Geological Storage of CO_2 from Combustion of Fossil Fuel

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SUMMARY REPORT
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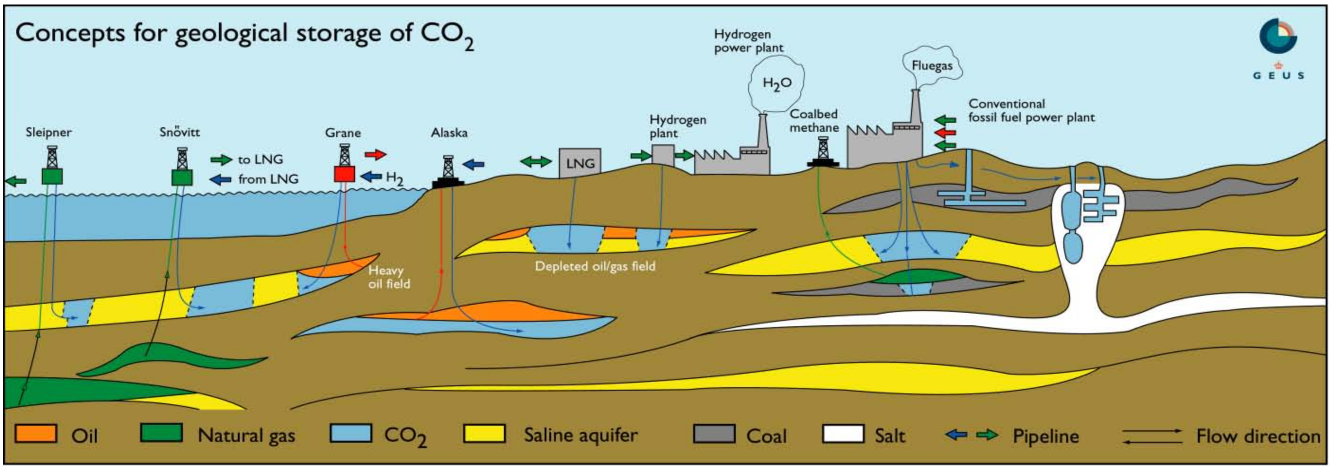

Assessing European Potential for Geological Storage of CO_2 from Fossil Fuel Combustion

Is geological storage of CO_2
a viable method capable
of wide-scale application?

PARTNERS

END-USERS, ASSOCIATES & CONTRACTORS

The GESTCO project

Summary Report

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Foreword

GESTCO is an acronym for European Potential for the Geological Storage of CO_2 from Fossil Fuel Combustion. The GESTCO project started on 1st March 2000 and ended on 28 February 2003.

This report is the published product of a study by Danmark og Grønlands Geologiske Undersøgelse (GEUS), British Geological Survey (BGS), Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Bureau de Recherches Géologiques et Minières (BRGM), Ecofys, Geological Survey of Belgium (GSB), the Greek Institute for Geology and Mineral Exploration (IGME), Norges Geologiske Undersøgelse (NGU) and the Netherlands Institute of Applied Geoscience (TNO-NITG). Valuable contributions to the project were made by Flemish Institute for Technological Research (Vito, Belgium), Public Power Corporation of Greece, Compagnie Française de Geothermie (CFG), Danish Oil and Natural Gas Company (DONG), CE-Transform (Netherlands) and the Tyndall ºCentre (UK).

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The goals of the GESTCO project

The primary goal of the project was to determine whether the geological storage of carbon dioxide captured at large industrial plants is a viable method of reducing greenhouse gas emissions capable of widespread application in Europe.

This was established by a series of case studies that evaluated the CO_2 storage potential of saline aquifers, geothermal reservoirs, coal seams and oil and gas reservoirs. The case study approach was used so that currently available, largely theoretical generic information could be applied to real geological situations. This resulted in more rigorous identification of the important issues, which will enable any necessary further research or development to be better focused.

In addition the economic aspects and aspects of safety and environment, conflicts of using underground space and public and stakeholder perception were evaluated.

Secondary goals of the GESTCO project were to establish a CO_2 storage GIS for Europe and a Decision Support System (DSS) to serve as an economic analysis tool for CO_2 storage in Europe.

1 Introduction

The project was divided into the following topics:

- An inventory of industrial point sources of CO_2 in Europe
- Case studies of geological storage of CO_2 in Europe
- Production and population of a CO_2 storage GIS for Europe
- Construction of a Decision Support System (DSS) for use as an economic analysis tool
- Analysis of sequestration systems (source – transport route – sink combinations) using the DSS
- Analysis of potential storage security issues and potential conflicts of use of the subsurface
- Analysis of public outreach
- Discussion as to whether CO_2 storage is a viable method of reducing greenhouse gas emissions capable of widespread application in Europe
- Conclusions
- Recommendations

The countries participating in the project were Belgium, Denmark, France, Germany, Greece, the Netherlands, Norway and UK. A full list of the reports produced in the GESTCO project is given in Appendix II.

2 Inventory of major industrial sources of CO_2 in participating countries

Major industrial sources of CO_2 in the participating countries were identified and compiled into a database. Table 1 shows the annual emissions of CO_2 from major industrial point sources emitting >100,000 tonnes CO_2 per year in the participating countries (>20,000 tonnes in Norway). Note that these figures vary slightly from year to year.

Table 1. Annual total CO_2 emissions and emissions from major industrial point sources in participating countries

Country	Annual CO_2 emissions (10^6 tonnes)	
	Major industrial point sources	Total emissions (IEA, 1998)
Belgium	75	122
Denmark	29	60
France	191	413
Germany	393	886
Greece	43	100
Netherlands	96	181
Norway	23	42
UK	218	546
Total	**1068**	**2350**

In 1990, the Kyoto Agreement basis year, EU-15 CO_2 emissions were about 3324 million tonnes. The EU Kyoto commitment is an 8% reduction of greenhouse gas emissions to be achieved between 2008 and 2012. To fulfil this first modest target, an annual reduction of some 334 million tonnes of CO_2 equivalent is required with respect to the 1990 emission level.

In almost all countries, the major sources of CO_2 are power plants, integrated steel plants, refineries/petrochemical complexes and cement works. The exception is Norway, which relies almost entirely on hydropower for electricity production. In Norway, many of the major sources of CO_2 are generators at offshore oil and gas fields. The location and details of the sources of CO_2 are accessible via the Gestco web-enabled GIS at http://www.bgs.ac.uk/gestco/

In many countries, a relatively small number of industrial point sources account for a significant proportion of the total CO_2 emissions. For example, in the UK the 20 largest sources produce about 132 million tonnes CO_2, almost 24% of the UK total annual emission of 558 million tonnes (2000 data). This indicates, that a significant reduction in total national emissions could be achieved by adapting a relatively small number of plants for CO_2 capture and storage.

3 CO_2 Storage in oil and gas fields

Although the potential storage capacity of deep saline aquifers is many times greater than that of hydrocarbon structures, there are some distinct advantages of using depleted hydrocarbon fields as storage sites:

- The hydrocarbon fields have proved their capability to retain fluids and gases, in many cases for millions of years.
- The reservoir is well understood due to the intensive data gathering prior to and during the producing life of the field.
- Infrastructure for the production and transport of fluids and gases is already in place. With all necessary workovers and modifications, this infrastructure might be partly re-used to deliver and inject CO_2 for storage in such fields.
- The natural-gas industry has routinely used depleted gas fields for the underground storage of natural gas (UGS).
- The oil industry has routinely, but nearly exclusively confined to North America, used CO_2 injection for enhanced oil recovery (EOR). In some cases, the benefits of incremental oil production could more than offset the costs of CO_2 capture and injection.

In many gas fields, production of gas occurs mainly because the natural gas pressure found in the untapped reservoir is much greater than atmospheric pressure so gas flows to surface via the production wells and the reservoir pressure is gradually depleted (this is known as depletion drive). Even though the gas pressure in the pore space is depleted, in some fields little or no water flows into the pore spaces of the reservoir rock (there is low water drive) and although there may be some compaction of the reservoir rock as a result of the lowering of fluid pressure within it, the combined effect of water inflow and compaction may only reduce the reservoir pore volume occupied by low pressure gas by a few percent. At least some of the major gas fields in the southern North Sea are of the depletion drive type. Gas production from these fields has created a significant volume of low-pressure gas-filled pore space in the field, which subsequently can be filled with CO_2.

The CO_2 storage potential of the hydrocarbon fields of Denmark, Greece, Germany, the Netherlands, Norway, and the UK including the North Sea region was investigated. The potential of oil and gas fields was analysed with one consistent method for all countries enabling mutual comparison of the calculated storage potential. Based on the 1:1 volumetric replacement of recoverable reserves of oil and gas by CO_2, the storage potential of the oil and gas fields in these countries is shown in Table 2. Also shown are current national CO_2 emissions from industrial point sources and the approximate number of years storage capacity available for these emissions in the oil and gas fields. The approximate number of years storage capacity is based on 1.3 times the current emissions because extra CO_2 will be generated by the capture process.

The assumption of 1:1 volumetric replacement indicates the maximum theoretical storage capacity of the fields used in the GESTCO work. In reality, capacities may in some cases be higher. In gas fields it assumes that there is no residual gas saturation, no water influx into the field, no compaction of the reservoir rock and 100% CO_2 sweep efficiency. For oil fields it has been assumed that storage operations would commence only after oil production has ceased. Any EOR potential would be part of the oil production operation and CO_2 consumption/storage from such activities would thus be in addition to the potential estimated in this study.

Table 2. Maximum potential CO_2 storage capacity of the oil and gas fields of selected European countries compared to their annual emissions from major point sources.

Country	Oil fields (10^6t CO_2)	Gas fields (10^6t CO_2)	Total storage capacity (10^6t CO_2)	Annual point source CO_2 emissions (10^6t CO_2)	Number of years storage capacity from current point sources (approx.)
Denmark	176	452	628	29	17
Germany	103	2227	2330	393	5
Greece	17	0	17	43	0.3
Netherlands	54	10907	10961	96	88
Norway	3453	9156	12609	23	422
UK	3005	7451	10456	218	37
Totals	**6808**	**30193**	**37001**	**802**	

The totals include all gas fields with ultimately recoverable reserves (URR) >2 x 10^9 standard cubic metres (scm) and all oil fields with URR >1 x 10^6 scm. Only Hydrocarbon fields south of 67ºN are included for Norway.

It is not known how much of this potential storage capacity is actually likely to be deployed for CO_2 storage. This is largely a question of economics, potential conflicts of use, public acceptance and safety and security of storage:

Firstly, all of the potential CO_2 storage capacity in oil and gas fields in Denmark, Norway, Greece and the UK lies offshore. In practice there may well be only a relatively short window of opportunity to exploit the storage capacity of the offshore fields. Once the production infrastructure has been removed the opportunity may be lost because the costs of installing new field infrastructure may be prohibitive. Furthermore, much of the UK storage capacity in oil and gas fields lies in the northern and central North Sea – at very long distances from most European point sources. Some kind of common CO_2 infrastructure e.g. that proposed by the CENS project would be required for full utilisation of North Sea oil and gas field CO_2 storage capacity (http://www.ieagreen.org.uk/sep62.htm).

Secondly, onshore (and some offshore) fields may have an alternative use – as natural gas storage facilities. Most of the potential storage capacity in the Netherlands (70% or approximately 7500 million tonnes) lies in the Groningen field. It is not known whether this will have an alternative use. This giant field is, however, expected to produce natural gas for several decades to come and consequently will not be available for CO_2 storage during that period.

Thirdly, in the long term, even the gas fields with depletion drive will presumably suffer significant water encroachment and will possibly lose some of their CO_2 storage potential in those situations where the aquifer encroachment cannot be reversed.

Finally, concerns about safety and security of storage in depleted fields need to be considered. However, the success of natural gas storage facilities in disused gas fields suggests that leakage should not be an insuperable problem providing wells can be effectively sealed for the necessary very long time frame.

The main geological barriers to utilisation of the oil and gas fields for CO_2 storage was perceived to be the possibility of leakage through disused wells or through new migration paths created because of damages to the cap rock as a result of production operations or chemical reactivity with CO_2.

4 CO_2 Storage in aquifers, including geothermal aquifers

The CO_2 storage potential of selected saline aquifers in and surrounding the Southern North Sea was investigated in nine case studies. Some of these studies, e.g. the studies of Danish and Norwegian aquifers, confirmed that there is significant potential to store CO_2 in selected saline aquifers. Others, e.g. the study of the Bunter Sandstone Formation in the UK sector of the southern North Sea, indicate that further detailed work is required before significant storage capacity can be confirmed. In particular it is necessary to reduce uncertainties regarding storage structure integrity and the volumes of CO_2 that could be injected without unacceptable pressure rise. Identified storage capacity is summarised in Table 3. Note that in most cases these figures apply to selected areas only of the participating countries. The studies of aquifers in Belgium, the Paris Basin of France, onshore eastern England, and the Netherlands onshore suggest that at best there are only niche opportunities for CO_2 storage underground in these areas.

Table 3. CO_2 storage capacity of selected aquifers in participating countries.

Case study area	**CO_2 storage capacity (Gt)**	**Storage capacity from point sources[1]**	**Comments**
UK sector, southern North Sea	Up to 14.7	Up to 51 years	Detailed study of integrity and injectivity of individual storage structures in the Bunter Sandstone Fm required to firm up potential
Selected onshore & near shore aquifers, Denmark	16	424 years	Study focused on 11 individual storage structures (structural traps)
Germany	23 to 43	45 to 84 years	Capacity mainly located within the North German basin
Offshore Norway	13 (in structural traps)	435 years (point sources >20 000 t/year)	Estimated potential of >286 Gt if storage is not in conventional traps for buoyant fluids
Netherlands entire onshore and offshore area	1.6	13 years	Potential for traps either calculated on the basis of identified traps or on the basis of an extrapolated volumetric trap percentage. Capacity includes potential of 2 mega-traps
Greece, entire onshore and offshore area	2.2	39 years	
Campine Basin, Belgium	0.1	1 year	Potential conflict of interest with natural gas storage
Paris Basin • Dogger aquifer • Triassic aquifer (Keuper & Buntsandstein)	 0.008–4 0.6–22	More than 3 years in total	Upper range for entire aquifer. Lower range for well-known recognized structural traps.
Geothermal aquifer, Copenhagen area	Uncertain	Not determined	Geothermal drilling in 2002 proved several high quality reservoirs, but a volumetric estimation of storage potential cannot yet be made

[1] The CO_2 emission of point sources was multiplied with 1.3 correcting for the efficiency loss due to the capture process.

The studies of geothermal aquifers (Paris Basin and Denmark) concluded that there were no significant advantages in injecting CO_2 in the return well of a geothermal doublet. The rate of injection was too low to be of interest for significant CO_2 sequestration and the volumes of CO_2 that possibly could be stored would be marginal. High well re-completion cost would be an additional obstacle. It was thus concluded that storage of CO_2 in conjunction with geothermal plants, from a volumetric point of view, would be of little overall importance, but could be of interest as a local option.

In addition to the volumetric estimates of storage capacity special attention was given to the chemical impact of CO_2 injection into carbonate rocks.

The case-study of the Dogger geothermal aquifer in the Paris Basin indicated that for this carbonate aquifer there is no significant CO_2 trapping by mineral precipitation. Indeed, coupled thermal-hydro-geochemical modelling of a geothermal doublet scenario makes it possible to show that, in the case of an injection of fluid saturated with CO_2 (0.92 mol/kgw), with a pressure of 160 bars, the solution pH would reach values of 3.6, typical of very aggressive water. This pH would involve the dissolution of carbonates near the injection well and could involve a risk of loss of the well. Carbonate precipitation would occur downstream but would be relatively limited. Thus, for 18,000 t of CO_2 injected over 20 years in the portion of reservoir modelled, 400 t would be mineralogically trapped at the end of 20 years of injection whereas more than 17,000 t would be released at the production well. The remaining 600 t would stay dissolved in the aquifer. However, the extreme conditions of the modelling do not allow a definitively negative conclusion as for the capacities of CO_2 geochemical trapping within a geothermal doublet in a carbonate aquifer. The simulation was carried out along a stream tube representing only 1% of the reservoir volume concerned with the geothermal loop and for the most direct path between the injection and production wells.

The case-study of the chemical and physical interaction of CO_2 and carbonate rock found that theoretical studies, experiments and observations from CO_2 injection in enhanced oil recovery operations suggest that there will be some dissolution of carbonate reservoir rocks in response to CO_2 injection. However, the amount of dissolution appears to be case-specific and it may not always be important. The response of dolomite reservoir rocks to up to 30 years of CO_2 injection in the Permian Basin, Texas, has, in general, been relatively minor. There has been some dissolution but not enough to compromise the stability of the reservoirs or interfere significantly with operations.

Laboratory experiments on Chalk from the Linde 1 well in Denmark resulted in restricted calcite dissolution that would not result in geomechanical instability of the rock. On the other hand "immediate and vigorous dissolution reactions with large axial strains and high strain rates" took place in laboratory experiments when Chalk from the Ekofisk field [North Sea, offshore Norway] was injected with CO_2-charged water. This does not bode well for CO_2 injection into North Sea Chalk fields. The major differences in results from these two studies of the effect of CO_2 injection on Chalk reservoirs, indicate that great care has to be taken to match the carbonate lithology and reservoir conditions of the potential reservoir in any experiments undertaken to determine the likely effect of CO_2 injection on carbonate rocks.

5 CO2 Storage in coal seams, coal mines and other mines and man-made cavities

The storage of CO_2 in coal seams is considered possible because CO_2 has an affinity to be adsorbed onto the macerals of coal. This affinity is greater than that of the methane (coalbed methane) that commonly occurs in nature adsorbed onto coal. Thus it may prove possible to use CO_2 to enhance coalbed methane production from coal seams whilst at the same time sequestering CO_2.

In theory, at least twice as much CO_2 would be sequestered in the coal seams as would be liberated to the atmosphere by burning the produced methane. Because the CO_2 would be adsorbed onto the coal it would be stored in a more stable way than if it was a free gas in the pore spaces of a conventional sandstone or carbonate reservoir rock.

This has led to the hypothesis that it might be possible to enhance the production of coalbed methane and at the same time sequester carbon dioxide by injecting flue gas into coal seams.

The development of CO_2-enhanced coalbed methane production (ECBM) technology is at an early stage and technical uncertainty remains. For example, the injection of CO_2 into coal seams is dependent on the presence of sufficient permeability in the seams. A value of more than 1 Millidarcy permeability has been suggested as a minimum requirement for economic (ECBM) production.

The *in situ* permeability of the Carboniferous coal seams of Europe is thought to be generally low and in many areas possibly too low for ECBM. The absence throughout Europe of economically viable coalbed methane production from virgin coal seams despite the abundant evidence of high methane content is mainly due to low permeability and low gas saturation.

The *case-study of the potential to sequester CO_2 in the Campine coal basin* in Belgium indicates that 432 million tonnes of CO_2 could be stored associated with ECBM. The *case-study of the storage potential in coals of the Netherlands* resulted in a capacity of 173 Mt CO_2 in ECBM operations at depths of less than 1500 m. A capacity of 850 Mt was calculated for the depth window of 1500 to 2000 m.

The theoretical potential for storage of CO_2 in coal mines varies across the participating countries. It technically depends on the degree of isolation of abandoned coal mines and the depth of closure. However, in order to store large volumes, overpressured conditions (i.e. pressures greater than hydrostatic) would be required in order to facilitate injection of CO_2 into the coal seams. In Belgium the main uncertainty is the sealing capability of the overlying Chalk strata under overpressured conditions. *A case-study of the Belgian Beringen-Zolder-Houthalen collieries* shows that sequestration in these coal mines is a viable option. At an injection rate of 300 000 ton/y, sequestration can be guaranteed for about 25 years. This is a conservative estimate, and it may prove possible to inject at 500 000 ton/y for 25 years, provided that injection would start before flooding of the mines. These are considerable contributions, approximately 3 to 6 % of the mitigation required to reach the Kyoto-target of Belgium, relative to the 1990 emission level.

In Germany and the UK there is abundant evidence of gas leakage to the ground surface in the major coal mining areas. This alone would prevent the storage of CO_2 in the mines in these countries because of the risk of asphyxiation if the CO_2 leaked into the built environment. In the UK, minewater recovery (the natural recovery of water levels in the workings to the level of the local water table or any drainage soughs installed in the mines) gradually drives out any free gas retained in the coal mines at the end of coal production. This would preclude the storage of free CO_2 in the mines although CO_2 eventually may be adsorbed onto the coal in seams surrounding the extracted seam(s).

It might be possible to store free CO_2 in certain salt mines. However, a *study of German abandoned salt mines* indicated that these generally have other uses that may be considered to have higher priority, e.g. storage of toxic or various levels of radioactive waste.

Relatively small volumes of CO_2 can be stored in solution-mined salt cavities. Purposely made solution salt cavities are, however, quite expensive to make and are primarily used as storage facilities for short term variations in consumption. Natural gas and hydrogen are thus stored in this way.

6 Safety and security of storage and potential conflicts of use

The case-studies of *safety and security of storage in Germany* and *potential conflicts of use in Germany* indicate that these subjects are dependent on the inter-relationships between geological, societal, technical and economic factors affecting CO_2 storage underground. For example, the legal issues and the degree of public acceptance will affect the planning and regulatory requirements, which in turn will affect the economics of storage. Human intrusion, either accidental or deliberate, for example the destruction of wellheads is likely to be a legal consideration.

The *case-study of safety and security of storage in Germany* indicates that the injection of CO_2 onshore in Germany may be subject to mining law and water legislation. The federal water framework law (Wasserhaushaltsgesetz) prohibits injection or storage of substances that could cause negative alterations of groundwater properties. From the legal point of view saline brines in deep aquifers are groundwater. Thus, by analogy with the case of aquifer storage of natural gas, there is the necessity to comply with both, and obey the rights of land owners affected by the proposed storage.

Low leakage rates, causing annual losses in the order of less than 0.1% to 0.01% are necessary for stored CO_2 because of the very long time frames (i.e. hundreds or thousands of years) for which storage may be required. This means that the injection process has to be monitored and has to be controllable, and long term liability may need to be accepted by the state. Considerable experience exists in a number of the countries regarding transfer of liabilities and monitoring of abandoned mines.

The storage of CO_2 in abandoned salt mines in Germany is subject to conflicts of use with storage of waste. The storage of CO_2 in gas fields is subject to conflicts of use with the seasonal storage of natural gas. According to federal mining law, deep saline aquifers are deposits of geothermal energy and brines, which may be used for table water production, in spas, or as a source of base material for the chemical industry. The mining law is intended to give protection to resources, and may give priority to uses other than CO_2 storage. Furthermore, in North Germany natural gas is stored in aquifers at four locations. The down-dip catchment area of these existing storage structures cannot be used for CO_2 injection.

CO_2 sequestration activities on the land surface are – at least temporarily – in conflict with land use. Pipelines, injection and monitoring wells and surface installations may not be allowed within groundwater protection zones, protected natural reserves, and waste deposits. It may also be difficult to obtain permissions from property owners in urban, military, and industrial areas to build or operate surface infrastructure. Also, considerable parts of the land surface will not be available or will be difficult to use in both densely populated and rural areas. Areas of ecological importance cover large parts of northern Germany. Activities in these areas are either affected by various degrees of restrictions or they have a declared preferential use.

The *case-study of security of storage in the Bunter Sandstone of the UK sector of the southern North Sea* indicated that potential security of storage issues associated with the injection of CO_2 into a closed structure (e.g. a dome) developed in a reservoir rock are as follows:

Geochemical issues

- 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.

- 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, leading to shrinkage and the creation of new pathways for CO_2 through it.
- Dissolution of CO_2 into the pore fluid and transport out of the structure by natural or induced pore fluid flow.

Pore fluid pressure issues

- Fracturing of the cap rock, due to increased pore fluid pressures in the reservoir.
- The opening up of pre-existing but 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.

Well issues

- Escape of CO_2 via poorly sealed pre-existing wells or by failure of the injection well.
- 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. The highly saline pore water in the Bunter Sandstone is likely to be made more aggressive towards steel, and certainly more aggressive towards cement, by the addition of CO_2. However, at present very little is known, and nothing has been published, about the state of casings or cement plugs and bonds in the exploration and production wells in the southern North Sea, even though some have been in place for nearly 40 years. It is recommended that a materials selection study to identify suitable cements and borehole casings for CO_2 injection wells be undertaken.

Other issues

- The presence of unidentified migration paths through the cap rock.
- 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.
- Displacement of highly saline brines from the storage location.

It concluded that, providing adequate characterisation of the storage site is undertaken before injection starts, the most important concerns are (1) that there may be unidentified migration paths out of the structure and (2) concerns related to injectivity, in particular the potential for undesirable rapid pore fluid pressure rises to occur in the reservoir. Among the latter, there is a risk that unidentified permeability barriers may occur within the reservoir, effectively dividing it into compartments or reducing its permeability on the macro-scale. These could be either stratigraphic barriers (such as shales), fault-related barriers, or barriers resulting from pervasive cementation e.g. by salt (halite). This could result in the threshold reservoir pressure being reached very early and the possible failure of the project. It might also result in the opening of pre-existing faults. The best way to resolve this question would be by injection tests into the reservoir rock. However, these are likely to be extremely costly offshore.

There is a risk that salt will be precipitated and fill the pore space near the well as a result of water dissolving into the dry CO_2 injected down the well. This could possibly be remedied by injecting fresh water that would dissolve the salt cement. However, large quantities of fresh water are not easily available offshore. Alternatively this problem could be overcome by induced hydraulic fracturing combined with fresh water ‘washing’ using only limited amounts of fresh water.

The *case-study of a hypothetical ECBM project in Scotland* found that there had been only one ECBM pilot project in operation world wide from which significant results have been published. Thus there is very little practical experience of injecting CO_2 into coal seams and very little realistic knowledge of the practical safety and security of storage issues. The major issues highlighted in the case study are:

- Poor understanding of the physics and chemistry of $CO_2/CH_4/N_2$ adsorption onto and desorption from coal.
- The potential for CO_2 leakage. E.g. via hydraulic fractures induced in the coal seams to increase injectivity, faults or mining-induced cracks in the Coal Measures strata.
- The potential for CH_4 leakage. CH_4 is a much more powerful greenhouse gas than CO_2. Escape of even proportionally small amounts of methane could reduce the atmospheric benefits of storage of CO_2.
- Sterilisation of a potential energy resource. Coalbed methane accounts for only about 5% or less of the energy value of coal. Any attempt to mine or gasify the coal in situ after CO_2 storage would most likely lead to release of the CO_2 unless it was re-stored. Also CO_2 storage on coal could lead to conflicts of interest with the mining industry and any future Underground Coal Gasification (UCG) industry.

7 The CO_2 storage GIS

The objective for the GESTCO GIS was to produce a Geographical Information System that would incorporate the wide range of data provided by the project partners and allow meaningful access to the data.

The GIS allows users to simultaneously view one or more layers of data including the location of the CO_2 sources and possible CO_2 sinks. It also enables the user to perform extensive on screen analysis on all the available data.

Geoscience datasets included in the GIS comprise: location of potential aquifer storage sites, designated injection points in aquifers, hydrocarbon field locations and hydrocarbon field injection points, coal mines, coal fields and potential coal field injection points as well as the locations of the CO_2 sources, existing pipelines and pipeline terminals. Many other datasets have also been provided to enhance the capabilities and information held within the GIS, for example geological, tectonic zone and ecosystem data.

Other additional features within the GIS include links to external websites that contain relevant information; for example the websites of the Partners involved in the project.

Copyright information is also a feature of the GIS. Users must agree to abide by the copyright of the data before the GIS will open fully and there is also the ability to access the copyright information from within the GIS should users wish to read it again.

Case study data
Many case studies have been carried out for the project and the data from these has been included in the GIS. As this data has been provided in many different formats and is specific to particular case studies this data has not been merged into single datasets as with the general GIS datasets. There are many maps and diagrams that have been provided for the case studies, as it is highly useful to be able to view such maps, diagrams and seismic profiles, from within the GIS, hyperlinks have been set up. This enables the user to click on a feature with the hyperlink tool and view any maps or documentation associated to the feature.

GESTCO WebGIS
It was decided that the best way to allow the project partners and end-users to monitor the progress of the data collection was to set up a web-based GIS system. The GESTCO webGIS was developed using ESRI's ArcIMS® software, which allows the easy dissemination of GIS data over the Internet. The webGIS does not have the full functionality of the GESTCO GIS, however it does allow users to view the datasets on screen and perform simple queries on the data. The webGIS also became a very useful resource towards the end of the project when it was used by the project partners to do the final checks on the data they had provided in the preceding 3 years [www.bgs.ac.uk/gestco].

8 The Decision Support System and analysis of the economics of CO_2 sequestration

The GESTCO DSS

The Decision Support System (DSS) consists of a GIS front end, covering Europe and populated for the countries participating in the GESTCO project, and underlying calculation modules. A database with all relevant data is coupled to the DSS. The graphical user interface of the DSS enables the operator to select a source of CO_2 and a potential sink. The DSS determines if the storage potential of the selected sink is sufficient. If it is, an optimisation routine calculates the best transport route for the CO_2 using a cost grid of geographic factors such as topography, urbanisation, river crossings, the location of existing pipeline routes and pipeline landing points. The calculation modules allow the operator to calculate the costs of CO_2 separation, compression, transport and injection into the subsurface. Finally the cash flow calculations are performed in an Excel workbook that is linked to the DSS

The CO_2 sources in the Gestco GIS consists of existing, real sources of CO_2. This has a profound effect on the economics of CO_2 capture and storage because analysis of the costs associated with these plants, by definition, require retrofitting for CO_2 capture. Clearly this may not always be the most cost-effective method of CO_2 capture.

Analysis of costs using the DSS indicated total average costs for post-combustion capture and storage (for reasonable plant sizes, operational hours, transport distance, etc, *but for existing plants*) range between 100 and 14 €/tonne CO_2 avoided.

The economical evaluation comprises

- calculation of the cost of capture for all sources in the GESTCO source database
- uncertainty analysis and sensitivity analysis of the four sequestration system elements, i.e. capture, compression, transport and storage of the carbon dioxide.
- case studies using the GESTCO-DSS application for specific sequestration systems in the European countries participating in the GESTCO project. The case studies are based on existing carbon dioxide sources and real reservoirs that are suitable candidates for the storage of the captured carbon dioxide.

Capture costs

For over 350 power supply installations in the eight European GESTCO countries the carbon dioxide capture costs were determined using the GESTCO-DSS. The capture costs include all costs to separate the carbon dioxide from the energy conversion process and exclude compression, transport and storage costs. The costs are calculated for the post-combustion capture method using the amine absorption technology and the pre-combustion method. In addition for approximately 340 industrial installations the capture costs were also computed. For the industrial installations, the costs are calculated for the post-combustion capture method using the amine absorption technology. The cost calculations are performed using the default parameter values in the GESTCO-DSS.

Cost analysis

Figures 1 and 2 show the capture costs per Mg of carbon dioxide avoided for the power installations (1 Mg = 1 tonne). It should be noted that the cost calculations for each power installation are performed twice. Therefore, the cumulative amount of carbon dioxide avoided depicted in the two figures should not be summed up. Table 4 presents the avoidance potential per sector together with the average capture costs. Distinction is made as to type of installation and type of fuel used.

Figure 1.
Cost curve for carbon dioxide capture costs for power installations in the GESTCO source database using the <u>post-combustion method</u> based on amine technology
(1 Tg = 1 Mtonne)

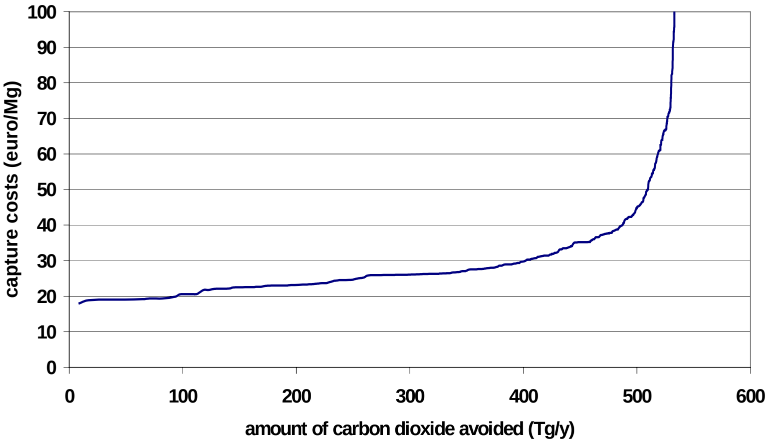


Figure 2.
Cost curve for carbon dioxide capture costs for power installations in the GESTCO source database using the <u>pre-combustion method</u> (1 Tg = 1 Mtonne)

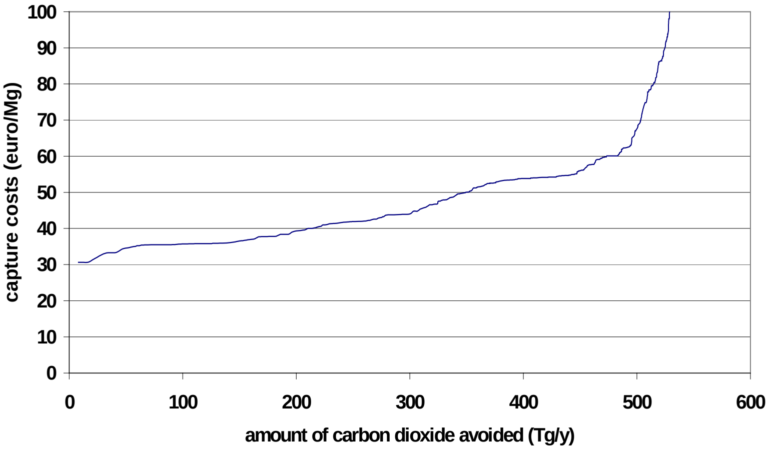


Table 4.
Average costs of capture at power installations in the GESTCO source database
(1 Tg = 1 Mtonne)

	avoided emission	average size of emission	avoidance costs (pre-combustion)	avoidance costs (post-combustion)
	Tg/y	Tg/y	euro/Mg	euro/Mg
all plants	534	1.5	47	28
by technology				
conventional boiler	417	2.1	47	26
combined cycle	117	0.8	45	37
by fuel				
coal	395	3.0	45	25
gas	113	0.6	52	38
oil	27	0.9	48	35

Figure 3 and Table 5 show the capture costs per Mg of carbon dioxide avoided for *industrial* installations. In total about 230 Tg (1 Tg = 1 Mtonne) of carbon dioxide can be avoided at average costs of about 26 euro per Mg of carbon dioxide avoided. About 13 Tg can be captured from industrial installations against avoidance costs of about 1 euro per Mg CO_2 avoided. The low-cost opportunities can mainly be found at hydrogen and ammonia production facilities.

Figure 3.
Cost curve for carbon dioxide capture costs for industrial installations in the GESTCO source database using the post-combustion method based on amine technology (1 Tg = 1 Mtonne)

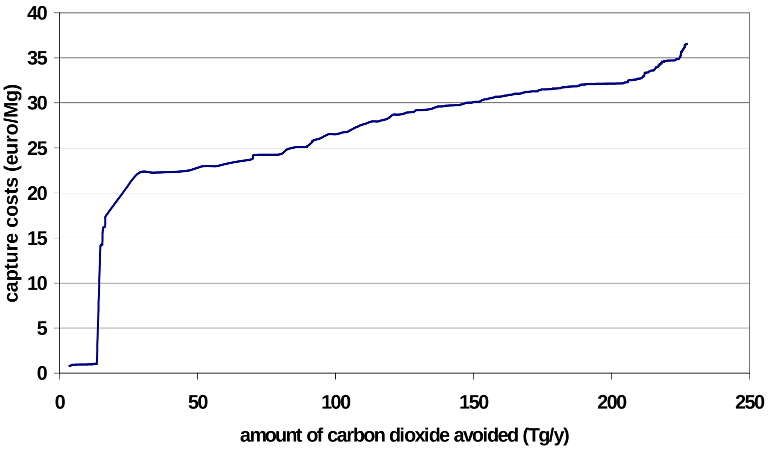


Table 5.
Average costs of capture at industrial installations in the GESTCO source database
(1 Tg = 1 Mtonne)

sector	avoidance potential	average capture costs
	(Tg CO2/y)	euro/Mg
all plants	227	26
by industry		
ammonia	15	12
of which pure stream	*10*	*1*
hydrogen	5	10
of which pure stream	*3*	*1*
ethylene oxide	1	32
cement	66	29
gas processeing	3	17
iron and steel	106	26
ethylene	33	32

Discussion

The capture costs as calculated in the previous section are higher than generally is quoted in other studies. The average costs in this study amounts to about 25 to 52 euro per Mg CO_2 avoided for the power installations. Often capture costs are quoted between 15 and 40 euro per Mg CO_2 avoided.

However, it should be taken into account that the following circumstances of the CO_2 capturing differ from other studies and which influence significantly the results of the cost calculations:

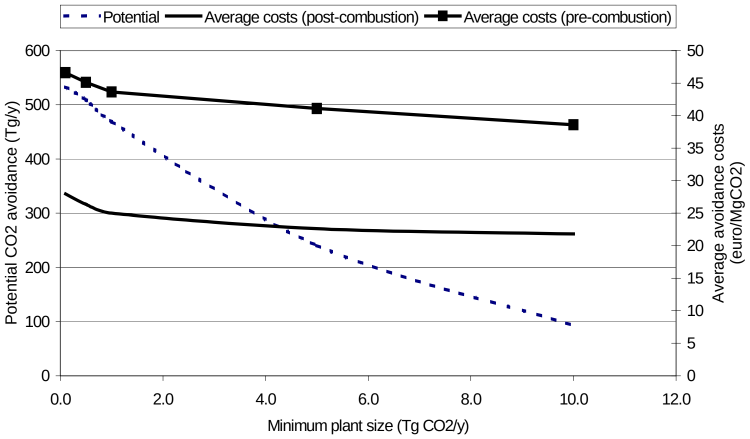
- The analysed plants are all existing plants; retrofitting old plants is more costly than constructing new plants with capture facilities. On average investment costs might be about 30% lower for new installations. Also the integration of the capture process can be done more efficient in new plants than in existing plants.

- The operational time per year (the load factor) of the plants are relatively low compared to other studies. In the cost calculations, the operational time is assumed to be the same as the load factor without the capture installation. The load factor is taken from the source database inventory. In practise, however, it would be more realistic that installations with capture installation will increase their load factor and reduce in that way the avoidance costs. An average load of 8000 hours per year instead of the actual load factor will decrease the capture costs by about 25% compared to the load factor in current existing installations.

- In the database, many relatively small plants are included. Generally, cost calculations are performed for power plants with a size of at least 500 MWe. Capture costs (expressed in euro per Mg CO_2 avoided) at smaller plants are significantly higher than capture costs at larger plant.

Figure 4 clearly shows the dependence of size with the capture costs. In the figure the average avoidance costs are depicted for plants with a threshold emission size. The interrupted line depicts the total potential at that threshold size. For instance, for plants equipped with post-combustion capture, the average costs decreases from about 28 euro when all plants are taken into account to 23 euro/Mg CO_2 for plants with an emission larger than 5 Tg/y. The total avoidance potential decreases from over 500 Tg to about 150 Tg per year.

Figure 4.
CO_2 avoidance costs and capture potential for existing power installations
(1 Tg = 1 Mtonne)



The average calculated costs for coal-fired power plants are considerably lower than for natural gas-fired plants (see Table 4). This can largely be explained by the fact that the average operational time of natural gas plants (often equipped with gas turbines) is considerably lower than for coal-fired power plants. Also the average size of coal-fired power plants is much larger than natural gas-fired power plants. In terms of carbon dioxide emissions coal-fired power plants emit on average five times as much carbondioxide than natural gas-fired installations. These economics-of-scale factors explain largely the cost difference between the two types of fuel.

The calculated capture costs of pre-combustion technologies are on average over 60% higher than the post-combustion technology. This can be explained by the fact that currently almost no integrated coal gasifier combined cycles (IGCC) are installed. This type of power plant is relatively attractive to apply the pre-combustion method. Pre-combustion at existing boiler/steam-turbine installations on the other hand is relatively expensive and not recommendable. The average capture costs for new IGCC plants with high load factor will therefore be considerably lower and will amount to about 20 to 25 euro per Mg CO_2 avoided.

Sensitivity and uncertainty analysis

A sensitivity and uncertainty analysis has been carried out for the economical calculation in the GESTCO-DSS. Probability distributions are derived for the costs of capture, compression, transport, storage and for the total costs of CO_2 sequestration systems. Furthermore the influence on the total cost of various cost parameters is examined. For the purpose of the analysis, the economical calculations for the whole chain from capture to storage had been implemented in a stand-alone Excel workbook. The Excel add-in @risk performs the analysis using Monte Carlo simulation. Distributions are assigned, using @risk, to the most relevant input parameters.

The total costs [€/MgCO_2], that is the sum of the specific investment, operations and maintenance (O&M) and energy costs, has been selected as output parameter for each component, capture, compression, transport, storage and the total costs.

Input distributions

The whole carbon dioxide sequestration system consists of four main steps: capture, compression, transport and storage. In principle a wide variety of parameters determines the specific costs, i.e. costs per Mg of carbon dioxide avoided. For the sensitivity and uncertainty analysis the a priori most relevant parameters are selected for each sequestration step. The distributions of the parameters are chosen with realistic limits. Nevertheless, it may be possible that for individual cases the value of (some) of these parameters are not within the range of the values chosen in this analysis. The parameters that are chosen for the Monte Carlo analysis are listed in Table 6. For all parameters a uniform distribution is used. The minimum (Min) and maximum (Max) value of the distributions are listed in the table below which comprises input distributions for the sensitivity and uncertainty analysis. The parameters in italics are selected for the sensitivity analysis.

Table 6. Input parameters chosen for the Monte Carlo analysis

Parameter	**Unit**	**Min**	**Max**
Capture			
Concentration CO_2 in flue gas	%	2	20
Annual CO_2 emission plant without capture	kg/y	200	5000
Operational hours of plant	h/y	5000	8700
Waste heat available (as % of total heat required)	%	10	50
Emission factor fuel	kgCO_2/GJ	0	104
Investment of capture installation (1)	Meuro/(kg/s)	2.0	4.0
Specific fuel costs	*euro/GJ*	*1.0*	*4.0*
Specific electricity costs	euro/GJe	7.0	15.0
O&M costs (% of investment)	%	2	6
Compression			
Electricity consumption	*kJ/kg*	*390*	*580*
Investment (range)	-	0.7	1.3
Transport			
Onshore pipe length	*km*	*0*	*100*
Onshore terrain factor (2)	-	0.9	1.4
Specific investment pipeline	euro/m	800	1500
Storage			
Depth of reservoir	m	1000	3000
Number of wells	-	1	5
Investment costs of platform	Meuro	1.0	30.0
Drilling costs per meter	*euro/m*	*1000*	*3000*
Fixed O&M costs (% to investment)	%	2	6
Variable O&M costs	euro/MgCO_2	0.5	1.5
Discount rate	*%*	*4*	*12*

1) Investment under standard conditions (size and concentration CO_2 in flue gas)
2) Factor of 1 indicates average/normal terrain conditions

Output distributions

A Monte Carlo simulation has been set-up using uniform distributions of the input parameters listed in the table above with the corresponding minimal and maximal values. A number of 10,000 iterations are performed in order to obtain the distributions of the total costs of each component in a sequestration system and the total cost. The statistics of the distributions are summarised in table 7 below.

Table 7. Results from Monte Carlo analysis of costs related to CO_2 sequestration systems

Costs €/MgCO_2	Minimum	Maximum	Mean	Std Dev	p5	p95
capture	11.3	105.2	30.5	10.1	17.4	49.4
compression	3.5	26.1	8.4	2.5	5.1	13.2
transport	0.0	22.4	2.6	2.2	0.2	6.9
storage	0.3	37.7	3.1	3.7	0.7	10.6
Total costs	18.4	170.6	44.6	14.9	26.6	74.2

CO_2 sequestration case studies

In the GESTCO project the geological surveys of the participating countries designed and evaluated seventeen carbon dioxide sequestration case studies. The economic evaluation is carried out using the GESTCO-DSS software application that is developed in the GESTCO project.

The designed carbon dioxide sequestration systems for the case studies diverged largely in size. The smallest project (an ammonia plant) avoids about 18 Gg (1 Gg = 1000 kg = 1 ktonne) of carbon dioxide per year or about 100 Gg carbon dioxide (power plants), while the largest projects (power plants) avoid yearly 6000 to 8000 Gg of carbon dioxide. The case study projects were primarily chosen on readily available data on sources and storage reservoirs and to a lesser extend to (financial) suitable project. All the projects described in the case studies deal with existing plants (except for Skogn in Norway), which are more expensive to equip with carbon dioxide capture than newly built plants.

The listing below shows the classification to type of source and to type of storage reservoir. In the case studies six industrial plants are evaluated (of which three plants with pure streams and three plants with diluted streams of carbon dioxide) and eleven power plants (Table 8).

For the storage, fourteen cases comprise aquifers while three cases are oil and/or gas field (without enhanced oil recovery) (Table 9).

Table 8. CO_2 emission sources analysed in case studies

CO_2 Emission Sources	
Type of source	***N^o of this source***
Power plant	11
- of which NG-fired	*(8)*
- of which coal-fired	*(3)*
Ammonia	2
Hydrogen	1
Oil refinery	2
Sugar factory	1

Table 9. Type of storage reservoirs analysed in case studies

Case Study Storage Reservoirs	
Type of reservoir	***N^o of this reservoir***
Aquifer	10
Oil/gas field	6
Coal mine	1

The highest total costs amount to about 100 euro per Mg of carbon dioxide avoided. These costs are calculated for relatively small systems running 40% or less of the time. The lowest cost of 14 euro/Mg of CO2 avoided is found for an ammonia plant with a pure stream of carbon dioxide. The ammonia plant is located nearby a suitable storage reservoir. Avoidance costs for an ammonia plant in the Netherlands amount to 53 euro/Mg of CO_2 avoided. The emissions of the plant are very small (18 Gg of annual emission) and the sequestration activity has therefore high specific transport and storage costs.

The lowest costs for a power plant case study project are obtained for a large coal-fired power plant (1528 MWe) in Denmark. The total avoidance costs amount to 32 euro per Mg of carbon dioxide avoided, of which 2/3 is required for the capture process.

The results of the 17 case studies are listed in Table 9. (next page).

Table 9. Summary of the carbon dioxide sequestration case studies designed and evaluated in the GESTCO project

Case study		Langerlo	Havnso	Tyra	Greifswalder Bodden-1	Greifswalder Bodden-2	Afeld-Elze	N.Karvali	Komotini	Rijnmond1
Country		Belgie	Denmark	Denmark	Germany	Germany	Germany	Greece	Greece	Netherlands
Type of plant		NGCC	coal-fired power plant	coal-fired power plant	NG-fired power plant	NG-fired power plant	Sugar factory	Ammonia plant	NGCC	Hydrogen
Capacity		90 MWe	1524 MWe	657 MWe	1200 MWe	1200 MWe		138 kt NH3/y	330 MWe	17.6 kt/y
Load	h/y	3686	8000	8000	7500	7500	1920	8000	3115	7000
Yearly emission	Gg/y	129	10314	4447	2969	2969	61.5	166	401	56.2
Type of capture		post-combustion	post-combustion	post-combustion	pre-combustion	post-combustion	post-combustion	pure source	post-combustion	pure source
Type of storage		Abandoned coal mine	aquifer (Asnaes)	Oil/gas field (Tyra)	Aquifer (Bunter)	Aquifer (Bunter)	aquifer	aquifer (Prinsos)	aquifer (Prinsos)	depleted gas field
Captured CO2	Gg/y	133	11909	5134	3010	2985		166	412	56.2
Avoided CO2	Gg/y	103	7856	3382	2545	2528		150	311	50.7
Capture costs	euro/Gg	82.1	21.5	25.3	33.2	26.8	75.5	0.6	76.3	0.7
Compression costs	euro/Gg	12.8	7.4	7.4	4.4	6.1	15.9	7.2	13.5	7.8
Transport costs	euro/Gg	3.5	1.4	14.8	1.1	1.1	1.1	3.4	13	9.7
Storage costs	euro/Gg	4.0	1.3	4.1	0.6	0.6	8.3	2.6	2.5	12.2
Total costs	euro/Gg	102.4	31.6	51.6	39.3	34.6	100.8	13.8	105.3	30.4

Case study		Rijnmond2	Eemshaven1	Eemshaven2	Mongstad-1	Mongstad-2	Skogn	King's Lynn	Eggborough
Country		Netherlands	Netherlands	Netherlands	Norway	Norway	Norway	UK	UK
Type of plant		Ammonia	NGCC	NGCC	Oil refinery	Oil refinery	NGCC	al-fired power plant	NGCC
Capacity		15.2 kt/y	3134 MWe	519 MWe	9285 kt/y	9285 kt/y	721 MWe	340 MWe	2005 MWe
Load	h/y	8000	7000	5871	8300	8300	8000	7212	3637
Yearly emission	Gg/y	18.3	8586	2455	1926	1926	2250	956	5067
Type of capture		pure source	pre-combustion	post-combustion	post-combustion	post-combustion	pre-combustion	post-combustion	post-combustion
Type of storage		depleted gas field	depleted gas field	depleted gas field	depleted gas field (Odin)	aquifer (Sognefjord)	aquifer (Tilje)	aquifer (Bunter)	aquifer (Bunter)
Captured CO2	Gg/y	56.2	8875	2815	1985	1985	2333	982	5781
Avoided CO2	Gg/y	50.7	6926	1883	1492	1492	1814	753	3869
Capture costs	euro/Gg	0.6	32.5	32.2	27.5	27.5	38.7	38.4	35.1
Compression costs	euro/Gg	7.2	4.6	8	7.4	7.4	5	8.5	9.1
Transport costs	euro/Gg	11.6	1.7	3	6.7	2.6	7.4	6.5	4.4
Storage costs	euro/Gg	33.8	1.1	1.5	8.3	8	7.2	13.2	2.6
Total costs	euro/Gg	53.2	39.9	44.7	49.9	45.5	58.3	66.6	51.2

9 Analysis of public outreach

Certain clear messages have come out of public outreach studies and events held to date. These are summarised below. The summary refers to stakeholders (those who have some kind of interest vested in the technology) and the public (those who do not have a direct vested interest but may be affected by the technology).

Outreach to stakeholders

It is important that stakeholders see that messages communicated at previous events have been heard; if it is felt that the same questions are being asked again, stakeholders will be reluctant to engage in the process and will become cynical. Factors that we can assume to be pre-requisites in engaging stakeholders in the debate are listed below – future stakeholder processes should move from these as a starting point:

- Ocean storage is not likely to be accepted in Europe – NGO's and the public have demonstrated deep seated objections to this approach; [though in case of the public research, there has not been a detailed discussion of the scientific arguments for and against ocean storage].
- Carbon storage must be evaluated in the context of other carbon mitigation options and as part of broader debate of energy policy; it should not be considered in isolation.
- Given the above, investment in Carbon Capture and Storage (CCS) technology must not be at the expense of (i.e. lead to the diversion of funds away from) other carbon mitigation options, such as renewable energy technologies and energy efficiency improvements.
- Even the more sceptical stakeholders may view CCS more positively if its role is identified as part of a bridging strategy towards a more truly decarbonised energy infrastructure.
- Government signals are required before industry can proceed with the technology.
- The debate about the desirability of CCS is really about the long term use of fossil fuels - maintaining this is used either as an argument in its favour (for example, to address concerns over energy security, diversity of supply and maintenance of the existing energy sector) or an argument against the approach (e.g. that the sooner we give up the fossil fuel 'habit', the better).

It is often assumed, by those outside the sector, that the fossil fuel industry is universally interested in promoting CCS technology. The reality is much more complex – in the case of offshore applications the claims that EOR provides the economic opportunity for early implementation of CCS may prove rather optimistic (Espie *et al.* 2002)[1].

Although certain industrial players recognise potential opportunities offered by CCS, the economic/policy mechanism through which the additional costs required for CCS are covered is not certain. Thus, industry is waiting for a lead from government in this area – and the management of this relationship and how it is viewed by the public, remains an important factor in the social acceptability of the introduction of the CCS technology.

Without some sort of financial incentive, companies will not commit the long-term

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[1] Espie, A. A., Brand, P. J., Skinner, R. C., Hubbard, R. A., Turan H. I. (2002), Obstacles to the storage of CO2 through EOR operations in the North Sea, *Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies*

investment necessary to bring the technology into mainstream use (Gale 2002)[2] The public presentation of any incentive system developed by government could have an important bearing upon subsequent stakeholder and public reactions.

Outreach to the public

Preliminary (unpublished) results from the Tyndall Citizen panels show that, in the UK at least, the science and severity of impacts of climate change and the urgency and challenge of its mitigation are not well appreciated by the general public. Initial reactions to the concept of CCS tend to be sceptical and it is only within the context of the broader discussion of climate change that opinions become more receptive to the approach. The two groups convened to date were selected to be of above average socio-economic status but with no involvement with, or membership of, environmental campaigning groups.

Typically, participants of these groups were clear that other approaches such as energy efficiency measures and demand reduction should be pursued as a priority and that CCS should not be developed as a straight alternative. There was a moderate to deep level of scepticism amongst the participants towards both the government and industry and what may motivate their promotion of CCS but there was also some distrust of messages promoted by environmental groups.

It is understood that other research groups in Europe may also be planning public participation work within this area, including the Potsdam Institute für Klimafolgenforschung.

The view that negative reactions from the public are essentially a reflection of lack of information, has been referred to in the literature as the “deficit model” (Irwin & Wynne 1995)[3]. This raises a distinction between two different notions of public interaction: a) public participation, as two-way dialogue, and b) communication or marketing exercises, the intention being that the public becomes 'better informed' and hence better able to make rational decisions. Which of these underlying concepts of public interaction is being adopted by the research groups will have a strong influence on the way that public perception and involvement evolves.

Recommendations for future outreach activities

There remains a widespread attitude amongst certain stakeholders that the activities described in this report are about ways of promoting or “selling” the technology. The majority of those stakeholders (from the energy and climate change communities) not directly involved in CCS have not reached a position of acceptance of the need for CCS. Thus outreach activities should recognise, that the need for genuine participation remains in addressing questions such as whether public and stakeholders want CCS to play a role, what form it should take, how much storage is necessary, how it should be funded, other conditions that need to be met - all in the context of broader energy / climate policies. Furthermore, the R&D community needs to recognise from the Brent Spar experience, that stakeholders and members of the public will evaluate individual projects in the context of an anticipated trajectory of similar future developments and projects. To refer to the terminology used earlier, the 'information deficit model' of public communication should be replaced with a 'pro-active participative engagement' model.

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[2] Gale, J.(2002), Broadening the Dialogue on Capture and Storage of CO_2, IEA GHG File Note, September 2002

[3] Irwin, A. & Wynne, B. (Eds.) (1995), 'Misunderstanding Science? The public reconstruction of science', CUP, Cambridge).

10 Discussion as to whether CO_2 storage is a viable method of reducing greenhouse gas emissions capable of widespread application in Europe

The inventory of major point sources of CO_2 compared with the geological storage potential mapped in the GESTCO project indicate that individual countries could make a significant impact on their national CO_2 emissions by capturing the emissions from a relatively small number of the largest point sources and storing them underground. However, no matter how much storage capacity is available, CO_2 capture and storage cannot be a panacea for greenhouse gas emissions because realistically it can be applied only to large stationary point sources of CO_2 and these currently account for less than 40% of national CO_2 emissions. Over the long term, however, this percentage may increase significantly with the introduction of hydrogen fuel cells for transportation and smaller stationary applications.

The GESTCO project has confirmed by seismic mapping, analysis of well logs and reservoir simulation, the presence of significant CO_2 storage capacity in structural traps in underground porous and permeable reservoir rocks in onshore and near shore sedimentary basins, particularly in Denmark and Germany. The pore spaces of these reservoir rocks are currently filled with saline water, which has few other uses (they are so-called 'saline aquifers'). Significant storage capacity is also thought likely to exist in the Bunter Sandstone Formation of the UK sector of the southern North Sea (on the basis of maps derived from interpretation of 2D seismic data). However, this potential requires to be firmed up by detailed studies of the identified storage structures. A huge potential exist offshore Norway as demonstrated in this and previous studies, and it is likely – but not investigated in this study – that very large additional offshore aquifer potential exists in British and Danish sectors of the North Sea. In the Netherlands and Belgium – which are also located in favourable sedimentary basin settings – the storage potential is primarily related to exhausted gas fields and coal mines, in the case of Belgium. The Paris Basin aquifer potential could be quite large in the Triassic sandstone formation and the Dogger carbonate formation. However there is limited storage capacity in the well-known recognised structural traps within these aquifers. Further detailed studies are required to identify other potential storage structures. Combination of CO_2 storage with geothermal operations would be of little interest. It is anticipated that a considerably larger French CO_2 storage potential exists in other aquifers and abandoned hydrocarbon fields. The Greek storage potential is composed of aquifers as well as a few hydrocarbon fields. The location of the geological storage opportunities relative to emission points form interesting combinations, e.g. for future application of lignite based power generation.

By the very nature of studies such as GESTCO, it is not possible to cover neither every aquifer nor all of the geographical territory of the participating countries. The study however clearly shows that in a number of the areas selected for study well-defined and likely geological structures and formations do exist. Furthermore, the indicated storage capacities in e.g. Germany and Denmark are sufficiently great to warrant further and more detailed investigation (cf. the EU FP5 CO_2Store Project). Based on these findings, it is anticipated that there is likely to be enough storage capacity for the technology to be used as a bridging technology for a significant time whilst low carbon or carbon free energy systems are installed.

There is also significant storage capacity in the gas and oil fields of northern Europe, particularly in the North Sea and onshore in the Netherlands and Germany. There is likely to be an economically defined window of opportunity to exploit the offshore oil and gas field potential. This window of opportunity will close when the production infrastructure is removed.

There is vast theoretical potential for CO_2 to be adsorbed onto coal but this is largely conceptual at present and requires further research and demonstration to see if the concept of CO_2-enhanced coalbed methane production can be turned into reality in Europe, where the majority of coal seams are significantly less permeable than those of the San Juan Basin in the USA, where field trials have taken place.

The case studies of safety and security of storage and potential conflicts of use in Germany suggest that onshore CO_2 storage underground might face considerable planning and national legal obstacles. From this perspective it appears likely that in some cases large scale CO_2 storage would take place offshore rather than onshore, providing that there are no legal barriers within international treaties such as the OSPAR and London Conventions.

Issues such as capture technology and associated cost as well as the question of overall capacity, are the key issues for the further advance of the concept and will be of great importance to policy makers and regulatory authorities. When it comes to public perception and public acceptance, the key issues will be safety and security of the storage operation.
The public appears to hold a relatively positive opinion about CO_2 capture and storage, provided that it is not considered a stand alone solution, but rather is seen as an integral part of a long term development towards less environmental impact from energy production.

The GESTCO study – and a number of previous studies – clearly show that the key economy factor is cost of capture and compression of the CO_2. The GESTCO study capture cost analysis result in a range from 25 to 52 euro/tonne CO_2 avoided at retrofit power plants, while pre-combustion plants are anticipated to capture the CO_2 at about 30% less cost. All other things being even, this is in the same cost range as a number of other options, including several renewable energy sources. Realistically, CO_2 capture and storage would only be able to provide limited contributions toward the fulfilment of the Kyoto Agreement – mainly because of the time constraints. In the longer term, CO_2 capture and storage has the potential to produce very deep cuts in the CO_2 emissions, whilst rendering fossil fuel energy sources almost CO_2 neutral.

For CO_2 storage to become an important mitigation technology, a number of further activities would be advisable:

- Extend mapping of capacity and quality of European geological storage potential.
- Assessment and inventorying of new power requirements and existing emission sources, particularly in the new and coming EU member states.
- Research into safety and security aspects of storage, reducing geological and engineering uncertainties, and wherever possible doing this in conjunction with demonstration of the technology and including public outreach and acceptance.
- Building European technical standards for CO_2 capture and storage operations, including monitoring requirements and targeted research into chemical and fluid forecasting over very long time spans.
- Provide input for national and EU legislation.

Gestco Project reports Appendix I

(as contained in CD-ROM issue)

The Gestco Project – An introduction *N.P. Christensen (GEUS)*

1. **Summary report** *N.P. Christensen (GEUS) & S. Holloway (BGS)*

Work Package 1: Definition of representative study areas

2. **Details of the regional studies of CO_2 storage capacity included in the GESTCO project** *S. Holloway (BGS) and R&D partners*
3. **GESTCO: Sources and capture of carbon dioxide** *C. Hendriks, A.-S. van der Waart, Carsten Byrman & Ruut Brandsma (Ecofys)*

Work Package 2: Storage capacities of study areas

4. **Storage potential of the Bunter Sandstone in the UK sector of the southern North sea and adjacent onshore area of Eastern England (study area A1)** *M. Brook, K. Shaw, C. Vincent & S. Holloway (BGS)*
5. **North Germany (study area A2)** *F. May & P. Krull (BGR)*
6. **CO_2 Storage scenarios in North Germany, GESTCO project case studies (study area A2)** *F. May, P. Krull & P. Gerling (BGR)*
7. **CO_2 storage potential of saline aquifers in the Netherlands onshore region (study area A3)** *T. Wildenborg, F. van Bergen & H. Dudok van Heel (TNO-NITG)*
8. **CO_2-sequestration possibilities in the deep aquifers of the Campine Basin (Northern Belgium) (study area A4)** *P.C.H. van Tongeren (Vito)*
9. **CO_2 storage potential of selected saline aquifers in Denmark (study area B1)** *M.. Larsen, T. Bidstrup & F. Dalhoff (GEUS)*
10. **Chemical and physical interaction of CO_2 and carbonate rock (study area B2)** *D. Olsen & N. Stentoft (GEUS)*
11. **CO_2 point sources and subsurface storage capacities for CO_2 in aquifers in Norway (study area C)** *R.. Bøe, C. Magnus, P.T. Osmundsen & B.I.. Rindstad (NGU)*
12. **Greek onshore and offshore Tertiary sedimentary rocks (study area D)** *G. Hatziannis & M. Xenakis (IGME)*
13. **Feasibility of CO_2 storage in geothermal reservoirs example of the Paris Basin – France (study area E1)** *Didier Bonijoly (BRGM)*
14. **Feasibility of CO_2 storage in combination with geothermal plants, Denmark (study area E2)** *Mathiesen (GEUS), M. Larsen (GEUS) & A. Mahler (DONG A/S)*
15. **Feasibility of CO_2 sequestration in coal mines (study area F1)** *K. Piessen & M.. Dusar (GSB)*
16. **Residual space volumes in the abandoned subsurface coalmines of the Campine Basin (northern Belgium) (study area F2)** *P.C.H. van Tongeren & B. Laenen (Vito)*

17. **Coalbed methane potential of the Campine basin (N. Belgium) and related CO_2-sequestration possibilities (study area F3)** *P.C.H. van Tongeren & B. Laenen (Vito)*
18. **Salt mines (study area F4)** *F. May (BGR)*
19. **Coal mines (study area F5)** *F. May (BGR)*
20. **Inventory of CO_2 storage potential of Carboniferous coal layers in the Netherlands (study area F6)** *F. van Bergen & T. Wildenborg (TNO-NITG)*
21. **Storage capacity and quality of hydrocarbon structures in the North Sea and Aegean region (study area G)** *J.D. Schuppers (TNO-NITG), S. Holloway (BGS), F. May (BGR) P. Gerling (BGR), R. Bøe (NGU), M. Larsen (GEUS), P.R. Andersen (GEUS) & G. Hatzyannis (IGME)*
22. **Simulation cases of CO_2 sequestration** *A. Obdam (TNO-NITG), L. van der Meer (TNO-NITG), F. May (BGR), N. Bech (GEUS), C. Kervevan (BRGM) & A. Menjoz (BRGM)*

Work Package 3: Storage safety and conflicts of use

23. **Case-studies of safety, security and potential conflicts of use** *S. Holloway (BGS) & F. May (BGR)*

Work Package 4: Decision support and risk analysis system

24. **GESTCO-DSS; Software Requirements Specification** *F. Floris & T. Wildenborg (TNO-NITG)*
25. **GESTCO-DSS; A Decision Support System for Underground Carbon Dioxide Sequestration** *P. Egberts (TNO-NITG), J.F. Keppel (TNO-NITG), T. Wildenborg (TNO-NITG), C. Hendriks (Ecofys) & A.-S. van der Waart (Ecofys)*
26. **GESTCO-DSS; Software Design Description** *J.F. Keppel (TNO-NITG) & C. Byrman (Ecofys)*

Work Package 5 and 6: Economic modelling of scenarios

27. **Potential and cost comparison renewables** *C. Hendriks & M. Kerssemeeckers (Ecofys)*
28. **Carbon dioxide sequestration systems: economic evaluation and case studies** *C. Hendriks (Ecofys), P. Egberts (TNO-NITG) & R&D partners*

Work Package 8: Project management and exploitation plans

29. **CO_2 storage: Public hearing report** *I. Tellam & J.P. van Soest (CE-Transform)*
30. **Public and stakeholders perceptions of carbon dioxide capture and storage** *C. Gough & S. Shackley (Tyndall ºCentre)*

Additional CD-ROM issues available through the project manager

CD-1: Gestco DSS including DSS manual

CD-2: Gestco GIS including inventory of major industrial point sources of CO_2 in participating countries (Belgium, Denmark, France, Germany, Greece, Netherlands, Norway and UK)