

Assessing the European potential for geological storage of CO₂: the *GESTCO* project

Niels Peter Christensen and Michael Larsen

GESTCO is an acronym for European potential for the Geological Storage of CO₂ from fossil fuel combustion. The project formed part of the ENERGIE Programme of the European Union 5th Framework and was concluded in 2003. The Geological Survey of Denmark and Greenland (GEUS) led the project, with the national geological surveys of Belgium, France, Germany, Greece, the Netherlands, Norway and UK as research partners (Fig. 1).

The primary goal of the *GESTCO* 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 in Europe (Christensen 2000; Gale *et al.* 2001; Christensen & Holloway 2003). This was evaluated by a series of case studies that assessed the CO₂ 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. In addition 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 an inventory of major CO₂ point sources in Europe and a Decision Support System (DSS) to serve as an economic analysis tool for CO₂ storage in Europe.

Inventory of large CO₂ point sources

Major industrial sources of CO₂ in the participating countries were identified and compiled into a database. In almost all countries, the major sources of CO₂ are power plants,

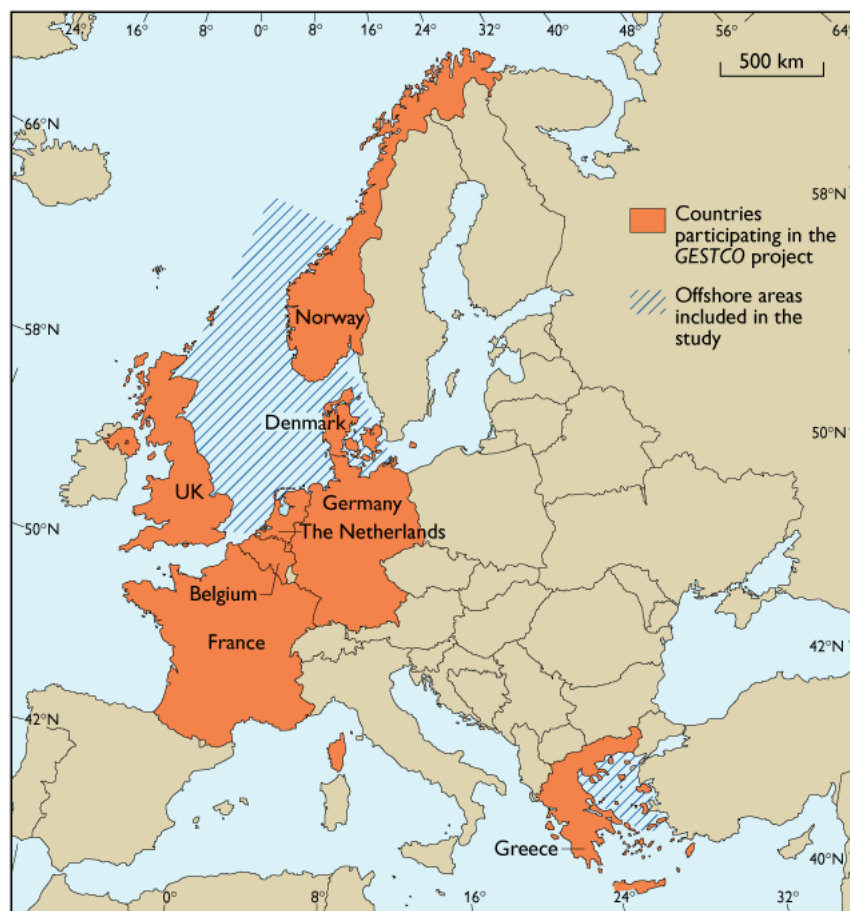


Fig. 1. Map of Europe showing the participating countries and offshore study areas included in the *GESTCO* project.

integrated steel plants, refineries/petrochemical complexes and cement works. The exception is Norway, where many of the major sources of CO₂ are generators at offshore oil and gas fields. The location and details of the sources of CO₂ are compiled into a Geographic Information system (GIS) enabling qualified search routines.

In Denmark, the annual emission of greenhouse gases is close to 60 Mt of which approximately half originates from fossil fuel combustion related to power and heat generation. Major CO₂ point sources were identified based on yearly reports to the Danish Energy Authority. These point sources alone contribute 29 Mt CO₂ of the total CO₂ emission in Denmark. The largest single source is the coal-fired power plant Asnæsværket in Kalundborg, with an average yearly emission of 5.8 Mt CO₂ in the period 1994–1999. Considering CO₂ sequestration from Asnæsværket could thus account for approximately half of the greenhouse gas reductions required for Denmark in the Kyoto agreement (Larsen *et al.* 2003a).

European storage capacities

Underground storage capacities in the case study areas were evaluated by seismic mapping, analysis of well logs and reservoir simulation. The results are summarised in Christensen & Holloway (2003). The major part of the mapped storage capacity was related to deep saline aquifers in onshore and nearshore sedimentary basins in Denmark, Germany, southern UK and northern France. In the Netherlands and Belgium the storage potential is primarily related to exhausted gas fields and coalmines. A huge potential exists in aquifers offshore Norway, and it is likely that very large additional offshore aquifer potential exists in British and Danish sectors of the North Sea. The Greek storage potential is composed of

aquifers as well as a few hydrocarbon fields. Significant storage capacity is related to the gas and oil fields of northern Europe, particularly in the North Sea and onshore in the Netherlands and Germany.

Geological storage capacities in Denmark

The potential storage capacity in Denmark was evaluated through case studies of onshore and nearshore saline aquifers, and hydrocarbon fields of the Danish North Sea sector.

Deep saline aquifers

Large sedimentary basins of Late Palaeozoic – Cenozoic age are present in Denmark and provide a potential for CO₂ storage. In the onshore or nearshore Danish area the reservoir units comprise porous sandstone layers of the Lower Triassic Bunter Sandstone Formation / Skagerrak Formation, the Upper Triassic – Lower Jurassic Gassum Formation, the Middle Jurassic Haldager Sand Formation, and the Upper Jurassic Lower Cretaceous Frederikshavn Formation. Mapping and initial description of these units has been undertaken in the search for hydrocarbons and geothermal reservoirs (cf. Nielsen *et al.* 2004, this volume).

The *GESTCO* aquifer study was focused on sandstone formations within a depth range of 900–2500 m, i.e. between the depth required for CO₂ to become a dense fluid and the depth below which reservoir quality typically deteriorates due to diagenetically induced reduction of porosity and permeability.

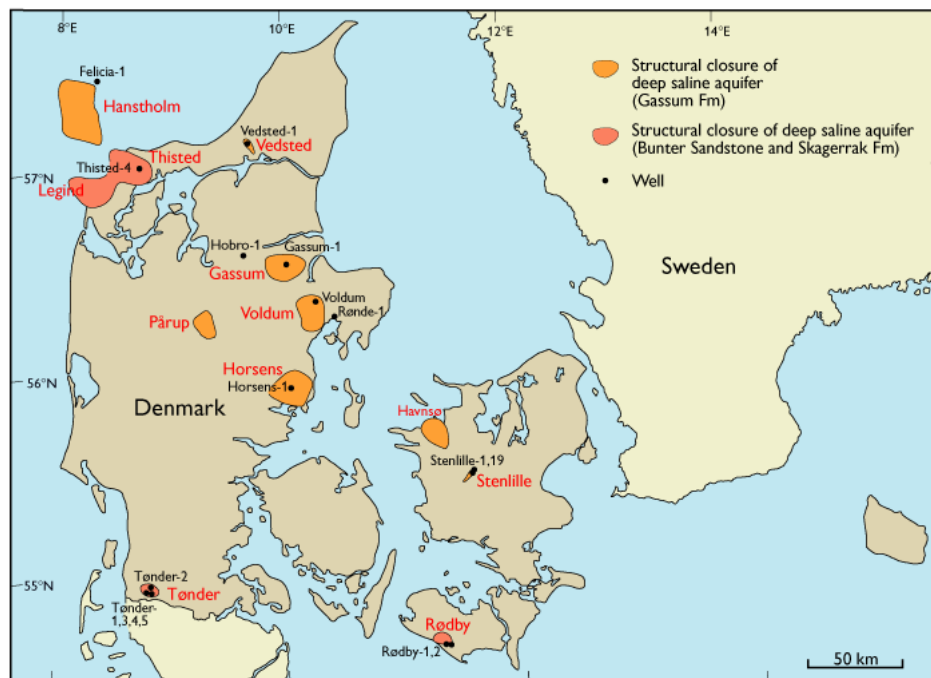
The total storage capacity of unconfined aquifers in Denmark has been estimated to be 47 Gt of CO₂, although only a small part of the volume was related to structural closures (Holloway *et al.* 1996). In order to gain public and

Table 1. CO₂ storage capacity of major aquifer structures in Denmark

| Structure | Formation | Area (km ²) | Top depth (m below msl) | Net sand (m) | Porosity (%) | Pore volume (km ³) | Reservoir density of CO ₂ (kg/m ³) | Storage capacity (Mt CO ₂) |
|------------------------|------------|-------------------------|-------------------------|--------------|--------------|--------------------------------|---|--|
| Gassum | Gassum | 242 | 1460 | 53 | 25 | 2.5 | 627 | 631 |
| Hanstholm* | Gassum | 603 | 1000 | 92 | 20 | 11.1 | 620 | 2752 |
| Havnsø* | Gassum | 166 | 1500 | 100 | 22 | 3.7 | 629 | 923 |
| Horsens | Gassum | 318 | 1506 | 24 | 25 | 1.9 | 630 | 490 |
| Pårup* | Gassum | 121 | 1550 | 30 | 10 | 0.4 | 625 | 90 |
| Rødby | Bunter Sst | 55 | 1125 | 45 | 24 | 0.6 | 620 | 151 |
| Stenlille† | Gassum | 10 | 1507 | 100 | 25 | 0.2 | 631 | 62 |
| Thisted/Legind | Skagerrak | 649 | 1166 | 449 | 15 | 43.6 | 641 | 11 187 |
| Tønder‡ | Bunter Sst | 53 | 1615 | 35 | 20 | 0.4 | 634 | 93 |
| Vedsted | Gassum | 31 | 1898 | 103 | 20 | 0.6 | 633 | 161 |
| Voldum | Gassum | 235 | 1757 | 30 | 10 | 1.1 | 630 | 288 |
| Total storage capacity | | | | | | | | 16 867 |

* Extrapolated values. † A natural gas storage facility operated by DONG. ‡ Reserved for Natural Gas Storage. Based on Larsen *et al.* (2003b).

Fig. 2. Map showing the position and outline of the eleven structural closures mapped in the Danish aquifer case study of the *GESTCO* project. **Black dots** indicate the position of deep exploration wells used in the evaluation of the reservoirs. Modified from Larsen *et al.* (2003a).



political acceptance, structural traps are considered essential, at least initially, when considering storage onshore Denmark, and consequently the *GESTCO* study was focused on eleven large structures (Fig. 2; Table 1). These structures were mapped from seismic surveys and evaluated using data from existing deep wells to assess the storage potential (Larsen *et al.* 2003b).

Based on many years of experience from aquifer storage of natural gas in Denmark, Germany and France, it is assumed that 40% of the total pore volume within a trap could be filled with CO₂. This effective storage capacity will depend on a number of parameters including the geometry of the trap (e.g. difference in height between top point and spill point), the number of injection wells, injection rates and reservoir characteristics. The initial calculations carried out in the present study suggest that the eleven structures alone may provide storage for at least 16 Gt of CO₂ (Table 1; Larsen *et al.* 2003b). Note that almost two thirds of the calculated aquifer storage capacity is present in the Thisted/Legind structure.

As well as a proper reservoir, a tight cap rock is needed when considering underground storage of CO₂. Geological formations with good sealing properties are lacustrine and marine mudrocks, evaporites and carbonates. In Denmark the most important sealing rock type is marine mudstone, which often forms units several hundred metres thick and is present at several stratigraphic levels. In addition to the primary cap rock, chalk of Late Cretaceous – Danian age forms a possible secondary seal in most of the Danish area. The sealing effect of the chalk is dependent on chemical reactions between dissolved CO₂ and the carbonate rock.

Detailed site surveys will be needed in order to test the integrity of the seal at any future storage site.

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. First, the hydrocarbon fields have proved their capability to retain fluids and gases, in many cases for millions of years. Secondly, the reservoir is well understood due to intensive data gathering before and during the productive life of the field, and finally infrastructure for the production and transport of fluids and gases is already in place. With some modifications, this infrastructure may often be re-usable for delivery and injection of CO₂ for storage.

The reserve figures for 14 chalk fields and three sandstone fields of the Danish sector were included in the *GESTCO* project (Christensen & Holloway 2003). These comprise detailed estimates of the expected ultimate (*initial*) reserves, and rounded figures for low and high case reserves as given by the Danish Energy Authority (DEA 2002). The storage capacity of hydrocarbon reservoirs is calculated from the underground volume of ultimately recoverable oil or gas. The calculation assumes that the entire underground volume of recoverable hydrocarbons can be replaced by CO₂. For gas reservoirs, this is a straightforward assumption, since most gas reservoirs are of a closed nature. Formation water (the aquifer) does not significantly replace the drained gas during

the producing field life. For oil reservoirs, it is assumed that the amount of CO₂ that can be stored in the reservoir is approximately 30% of the oil initially in place. Since the Ultimate Recovery (UR) of most oil fields (as initially reported) also approximates 30–35%, the storage capacity can be approximated by the initial proven reserves (or UR). In addition to the volumetric estimates special concern is needed when considering storage of CO₂ in chalk, as chemical and physical reactions are likely to occur between CO₂ in solution and carbonate rocks.

Based on the above assumptions, the Danish storage capacity for existing oil and gas fields is estimated to be 629 Mt CO₂. Of this, 452 Mt can replace natural gas, while 176 Mt can replace oil (Christensen & Holloway 2003). However, all of the investigated fields of the Danish North Sea are in the production phase, and CO₂ injection will probably not be possible in the near future unless applied through Enhanced Oil Recovery (EOR) operations. The EOR option of the North Sea is currently under investigation and preliminary results have been presented by Markussen *et al.* (2003). The vision of the project is to capture CO₂ from the Danish power plants and export it through an extensive pipeline system to the offshore industry. Implementation of the EOR technology would have great impact on the lifecycle of Danish oil and gas production.

Conclusions

The inventory of major point sources of CO₂ and the geological storage potential mapped in the *GESTCO* project indicate that the eight European countries could make a significant impact on their national CO₂ emissions by capturing the emissions from a relatively small number of the largest point sources and storing them underground.

In Denmark, mapping of geological structures suitable for underground storage of CO₂ suggests that enough storage volume is present within the subsurface to store several hundred years of total CO₂ emissions from Danish industry and power production. Detailed site surveys and risk analysis, including long term monitoring, are needed to validate these storage capacities and should be the focus of future studies.

Acknowledgements

The project formed part of the ENERGIE Programme of the European Union 5th Framework Programme for Research & Development, Project No. ENK6-CT-1999-00010, and was 50% funded by the Programme.

In addition to the principal research partners, valuable contributions to the project were made by the 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 (the Netherlands) and the Tyndall Centre (UK).

Further contributions to the project were given by BEB (now EMPG), BP, Danish Energy Authority, Gaz de France, IEA Greenhouse Gas R&D Programme, Norsk Hydro, Norwegian Petroleum Directorate, Shell, Statoil, Total-FinaElf, the UK Department of Trade and Industry, and Vattenfall.

References

- Christensen, N.P. 2000: The GESTCO Project: assessing European potential for geological storage of CO₂ from fossil fuel combustion. In: Williams, D. *et al.* (eds): Proceedings of the Fifth International Conference on Greenhouse Control Technologies (GHGT-5), 261–265. Cairns, Australia: CSIRO Publishing.
- Christensen, N.P. & Holloway, S. 2003: Geological storage of CO₂ from combustion of fossil fuel. European Union Fifth Framework Programme for Research and Development, summary report, 34 pp. Copenhagen, Denmark: Geological Survey of Denmark and Greenland.
- DEA 2002: Oil and gas production in Denmark 2001, 98 pp. Copenhagen, Denmark: Danish Energy Authority.
- Gale, J., Christensen, N.P., Cutler, A. & Torp, T.A. 2001: Demonstrating the potential for geological storage of CO₂: the Sleipner and Gestic Projects. *Environmental Geosciences* **8**, 160–165.
- Holloway, S. *et al.* 1996: The underground disposal of carbon dioxide. Joule II project No. CT92-0031, summary report, 24 pp. Keyworth, Nottingham, UK: British Geological Survey.
- Larsen, M., Bidstrup, T. & Christensen, N.P. 2003a: Saline aquifer storage of CO₂ from major point sources – a Danish case study. In: Gale, J. & Kaya, Y. (eds): Greenhouse gas control technologies. Proceedings of the Sixth International Conference (GHGT-6), Kyoto, October 2002, 657–661.
- Larsen, M., Bidstrup, T. & Dalhoff, F. 2003b: CO₂ storage potential of selected saline aquifers in Denmark. *Danmarks og Grønlands Geologiske Undersøgelse Rapport* **2003/39**, 83 pp.
- Markussen, P., Austell, J.M. & Hustad, C.-W. 2003: A CO₂-infrastructure for EOR in the North Sea (CENS): Macroeconomic implications for host countries. In: Gale, J. & Kaya, Y. (eds): Greenhouse gas control technologies. Proceedings of the Sixth International Conference (GHGT-6), Kyoto, October 2002, 1077–1082.
- Nielsen, L.H., Mathiesen, A. & Bidstrup, B. 2004: Geothermal energy in Denmark. *Geological Survey of Denmark and Greenland Bulletin* **4**, 17–26 (this volume).

Authors' address

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. E-mail: npc@geus.dk