31.6	Denmark	2003
GESTCO	NG-fired power plant. Post combustion capture	Ca 33.2 C 4.4 T 1.1 S 0.6	2969/3010/2545	39.3	Germany	2003
GESTCO	NG-fired power plant. Postcombustion capture	Ca 26.8 C 6.1 T 1.1 S 0.6	2969/2985/2528	34.6	Germany	2003
GETSCO	Sugar factory. Postcombustion capture	Ca 75.5 C 15.9 T 1.1 S 8.3	61.5//	100.8	Germany	2003
GESTCO	Ammonia plant. Pure source	Ca 0.6 C 7.2 T 3.4 S 2.6	166/166/150	13.8	Greece	2003
GESTCO	NGCC Postcombustion capture	Ca 76.3 C 13.5 T 13.2 S 2.5	401/415/311	105.3	Greece	2003
GESTCO	Oil Refinery. Postcombustion capture	Ca 27.5 C 7.4 T 2.6 S 8	1926/1985/1492	45.5	Norway	2003
GESTCO	NGCC. Postcombustion capture	Ca 38.7 C 5 T 7.4 S 7.2	2250/2333/1814	58.3	Norway	2003
GESTCO	Coal fired power plant. Post combustion capture	Ca 38.4 C 8.5 T 6.5 S 13.2	956/982/753	66.6	United kingdom	2003
GESTCO	NGCC. Post combustion capture.	Ca 35.1 C 9.1 T 4.4 S 2.6	5067/5791/3869	51.2	United kingdom	2003
JOULE 11	Pulverised fuel with Flue gas desulphurisation	Ca 57.35[*] C 11.75[*] S 0.49[*]	CO$_2$ avoided 7.8 Mt/y	69.53[*]	United Kingdom onshore aquifer	1996
JOULE 11	Pulverised fuel with Flue gas desulphurisation	Ca 87.35[*] C 14.48[*] S 2.25[*]	CO$_2$ avoided 7.8 Mt/y	74.08[*]	Utsira offshore aquifer	1996
Marsh et al.[**]	Coal fired power station retro-fit	Ca 7.6[***] T 4.5[***] I 1[***] S 26			United Kingdom	2003
Marsh et al.[**]	New build IGCC	Ca 7.4 T 5.7[***] I 1[***] S 15			United Kingdom	2003
Marsh et al.[**]	New build GTCC	Ca 7.4 T 5.7[***] I 1[***] S 27			United Kingdom	2003

[*] Calculated in Ecu £1 = 1.3 Ecu   [**] Offshore depleted gas field no secondary recovery - similar costs to saline aquifers?   [***] In £t.

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