DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2007/3

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
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G E U S

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Executive Summary

Introduction

The Danish case study of the CO2STORE project comprises an analysis of the potential future capture and underground storage of CO_2 from two point sources located close to the city of Kalundborg; the coal fired power plant Asnæsværket and the Statoil refinery. Initial mapping of the storage structure during the EU funded research project GESTCO identified a large underground structure forming a potential, future storage site at Havnsø 15 km to the northeast of Kalundborg. The structure covers approximately 160 km2 and the reservoir at a depth of approximately 1500 m is formed by porous sandstones filled with saline water. A preliminary calculation suggests a storage capacity of nearly 900 million tonnes of CO_2 equal to more than 150 years of CO_2 emissions from the two point sources. In the case study a fictive capture and storage scenario has been formulated and modelled based on experiences learned through the SACS and GESTCO projects. Detailed geological modelling, reservoir simulation, reservoir and cap rock characterisation and risk assessment are important issues in the case study.

Asnæsværket and the Statoil refinery

The two point sources are located side by side close to the city of Kalundborg on the Northwest coast of Zealand in the Eastern part of Denmark. Asnæsværket is the biggest power plant in Denmark with an installed capacity of 1,057 MW_{el} and 602 MJ/s heat. The remaining lifetime of the existing units is however limited and this case study foresees and take into consideration that a new high-efficient pulverised-coal fired unit may be taken into operation within 10 years. The future CO_2 emissions are estimated to 3.4 Mt/year. The Statoil refinery is also the largest refinery in Denmark with a production capacity of 5.5 million tonnes of hydrocarbon products/year. The emissions have been almost constant around 0.5 Mt/year in the project period, but not all of the CO_2 will be available for the capture process. The power plant and the refinery have a long history of co-operation and capture and storage of CO_2 from the refinery will most likely be dependent on the realisation of the power plant capture and storage project.

Storage site selection and geological storage

The possibilities for underground storage of CO_2 in Denmark has previously been evaluated in two regional studies, Joule II and GESTCO including storage potential in depleted hydrocarbon fields and deep saline aquifers. In the Joule II report the total storage capacity for CO_2 in Denmark in unconfined onshore aquifers of Triassic and Jurassic age was estimated to 47 Gt based on a general assumption that 2% of the entire pore volume of the mapped formations was filled. Restricting the storage capacity to confined traps reduced the estimated total storage capacity to 5.6 Gt. Using experiences from natural gas storage facilities in Denmark, Germany and France the GESTCO study assumes that 40% of the total pore volume within a defined trap may be filled with CO_2. In the GESTCO project eleven well-defined closures all located in the central part of the Danish Basin were mapped from seismic surveys and their storage potential was evaluated using data from

existing deep wells. Initial calculations suggest that these structures alone may provide storage for at least 16 Gt CO_2. The different storage capacity estimates between the Joule II and GESTCO projects illustrates the principle of “less storage capacity with better confidence” and it is anticipated that the site characterization process developed in the CO2STORE project will increase the amount of knowledge, but also reduce the estimate of total storage capacity within the countries.

In the site selection phase four stratigraphic intervals were considered for potential storage in deep saline aquifers. These are Bunter Sandstone and Skagerrak Formations (Triassic), Gassum Formation (Upper Triassic-Lower Jurassic), Haldager Sand Formation (Middle Jurassic) and Frederikshavn Formation (Upper Jurassic-Lower Cretaceous) with the Gassum Formation being the most attractive regarding burial depth versus reservoir properties. The Gassum Formation consists of fine- to medium-grained, locally coarse-grained sandstones interbedded with claystones and the porosity and permeability are known from a number wells (porosity 18-27%, maximum 36% and permeability up to 2,000 mD) and acts as reservoir for storage of natural gas at Stenlille and as geothermal reservoir at Thisted.

The aquifer storage of CO_2 is dependent not only on the properties of the reservoir but also on the integrity of the sealing formation. The primary sealing unit for the Gassum Formation is marine mudstones of the Lower Jurassic Fjerritslev Formation characterised by a relatively uniform succession of marine slightly calcareous claystones. The formation is present over most of the Danish Basin with a varying thickness of up to 1,000 m. It is the sealing formation at the Stenlille natural gas storage site and has proven tight to natural gas stored in the Gassum reservoir below. A possible secondary seal is formed by carbonate rocks of Late Cretaceous-Danian age and chemical reactions between dissolved CO_2 and the carbonate rock (described in GESTCO).

Site selection for the Kalundborg case

Two structures, both domal closures at Gassum Formation level were initially considered for the Kalundborg case study. These are the Røsnæs structure and the Havnsø structure and based on the initial screening and comparison of the two structures the Havnsø structure was chosen for further work in the CO2STORE case study. The top of the Havnsø structure is situated close to the small seaport of Havnsø approximately 15 km northeast of the city of Kalundborg. The depth to the top point of the reservoir is 1,500 m and the closure is estimated to cover an area of 166 km2. The spill point is situated in the south-eastern part of the structure at approximately 1850 m depth and the size of the structure makes it attractive not only for storage from the local CO_2 sources, but potentially also from point sources in the Copenhagen rural area approximately 85 km away.

The structure is identified on old (low-quality) 2-D seismic lines and at present no structural map has been published and the interpretation is based on internal GEUS work. The structure has not yet been drilled and the aquifer data are extrapolated from wells at Stenlille and Horsens. Lithologically the aquifer is expected to be roughly similar to that described for the Gassum Formation at the Stenlille gas storage facility were the basal part records a thick, relatively coarse-grained sandstone unit followed upwards by four sequences containing fine-grained sandstones and mudstones. The average porosity is estimated to 22% and the average permeability to around 500 mD. The net sand thickness is estimated to approximately 100 m and the structure has previously been calculated to hold 923 Mt CO_2, while a more detailed model suggests 846 Mt CO_2. The structure is sealed by a thick package of marine mudstones of the Fjerritslev Formation. The integrity of the mudstones towards CO_2 has not been tested in the laboratory, but geochemical modelling (see below) of the seal/ CO_2 reactions has been performed as part of the CO2STORE project.

Reservoir simulation and geochemical modelling

The reservoir in the Havnsø structure is divided into five reservoir units separated by clay or mudstones. The largest of the five units contains however 77% of the total storage volume of 846 Mt, corresponding to 651 Mt of CO_2. A preliminary simulation model running for a period of 100 years has been made for the Havnsø structure with the CO_2 injected into this main reservoir through a single 8 km long horizontal well completed over a length of 200 m. The calculations show that the rock properties in the reservoir will allow injection of 200 kg CO_2/sec equal to approximately 6 Mt/year (the total estimated emissions from the power plant and the refinery being approximately 4 Mt/year) in more than 100 years. The injected CO_2 will migrate to the top of the reservoir sequence while partly dissolving in the water. Eventually some CO_2 will escape by molecular diffusion, but numerical analysis suggests it will take more than one million years before such CO_2 reaches the surface.

Also long-term geochemical modelling was performed focusing on the role of low permeability clay layers within the reservoir, geochemical interactions in the cap rock and the temperature of the injected CO_2. These studies concluded that dissolution and precipitation will occur as a result of the acidity of dissolved CO_2. However the geochemical reactions are not expected to cause severe damage to the cap rock; after 4,500 years the CO_2 has entered the first 15 m of the cap rock.

Capture

The potential for CO_2 capture from Asnæsværket as well as requirements and technical aspects regarding capture has been described by ENERGI E2 as a constructed scenario and does not reflect the strategic plans of ENERGI E2. As the capture plant probably is to be used for both existing units as well as for a new power unit a conventional post combustion capture plant is anticipated. A flue gas rate of approximately 550 Nm3/s (dry, 6% O2) equal to round 1,800,000 Nm3/h (wet, act. O2) is estimated and a quite large capture plant is therefore needed. Dimensions of the absorber and stripper towers are expected to be 30-40 meters in height and 20-23 meters in diameter or alternatively divided into two towers each and a possible site for a future power unit and the capture plant has been located. An average CO_2 capture rate of 90% is expected and according to the EU project ENCAP a CO_2 delivery pressure of 110 bar and CO_2 delivery temperature of max. 30°C should be expected. There are no standards for CO_2 purity for different applications, but in the EU projects ENCAP and CASTOR CO_2 purity requirement is an area of investigation and provisional results prescribe purity for aquifer storage less restrictive than for e.g. Enhanced Oil Recovery or for ship transportation. Defined limits from ENCAP for the design case corresponding to pipeline transport and aquifer storage are anticipated to be quite easily reached, but on-going research may define more restrictive limits and a very high CO_2 purity may be very costly.

Surface transport

The requirements and costs for a 15 km surface pipeline from the power plant to the south-eastern flank of the Havnsø structure for transportation of maximum 6 Mt CO_2 per year has been evaluated by Statoil ASA as a “best guess” estimate. The lowest allowable pressure in the pipeline in order to prevent the CO_2 to change to gas phase is 60 bar and onshore gas pipelines are often operated at 80 bar. This will require an inside diameter of 0.330 m (13”), and the construction costs are estimated to be 625-750 € per metre or in total 9.4-11.3 Mill. € for 15 km pipeline. Calculations does however show that a change in pressure from 80 bar to e.g. 120 bar will not cause a dramatic change in diameter and the costs will thus not change significantly if a higher operating pressure is chosen.

A tentative pipeline route has been chosen to avoid densely populated areas and where possible to follow existing pipeline routes and high voltage cables. The pipeline would be dug into the ground and covered and it is anticipated that the soil types will not present major problems to the pipeline construction, but no geotechnical analyses have been made concerning the practicality of pipeline route and ground stability. Expropriation costs to landowners, cost for EIA and other costs covering the period from draft project to start of detailed project are not included in the estimate of the construction cost. Furthermore the cost estimate assumes that the pipeline and a normal ±25 m wide security zone with strict restrictions concerning buildings and general use can be constructed without conflicts with existing buildings.

Injection wells and monitoring

According to the reservoir model the Havnsø structure may be filled by one injection well, but to obtain the best injection control it is foreseen that three wells are needed. One of these wells is assumed to be reuse of a data acquisition well, planned as part of a fictitious data acquisition programme in the case study.

A monitoring system should be set up that will be able to prove that the CO_2 remains in the subsurface (with a view to obtaining CO_2 credits) and that no CO_2 leaks to the surface and thereby pose a risk to the environment, animals and humans. The feasibility of 4-D seismic as applied at the Sleipner Field, offshore Norway may be questioned in an onshore setting as the Havnsø structure for economic and practical reasons, while a number of shallow monitoring wells for detecting any gas migrating out of the storage structure as applied at the Stenlille gas storage may be used. In the project CO2SINK in Berlin a number of geophysical methods will be tested including cross-hole seismic and geoelectrical measurements and it is anticipated that a best practice manual will be issued on the monitoring possibilities.

Economic modelling

As part of the GESTCO project the economics in the Kalundborg case was modelled using the DSS module and it was calculated that the total cost would be 32€/t CO_2 avoided with the capture costs contributing with 2/3 of the amount. In the present case study a new economic evaluation using a modified version of the GESTCO DSS has been made. The conclusion from this sensitivity study was that a very high capture cost of e.g. 40€/t could make the scenario uneconomic which shall be seen in the light that most studies report present costs of 40-50 €/t CO_2 captured foreseeing reduction of capture costs to about 20 €/t.

Legal regulations and permission requirements

Emission reduction targets are linked to the Kyoto agreement and the EU is aiming at reducing greenhouse gas emissions by 8% relative to base year 1990. According to the EU's burden-sharing agreement the Danish contribution to be met in the period 2008-2012 is a 21% reduction. The EU Emission Trading Scheme (ETS) opened in 2005 for trading and exchange of CO_2 allowances and thereby sets a market price for CO_2. In Denmark a national system working in line with the ETS has been applied where each CO_2 emitter is allowed a specific CO_2 emission. Excess emission is taxed by 40 €/t in 2006/2007 rising to 100 €/t in 2008 onwards.

The OSPAR convention regulating the use of maritime areas and preventing any disposal of waste may come into force as 1/3 of the Havnsø structure is situated offshore. It is recommended that the risk of leakage from an underground storage should be evaluated against the effects of atmospheric CO_2 on the marine environment. The structure is also partly situated within an EF bird protection and special habitat area and EU RAMSAR area, but the underground storage facilities is not anticipated to be in conflict with these regulations. Pre-injection site surveys and monitoring surveys may however pose a problem and it is recommended that contact is made with the authorities early in the planning phase.

When building new large facilities or plants, the authorities must be contacted for an expression of whether an EIA will be necessary and most likely the permission requirements will include an EIA for capture plant, transport system and storage system, an environmental permission, a building permission and a technical approval of some parts of the installation. The EIA and environmental permission can progress in parallel and the total time for the two permissions is expected to be about 18 month. The time needed for building permission is anticipated to be negligible as the plant will be build on an existing power plant site. In planning of the pipeline and injection site special attention should however be made to the national Danish protection laws, although no conflicts are anticipated for the installations described in the CO2STORE scenario.

Risk assessment

The Quintessa FEP database (Features, Events and Processes) made available through the IEA Greenhouse Gas Programme has been used to address the risks related to underground CO_2 storage in the Kalundborg case study involving analysis of all relevant FEPs and identification of the most important FEPs: Geological features relating to the reservoir and cap rock, long term fate of injected CO_2 and impact on society and humans. Also project risks that could put the project on hold or eventually lead to exclusion of the storage site has been considered and several of these are related to project costs: Geological risks, low level leaks, monitoring, injectivity and well leak. Finally possible conflicts of use with geothermal energy, gas storage, hydrocarbon and drinking water has been investigated and are not expected to provide potential problems.

Recommendations

Indications are that the Havnsø geological structure is very suitable for storage of CO_2 and is probably one of the best in Denmark – possibly in Europe. With two large CO_2 emission point sources located in the nearby city of Kalundborg, a source – storage scenario with injection of 4-6 Mt CO_2 per year would be feasible, with the possibility of adding similar amounts of CO_2 transported in pipeline from sources in the greater Copenhagen area, less than 100 km to the east. In order to investigate and mature the Havnsø structure to become the first Danish saline aquifer CO_2 storage facility, a step-wise approach is envisaged:

1. Acquisition of new 3D seismic and a well to approx. 2,000 m and on-site dynamic flow test using small amounts of CO_2 for injection.
2. Injection of up to 100,000 tonnes of CO_2 per year in a number of years in an injection demonstration facility including monitoring systems.
3. Industrial storage of several Mt CO_2 per year.

Introduction

The Danish case-study of the CO2STORE project comprises the potential future capture and underground storage of CO_2 from two point sources. These are the coal fired power plant Asnæsværket and the Statoil refinery both located in the city of Kalundborg, Denmark.

Initial mapping of the storage structure was conducted as part of the EU funded research project GESTCO that was concluded in 2003. The study identified a large underground structure forming a potential, future storage site 15 km to the northeast of the city (Fig. 2). Porous sandstones filled with saline water at a depth of approximately 1.500 m form the reservoir. The structure covers approximately 160 km2 and a preliminary calculation suggests a storage capacity of nearly 900 million tonnes of CO_2 equal to more than 150 years of CO_2 emissions from the two point sources.

In the Kalundborg case-study, a fictive capture and storage scenario will be formulated and modelled. The scenario is based on experiences learned through the SACS and GESTCO projects. Detailed geological modelling, reservoir simulation, reservoir and cap rock characterisation and risk assessment will be important issues for the case-study.

The Geological Survey of Denmark and Greenland (GEUS) is project leader for the Kalundborg case-study. Information on CO_2 emissions from the point sources and technical and economical input for the three scenarios is provided by the industrial partners; ENERGI E2 and Statoil ASA. The scenario is designed only for this case study and does not reflect the strategic plans of ENERGI E2 nor Statoil ASA. Geochemical simulation and modelling studies on reservoir and cap rock were performed at Bureau de Recherches Géologiques et Minières (BRGM) in France. The CO2STORE project is performed within the European Community supported 5th Framework Programme.

Asnæsværket

Asnæs Power Station is located close to the city of Kalundborg on the Northwest coast of Zealand in the Eastern part of Denmark (Fig. 1). It is the biggest power station in Denmark with originally five units in operation with an installed capacity of 1,057 MW_{el} and 602 MJ/s heat. After closure of some of the units, the total installed capacity will be reduced to 787 MW_{el} and 552 MJ/s heat. Besides producing electricity for the grid, the power plant produces district heat for Kalundborg and process steam for the neighbouring industry.

As the remaining lifetime of the existing units is limited this case study foresees a new high-efficient pulverised-coal fired unit 6 to be taken into operation within 10 years. It is anticipated that the new unit 6 will be a unit of approximately the same size as the old unit 5 with regard to fuel input and flue gas rate (Table 1).

Figure 1. *The Asnæs power plant operated by Energi E2 (central part of photo) and the Statoil refinery (front of photo) in Kalundborg form the* CO_2 *sources of the fictive Kalundborg storage scenario exploiting the future possibilities for underground storage of* CO_2*. Photo courtesy of Energi E2.*

Technical data

Technical data of the three existing units (and provisional data of a new unit 6) are listed below:

		Unit 2	Unit 4	Unit 5	Unit 6 $^{1)}$
Commission	Year	1961	1968	1981	2015 ?
Rehabilitated	Year	1992, 2002	-	2004	-
Fuel		Coal / oil	Coal / oil	Coal / oil / Orimulsion	Coal / oil
Electrical output	MW	147	270	640	700
District heat output	MJ/s	100	-	150	-
Steam output	MJ/s	144	50	158	-
Electrical Efficiency $^{2)}$	%	40.0	40.3	39.9	48.0
Fuel input $^{2)}$	MJ/s	368	670	1,604	1,458
Flue gas (dry, 6% O_2) $^{2)}$	Nm^3/s	132	240	575	523
Max. CO_2 capture $^{2)}$	kg/s	31	57	137	125

Note $^{1)}$*: Under initial planning.* $^{2)}$*: Calculated with pulverized-coal as fuel.*

Table 1: *Technical data of the units at Asnæs Power Station.*

Emission sources

Unit 2 and unit 5 will presumably both be scrapped within 10-15 year and it is not anticipated that the flue gas from these units will be treated in the capture plant. Consequently, the capture plant will be designed and optimized to fit unit 6.

It is however still a possibility to build the capture plant as retrofit to unit 5 and when the new unit 6 goes into operation switch over and reuse the capture plant for unit 6. Data for unit 5 will therefore also be used in this report.

Emissions

The annual emissions of CO_2 from the units are estimated to:

Emissions		Unit 2	Unit 4	Unit 5	Unit 6 $^{1)}$
Operation mode		Peak load	Closes 2008	Base load	Base load
Production (equiv. full load hours)	h/year	1,500	None	6,200	6,800
CO_2 emissions $^{2)}$	tons/year	188,528	-	3,401,143	3,391,500
CO_2 capture $^{2)}$	tons/year	169,675	-	3,061,029	3,052,350
Flue gas (wet, act. O_2) $^{2)}$	Nm^3/h	443,927	809,307	1,913,644	1,708,181

Note $^{1)}$: Under initial planning. $^{2)}$: Calculated with pulverized-coal as fuel.
Calculations based on an emission of 95 g CO_2 pr. MJ coal and a CO_2 capture rate of 90%.

Table 2: *CO_2 emissions of the units of Asnæsværket.*

Statoil refinery

The Statoil refinery in Kalundborg is situated as close neighbour to the Asnæs Power station (Fig. 1). It is the largest refinery in Denmark with a production capacity of 5.5 million tonnes of hydrocarbon products/year (www.statoil.dk). Heavy oil and condensate from the North Sea are transported to the refinery by ship and final products are redistributed to Denmark (50%) and to countries surrounding the Baltic Sea. In addition to refining hydrocarbon products the refinery runs a fertiliser plant. The total CO_2 emission in 2004 was 491,476 tonnes according to the Statoil environmental report to the authorities. The emissions have been almost constant around 500,000 tonnes in the project period. But not all of the CO_2 will be available for the capture process as emission takes place from numerous smaller point sources with different flue gas composition scattered around the refinery. It is anticipated that any CO_2 captured at the refinery will be transported to the nearby power plant and stored together with the CO_2 captured there. Capture and storage will thus be totally dependent on the realisation of the power plant C&S project. The power plant and the refinery have a long history of co-operation within the ”Kalundborg industrial symbiosis” and products, heat and water are exchanged between the production units.

Storage site selection

The possibilities for underground storage of CO_2 in Denmark have previously been evaluated in two regional studies Joule II and GESTCO (Holloway *et al.* 1996; Larsen et al. 2003; Christensen & Holloway 2003). Both studies included storage potential in depleted hydrocarbon fields and deep saline aquifers.

Considering onshore storage in saline aquifers, structural traps will probably be the first option, in order to gain public and political acceptance. Storing CO_2 in well-defined traps in the subsurface thus, allow continuous monitoring of the fate of the injected CO_2 and eventually meets the demand for future recovery of all or parts of the injected gas. The concept is well-known from storage of natural gas e.g. at Stenlille and throughout Europe.

In the GESTCO (Geological storage of CO_2 from fossil fuel combustion) eleven well-defined closures were mapped from seismic surveys and their storage potential was evaluated using data from existing deep wells (Fig. 2).

The structural closures were selected on the basis of a number of criteria:

1. The top of the reservoir should be situated deeper than 900 m below the surface (the CO_2 gas changes into a supercritical fluid around 800 m).
2. The reservoir should be situated at depths less than 2,500 m in order to ensure that enough porosity/permeability is preserved (unless well data were present to validate porosity and permeability values)
3. The structure should be of significant size (storage capacity approximately 100 Mt)
4. A proper seal (cap rock) should be present
5. The structure and seal should be unfaulted
6. The structure should be within reasonable distance from a CO_2 source

Several other structures were part of the site selection screening, but excluded from the final list due to problems of satisfying one or more of the above criteria. These structures may form additional storage sites, but detailed site-specific studies are needed in order to prove their ability to store CO_2. The most common problem was the presence of faults either at the top of domal structures or forming the updip closure of traps (e.g. the Røsnæs structure close to Kalundborg, see Fig. 7). The fault bounded traps, however may present an interesting storage type along the Ringkøbing-Fyn-Møn High in the southern part of Denmark were domal storage structures are lacking.

Figure 2. *Map showing the position and outline of the eleven structural closures mapped in the GESTCO study. Black dots indicate the position of deep exploration wells used in the evaluation of the reservoir formation (From Larsen et al. 2003).*

Structure	**Stratigraphy**	**Formation**	**Available from**	**Area**	**Top depth msl**	**Gross thick**	**Net / gross**	**Net sand**	**Porosity**	**Pore volume**	**Effective storage volume**	**Reservoir density of CO_2**	**Storage capacity**
				km^2	m	m		m	%	km^3	%	kg/m^3	Mt CO_2
Gassum	U. Trias - L. Jurassic	Gassum	2002	242	1,460	130	0.32	53	25	2.517	40	627	631
Hanstholm[a]	U. Trias - L. Jurassic	Gassum	2002	603	1,000	230	0.40	92	20	11.095	40	620	2,752
Havnsø[a]	U. Trias - L. Jurassic	Gassum	2002	166	1,500	150	0.67	100	22	3.670	40	629	923
Horsens	U. Trias - L. Jurassic	Gassum	2002	318	1,506	94	0.26	24	25	1.943	40	630	490
Pårup[a]	U. Trias - L. Jurassic	Gassum	2002	121	1,550	130	0.23	30	10	0.362	40	625	90
Rødby	E. Triassic	Bunter Sst.	2002	55	1,125	256	0.18	45	24	0.608	40	620	151
Stenlille[b]	U. Trias - L. Jurassic	Gassum	Not available	10	1,507	130	0.76	100	25	0.247	40	631	62
Thisted	E. Triassic	Skagerrak	2002	649	1,203	756	0.6	454	15	44.158	40	622	10,987
Tønder[c]	E. Triassic	Bunter Sst.	2002	53	1,615	203	0.17	35	20	0.366	40	634	93
Vedsted	U. Trias - L. Jurassic	Gassum	2002	31	1,898	139	0.74	103	20	0.638	40	633	161
Voldum	U. Trias - L. Jurassic	Gassum	2002	235	1,757	128	0.38	49	10	1.143	40	630	288
Total storage capacity													**16,867**

[a] Extrapolated values, [b] Presently a natural gas storage operated by DONG, [c] Reserved for Natural Gas Storage

Table 3. *Table listing the key data for the eleven aquifer structures evaluated in the GESTCO project for future CO_2 storage in Denmark*

Geological storage

General geological setting

The geology of Denmark is characterised by a thick cover of sedimentary rocks of Late Palaeozoic – Cenozoic age. In the Danish Basin the sedimentary succession are up to 9 km thick (Fig. 3). The basin is bounded to the north by the Fennoscandian Border Zone characterised by a relatively thin succession of Triassic, Jurassic and Early Cretaceous age. To the south the Danish Basin is bounded by the northwest–southeast striking basement high, the Ringkøbing-Fyn-Møn High. The sedimentary cover on this structural high is relatively thin, 1–2 km and characterised by absence of Upper Permian sediments, thin Triassic and thin or absence of Jurassic sediments. The North German Basin is situated south of the basement high with sediment thickness comparable to the Danish Basin.

The sediments are affected by mainly northwest–southeast striking normal faults. In the Danish and North German Basin post depositional flow of Permian salt formed large domal structures, which strongly influenced later deposition. Locally the overlying sedimentary succession is deeply truncated over the top of rising saltdomes. Minor faults often accompany the salt structures.

The Chalk Group continues and thicken eastwards into the onshore area of Denmark where it reaches between 1 and 2 km in thickness in the Danish Basin. The presence of carbonates of the Chalk Group in the onshore and Kattegat areas may be of great importance providing a secondary chemical seal for CO_2 reservoirs situated in deep saline aquifers (Olsen & Stentoft 2003).

Deep saline aquifers

In the onshore or nearshore Danish area the potential reservoirs are of Mesozoic and Late Palaeozoic age. Mapping of these units has been performed in search for hydrocarbons and geothermal reservoirs (Michelsen 1981; Sørensen *et al*. 1998). Sørensen *et al*. (1998) summarises the reservoir parameters (porosity and permeability) whereas seal properties and presence of structural closures (trap) were not considered.

In the site selection phase four stratigraphic intervals were considered (Fig. 4)

- Bunter Sandstone and Skagerrak Formations (Triassic)
- Gassum Formation (Upper Triassic–Lower Jurassic)
- Haldager Sand Formation (Middle Jurassic)
- Frederikshavn Formation (Upper Jurassic–Lower Cretaceous)

The burial depth versus reservoir properties makes the Gassum Formation the most attractive storage option and the formation is currently used as reservoir for liquid natural gas (LNG) by DONG in the Stenlille area.

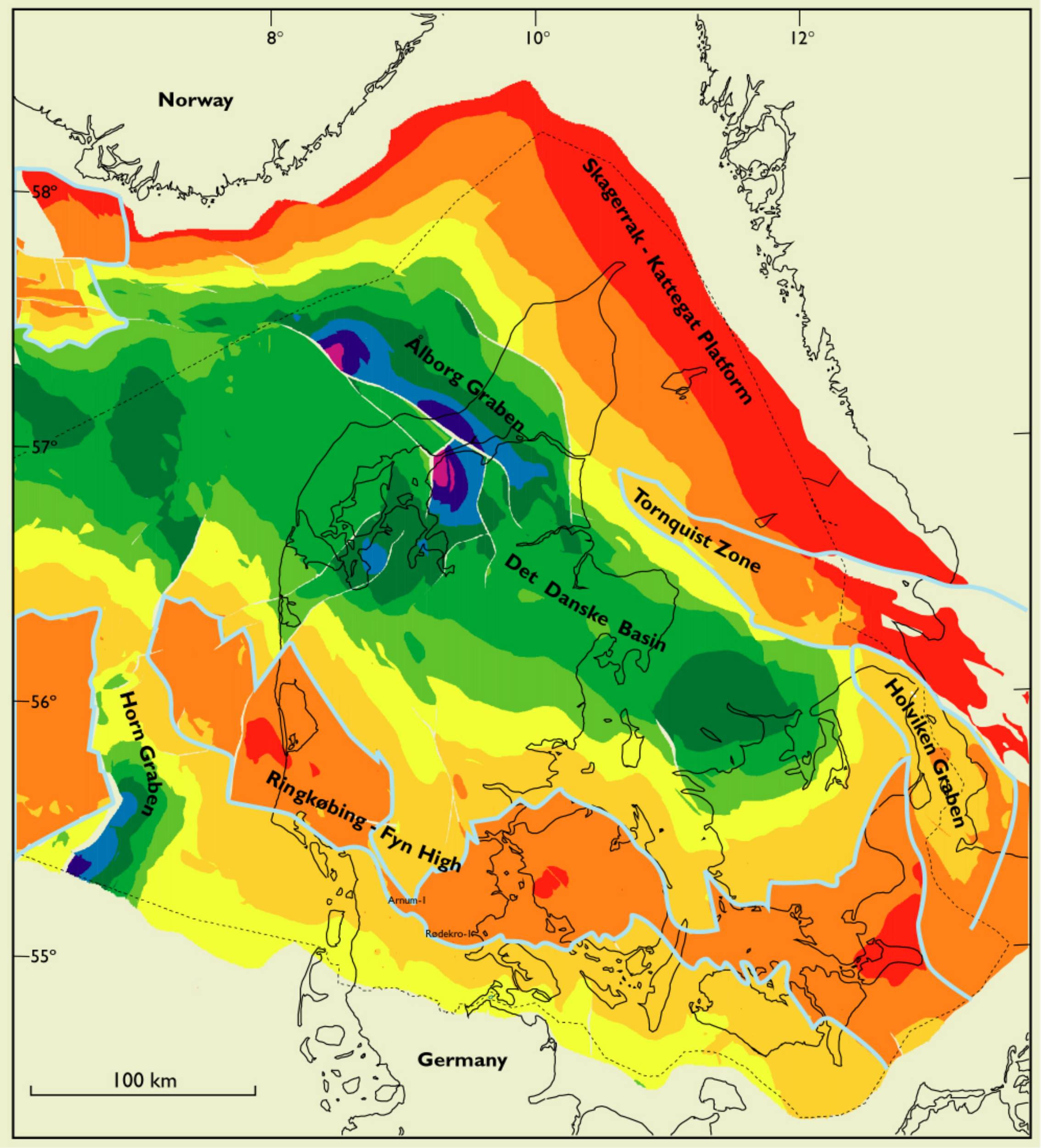


Figure 3. *Map showing major structural elements and depth (twt) to top Pre-Zechstein in Denmark. Modified from Vejbæk & Britze (1984).*

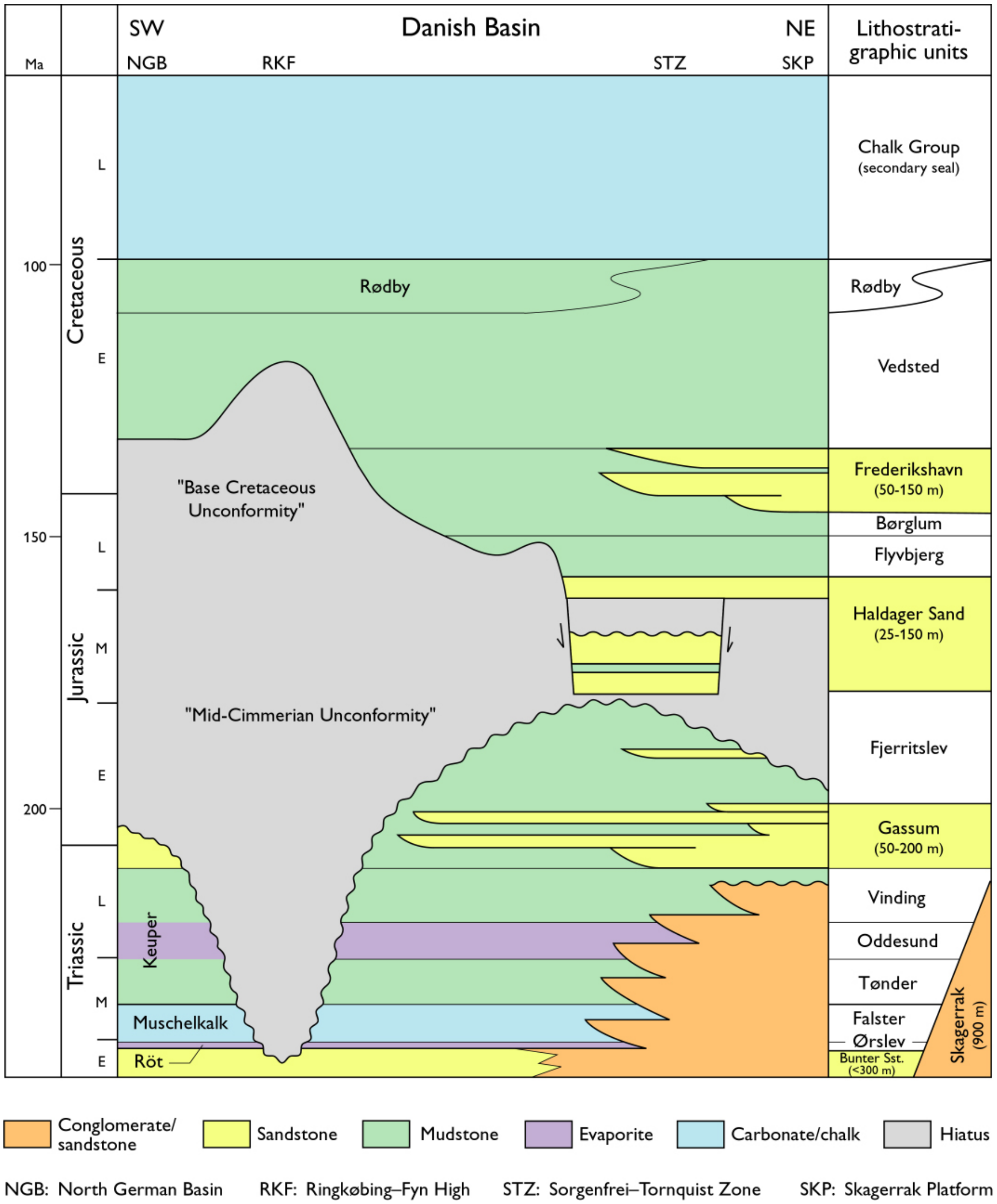


Figure 4. *Simplified stratigraphy and lithostratigraphy of the sedimentary succession in the Danish Basin. (Based on Bertelsen 1980, Michelsen & Clausen 2002; Michelsen et al. 2003).*

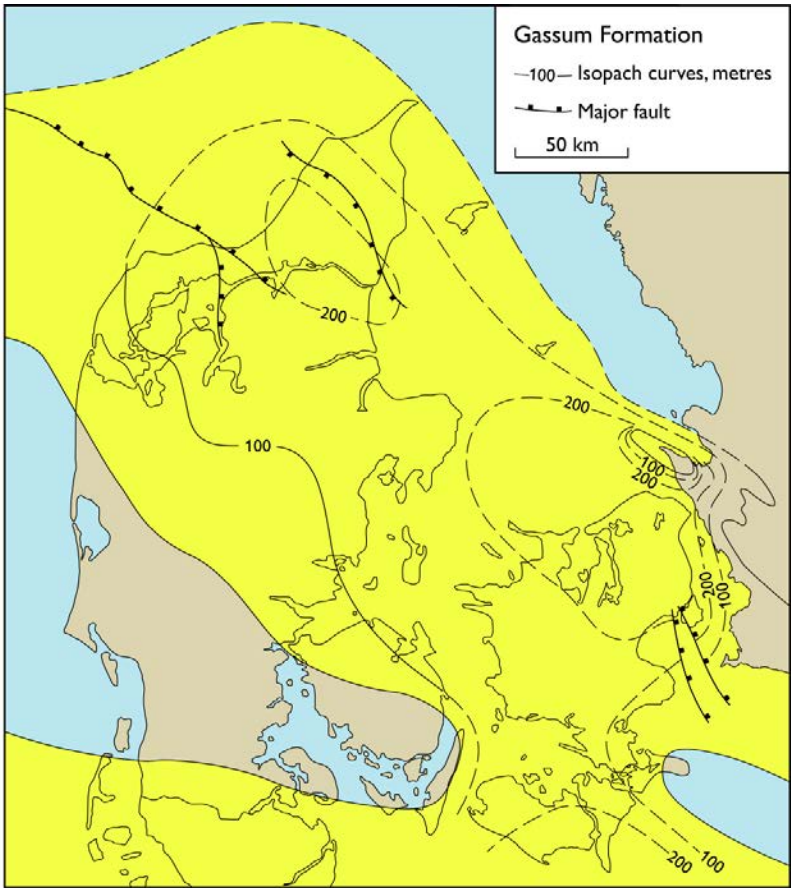


Figure 5. *Isopach maps showing the distribution and formation thickness of the Gassum Formation in the Danish area. Modified from Michelsen et al. (1981) and Haenel & Staroste (1988).*

Gassum Formation (Upper Triassic–Lower Jurassic)

The Gassum Formation consists of fine- to medium-grained, locally coarse-grained sandstones interbedded with heteroliths, claystones and locally thin coal beds (Michelsen *et al*. 2003; Nielsen *et al.* 2003). The formation is present in the Danish Basin, the North German Basin and on the Ringkøbing-Fyn High in the Lolland Falster area (Fig. 5). It shows a remarkable continuity with thickness between 100 and 150 m throughout most of Denmark, reaching a maximum thickness of 300 m in the Sorgenfrei-Tornquist Zone. The Gassum Formation is truncated by the base Cretaceous unconformity on the Ringkøbing–Fyn High (Fig. 4). The sandstones were deposited by repeated progradation of shoreface and deltaic units forming laterally continuous sheet sandstones separated by offshore marine claystones. Fluvial sandstones dominate in the lower part of the formation in the Fennoscandian Border Zone.

The porosity and permeability of the Gassum sandstones are known from a number of wells and illustrate the relation between reservoir properties and depth in the Danish Basin (Fig. 6). Generally the reservoir properties are excellent with porosity 18–27% (maximum 36%) and permeabilities up to 2,000 mD.

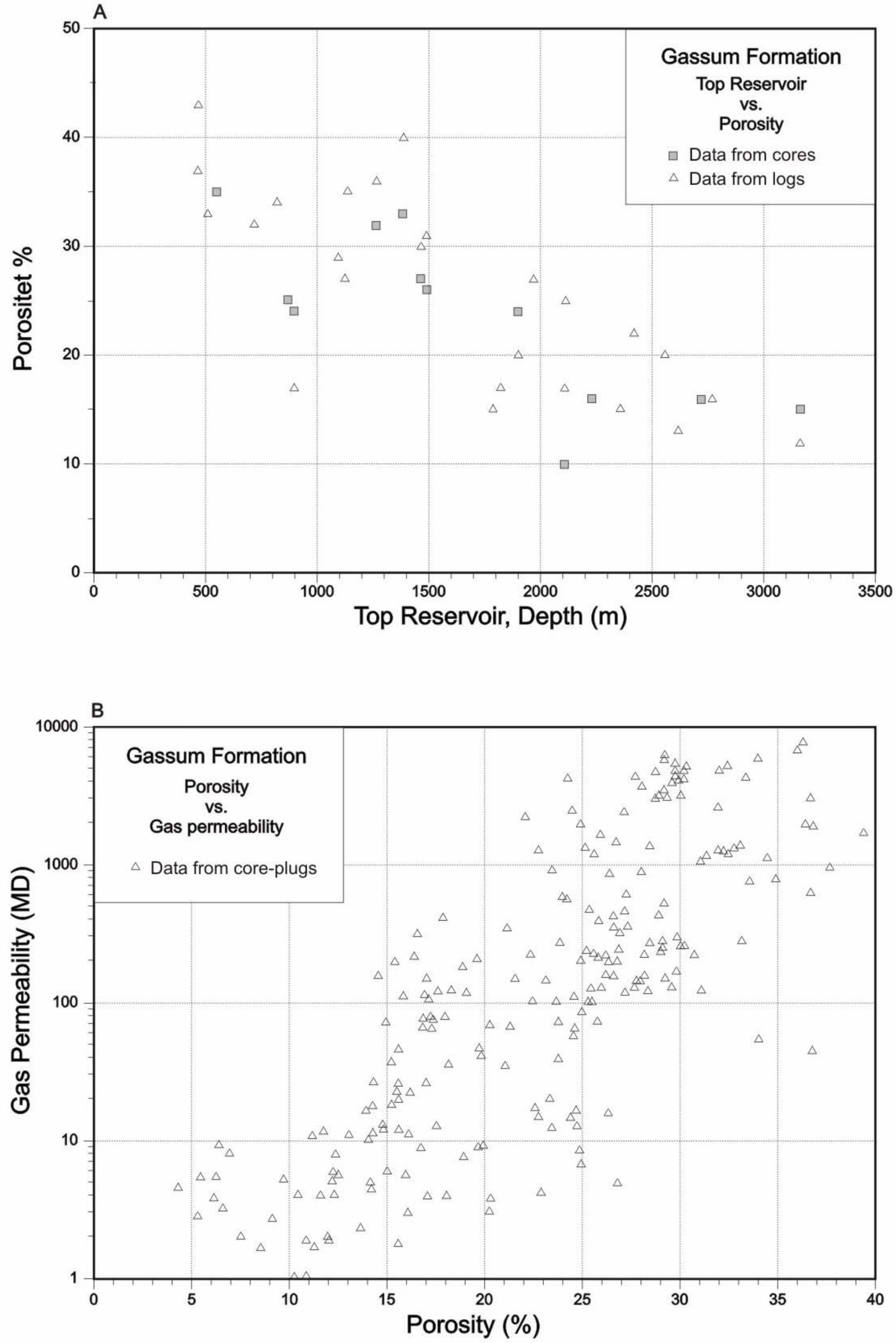


Figure 6. Porosity and permeability versus depth for the Upper Triassic–Lower Jurassic Gassum Formation. From Sørensen et al. (1998).

The Gassum Formation forms the reservoir in the Stenlille natural gas storage and has been studied in great detail (Nielsen *et al*. 1989; Hamberg 1994; Hamberg & Nielsen 2000;

Nielsen 2003). The studies illustrate the facies complexity and the lateral variability present within the reservoir units. In the Stenlille area the formation is thus shown to consist of stacked shoreface units with excellent reservoir properties separated with thin claystone or heterolithic units. Each of these units may act as discrete reservoir units and is characterised by a set of porosity/permeability parameters. Based on palaeogeographic reconstructions it is anticipated that the net/gross sand contents will decrease towards the northwest. In order to properly evaluate the storage potential within the formation, it may thus be necessary to address the individual sandstone units.

Seven structural traps are defined at Gassum stratigraphic level: The Hanstholm, Vedsted, Gassum, Voldum, Pårup, Horsens, Havnsø and Stenlille structures. The formation furthermore acts as geothermal reservoir in the geothermal plant at Thisted.

Seal

The aquifer storage of CO_2 is dependent not only on the properties of the reservoir but also on the integrity of the sealing formation. Geological formations in Denmark with sealing properties are lacustrine and marine mudrocks, evaporites and carbonates. The most important sealing rock type in the Danish area is marine mudstone, which is present at several stratigraphic levels. Leakage may take place through the cap rock due to slow capillary migration, through micro-fractures or along faults. Detailed site surveys will be needed in order to test the integrity of the seal at future storage sites. As part of the site screening criteria for storage structures it was assumed that no faults crossing the caprock were identified on seismic lines crossing the storage sites. Minor fractures and fault, however cannot be excluded in the screening phase. Due to the widespread occurrence of thick mudstone deposits no specific caprock criteria were formulated in the Kalundborg case.

Fjerritslev Formation

Marine mudstones of the Lower Jurassic Fjerritslev Formation form the primary sealing unit for the Gassum Formation. The formation overlies and locally interfingers with the sandstones of the Gassum Formation.

The formation is characterised by a relatively uniform succession of marine, slightly calcareous claystones, with varying content of silt and siltstone laminae. Siltstones and fine-grained sandstones are locally present being most common in the northeastern, marginal areas of the Danish Basin. Deposition took place in a deep offshore to lower shoreface environment (Michelsen 1975, 1978, Michelsen *et al*. 2003). The formation is present over most of the Danish Basin with a thickness of up to 1,000 m although this varies significantly due to mid-Jurassic erosion. At Stenlille natural gas storage site marine mudstones of the Lower Jurassic Fjerritslev Formation form the sealing formation. The mudrock was tested before the beginning of the gas injection. The seal has proven tight to natural gas stored in the Gassum reservoir below.

Chalk Group

In most of the Danish area a several kilometres thick succession of carbonate rocks of Late Cretaceous – Danian age forms a possible secondary seal (Fig. 4). The sealing effect is related to chemical reactions between dissolved CO_2 and the carbonate rock. These reactions are described in detail in the GESTCO report on the CO_2 – Carbonate system by Olsen & Stentoft (2003).

Subsurface storage capacity

The total storage capacity for CO_2 in Denmark was presented in the Joule II report (Holloway *et al.* 1996). The report concluded that 47 Gt CO_2 could be stored in the unconfined onshore aquifers of Triassic and Jurassic age based on the assumption that 2% of the entire pore volume of the mapped formations was filled. Restricting the storage to confined traps reduced the estimated total storage capacity to 5.6 Gt CO_2 due to the momentary pressure increase.

The low storage efficiency (2%) was based on reservoir simulations indicating that the CO_2 would spill from the traps before a significant amount of the formation pore space was filled. In the GESTCO study the storage capacity calculations were based on structural traps with well-defined spill points. Using experiences from Liquid Natural Gas (LNG) storage facilities in Denmark, Germany and France it was assumed that 40% of the total pore volume within a defined trap may be filled with CO_2. Initial calculations suggest that these structures alone may provide storage for at least 16 Gt CO_2 (Table 3) (Larsen et al. 2003).The effective storage capacity however, will depend on a number of parameters including the geometry of the trap e.g. difference in height between top point and spill point, number of injection wells and injection rates, migration barriers within the reservoir unit and reservoir characteristics.

Several reservoir units are present in a number of the described structures. These stacked reservoir units provide an upside potential for storage increasing the total storage capacity. The secondary reservoir units are, however, often poorly known and storage volumes have not been calculated for these units. The storage capacity presented in Table 3 is thus calculated for the primary reservoir unit alone.

The difference between storage capacity estimates in the Joule II project (based on regional aquifers) and the GESTCO project (based on defined traps) illustrates the principle of “less storage capacity with better confidence”. It is anticipated that the site characterisation process developed in the CO2STORE project will increase the amount of knowledge, but also reduce the estimate of total storage capacity within the countries.

Storage in confined and unconfined aquifer

In the Joule II project (Holloway *et al*. 1996) the saline aquifers were divided into open (unconfined) and closed (confined) systems, the latter representing storage potential within traps. The two types were assigned different reservoir properties. In the unconfined aquifers the CO_2 phase is allowed to displace the pore fluids within the entire extent of the aquifer.

In the case of confined systems the pore fluid is not able to migrate outside the trap. This results in instantaneous pressure increase at the beginning of CO_2 injection and a storage volume that is restricted by the compressibility of the pore fluid and the reservoir rock.

In this study the aquifers of the eleven structural closures are considered unconfined meaning that the saline formation water may be displaced to the aquifer outside the closure by the injected CO_2. It is however, assumed that the injected free phase CO_2 will stay within the closure defined by the structural trap.

Storage by dissolution of CO_2 into the formation water

CO_2 is dissolvable into water as demonstrated by sparkling water. The dissolution process is controlled mainly by temperature, pressure and salinity. Under normal geological conditions between 5 and 8% CO_2 may be dissolved. The rate of dissolution is dependent on the efficiency of mixing at the CO_2/water interface.

CO_2 is more buoyant and much less viscous than the saline formation water. Depending on the injection point the CO_2 will migrate from the head of the injection well towards the top of the aquifer trap. During this process a small proportion of the CO_2 will dissolve in the formation water. By choosing an injection point at the flank of the structures instead of the top the amount of CO_2 dissolved into the formation water may be increased due to the longer migration path of the CO_2.

Simulation of the reactions between the formation water and the injected CO_2 show that there is a slow, but continuous diffusion of CO_2 also after the CO_2 has reached the top of the structure. This process may in a long time perspective (thousands of years) remove all of the free injected CO_2 phase from the trap (Ennis-King & Paterson 2003).

Numerical simulations carried out in the present study are also considering CO_2 dissolution (Bech & Larsen 2005), see also section on Reservoir simulation, page 33.

Site selection for the Kalundborg case

Two structures were initially considered for the Kalundborg case study. Both are domal closures at Gassum Formation level situated in the Kalundborg area (Fig. 7). The reservoir units in both structures are shoreface sandstones of the Gassum Formation and marine mudstones of the Fjerritslev Formation as cap rock. Based on the initial screening and comparision of the two structures (Table 4) the Havnsø structure was chosen for further work in the CO2STORE case study.

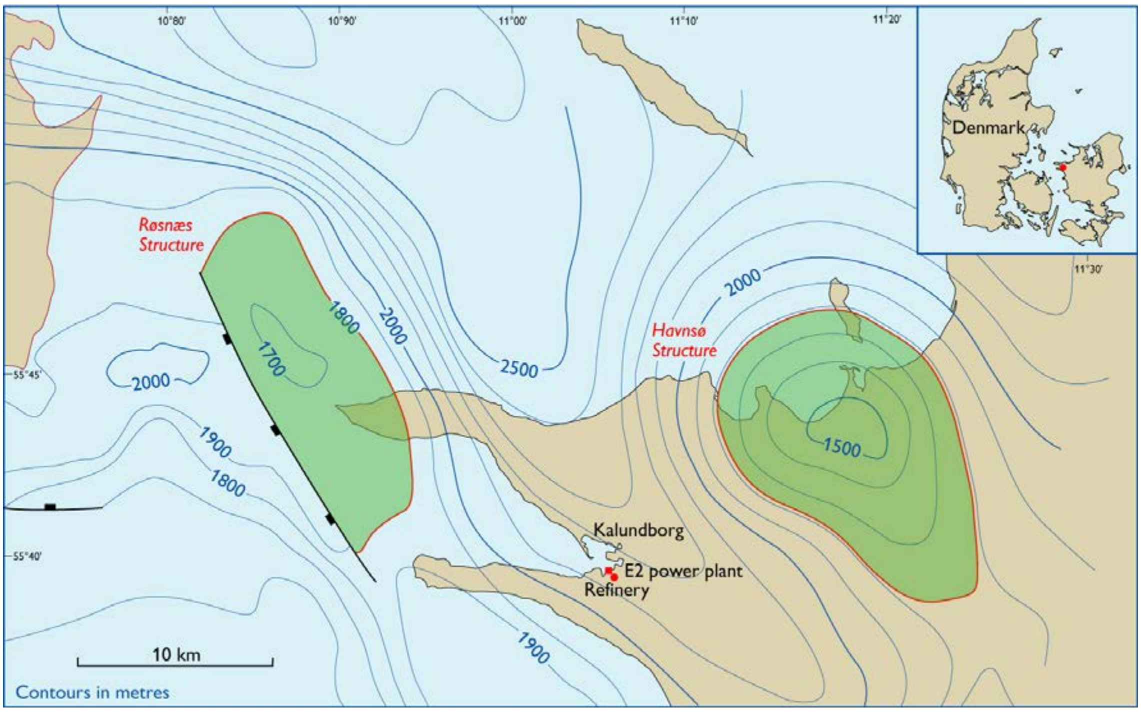


Figure 7. *Depth structure map of the Havnsø and Røsnæs closures. Both structures are defined in the Upper Triassic-Lower Jurassic Gassum Formation.*

Storage	**Havnsø**	**Røsnæs**
Onshore/offshore	2/3 onshore, 1/3 offshore	Offshore
Reservoir	Gassum Formation	Gassum Formation
Stratigraphy	Late Triassic	Late Triassic
Lithology	Siliciclastic sandstone	Siliciclastic sandstone
Top depth msl	1500 m	1700 m
Gross thickness	150 m	100 m
Net/gross	0.67	0.5
Net sand	100 m	50 m
Porosity	22	20
Permeability	500 mD	200 mD
Pore volume	3 670 km^3	900 km^3
Pressure	150 bar	170 bar
Temperature	~ 50 ºC	~ 55 ºC
Reservoir density of CO_2	629 kg/m^3	631 kg/m^3
Seal	Fjerritslev Formation	Fjerritslev Formation
Stratigraphy	Early Jurassic	Early Jurassic
Lithology	Marine mudstone	Marine mudstone
Gross thickness	500 m	500 m
Trap	4-D domal clossure	Fault closure (Neogene movement)
Area of closure	166 km^2	90 km^2
Distance to source	15 km	18 km
Effective storage factor	40%	40%
Storage capacity	923 Mt	227 Mt
Comments	Eclipse simulation	

Economic/Risk evaluation	**Havnsø**	**Røsnæs**
3-D seismic	High costs	Low costs
Drilling	Low costs	Medium costs
Transport	Onshore pipeline	Offshore pipeline
Monitoring	Wells	Seismic
Permission requirements	National and local authorities	OSPAR/ National and local authorities
Risk project	High seismic costs	Fault sealing capacity
Risk humans	Low	None
Risk environment	Low	Low

Table 4. *Comparison of the Havnsø and Røsnæs structures.*

Havnsø Structure

The closure is situated at the small harbour Havnsø approximately 15 km northeast of Kalundborg (Fig. 7). Approximately 1/3 of the structure is situated offshore, with the top point situated onshore. The structure was evaluated as possible natural gas storage in the eighties, but was excluded for the Stenlille structure. The depth to the top point of the reservoir is 1,500 m and the closure is estimated to cover an area of 166 km^2. The spill point is situated in the south-eastern part of the structure at approximately 1,850 m depth (Fig. 7).

The size of the structure make it attractive for storage of CO_2 not only from the local CO_2 sources but also from the point sources in the Copenhagen rural area. The distance to Copenhagen is approximately 85 km.

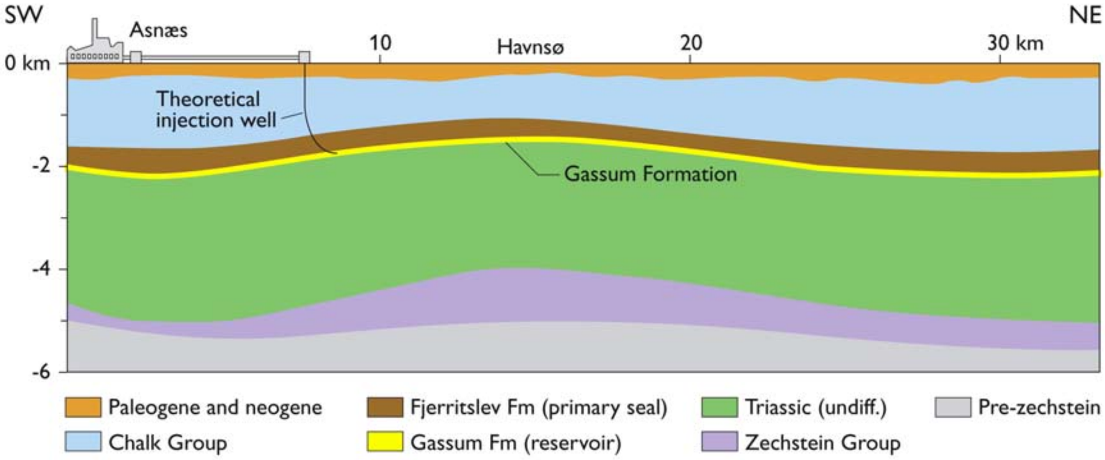


Figure 8. *Schmatic geological cross-section through the Havnsø structure.*

Seismic coverage

The structure is identified on old (low-quality) 2-D seismic SSL Survey lines 73/038 and 73/039 (Figs. 9, 10). At present no structural map has been published and the interpretation is based on GEUS internal work.

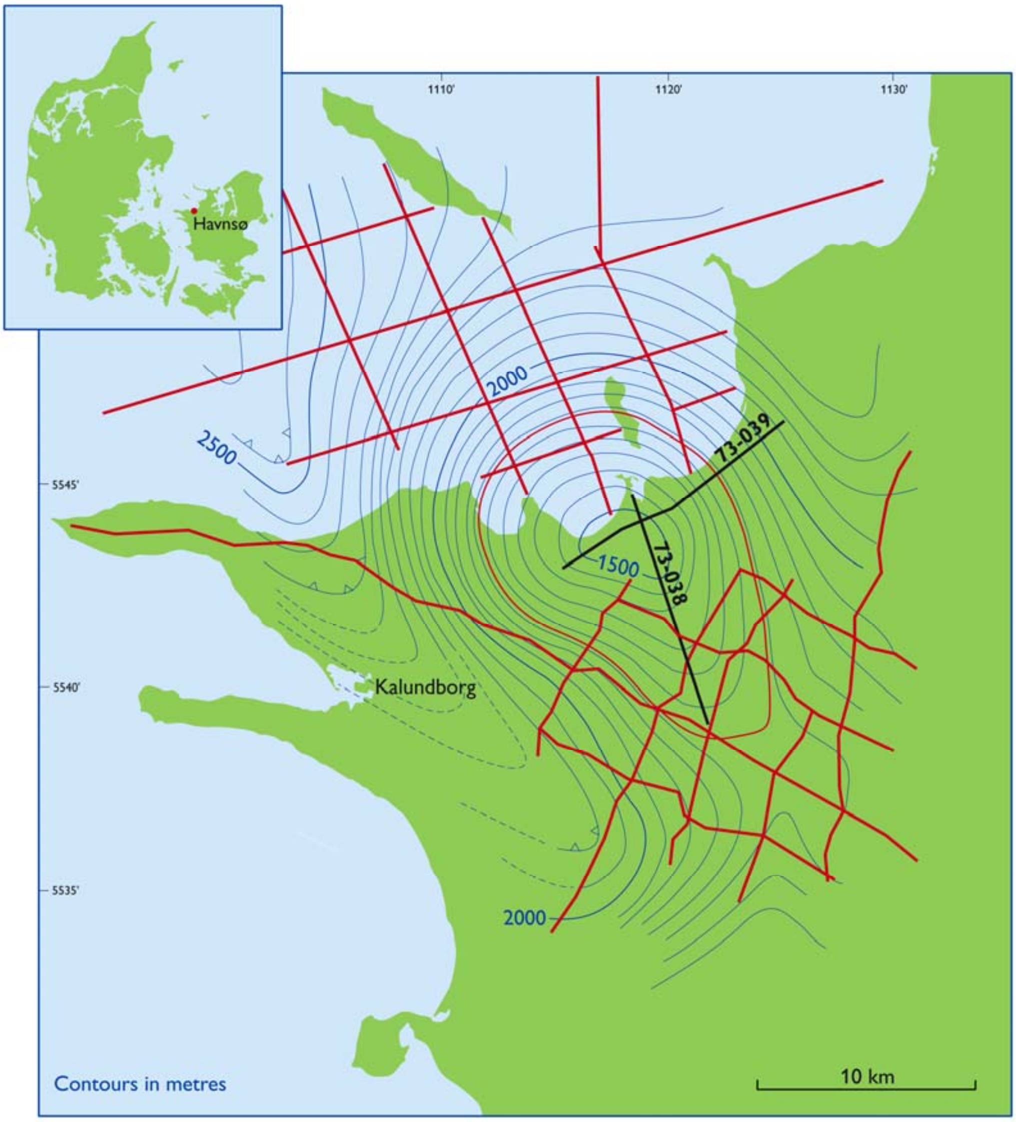
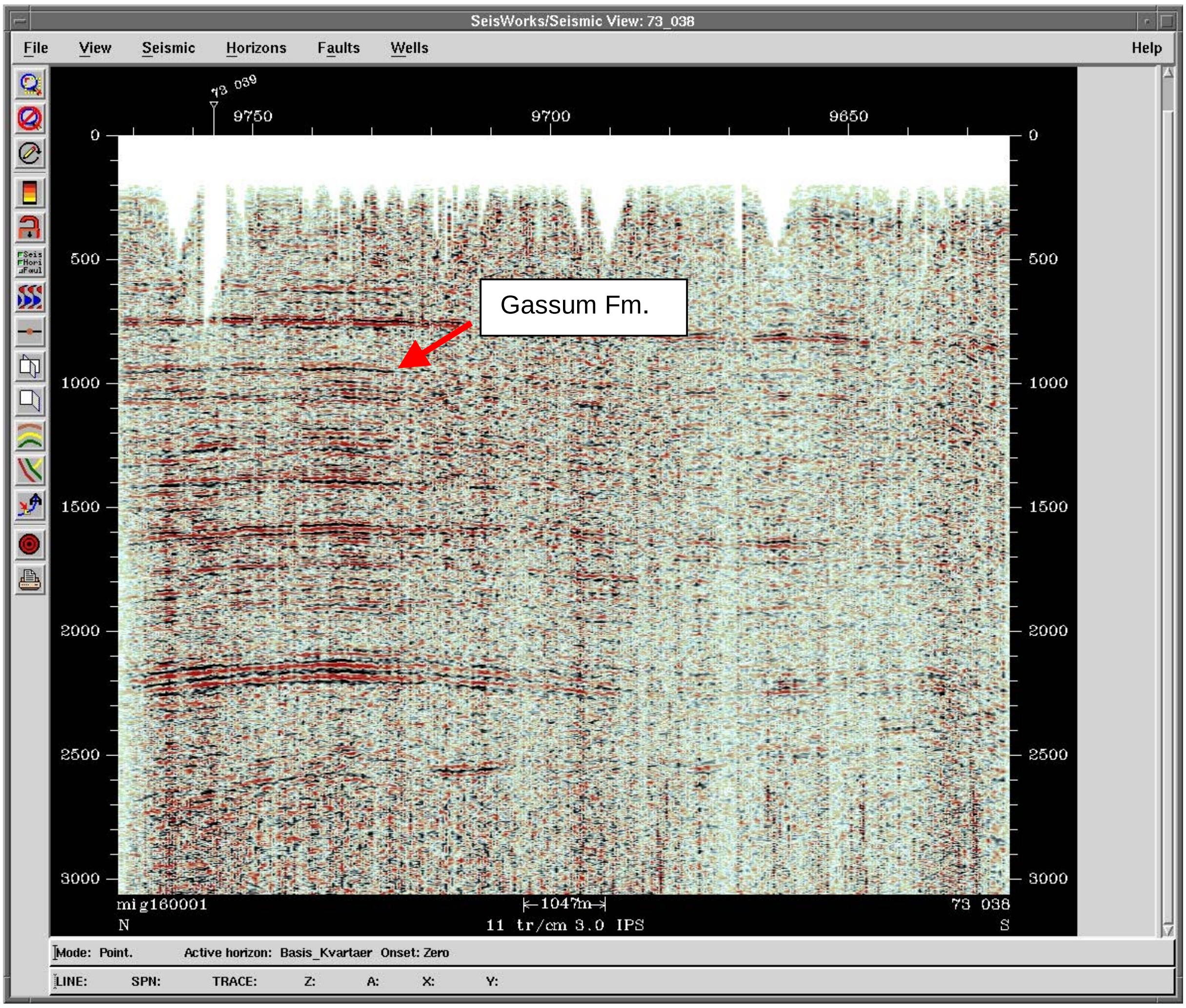


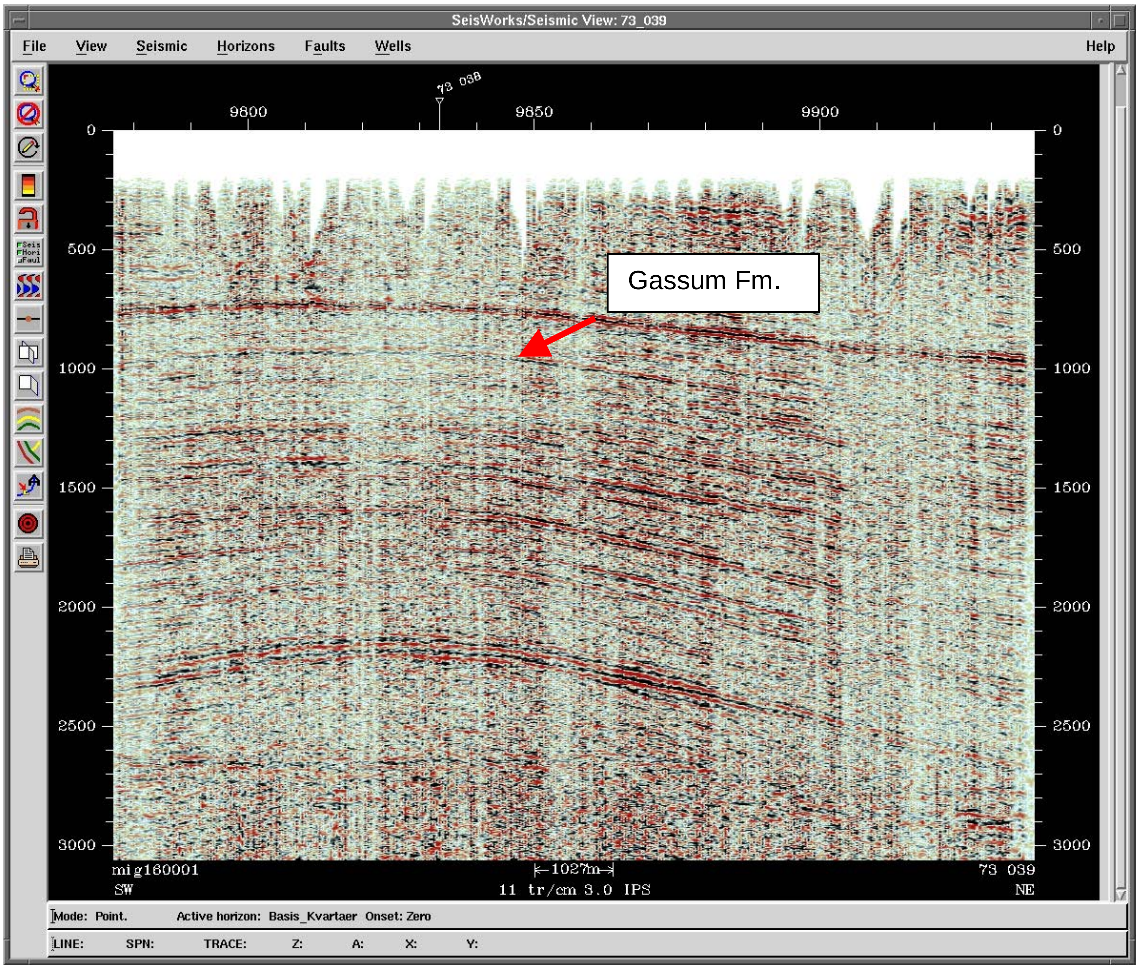
Figure 9. *Seismic line map. Two examples 73-038 and 73-039 are given below in figure 10 A and 10B.*



Mode: Point. Active horizon: Basis_Kvartaer Onset: Zero

LINE: SPN: TRACE: Z: A: X: Y:

Figure 10A. *North-south seismic line crossing the top of the Havnsø structure. Depth in TWT ms.*



Mode: Point. Active horizon: Basis_Kvartaer Onset: Zero

Figure 10B. *Southwest-Northeast seismic line crossing the top of the Havnsø structure. Depth in TWT ms.*

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Information from wells

The Havnsø structure has not yet been drilled and the aquifer data are extrapolated from the Stenlille-1, Stenlille-19 and Horsens-1 wells (Fig. 11 and Table 5). Palaeogeographic models suggest that the reservoir quality of the sandstones will decrease in an offshore direction towards the northwest relative to the Stenlille structure where the formation is well-known. The Gassum Formation has been described in detail by (Nielsen et al. 1989; Hamberg 1994; Hamberg & Nielsen 2000; Nielsen 2003).

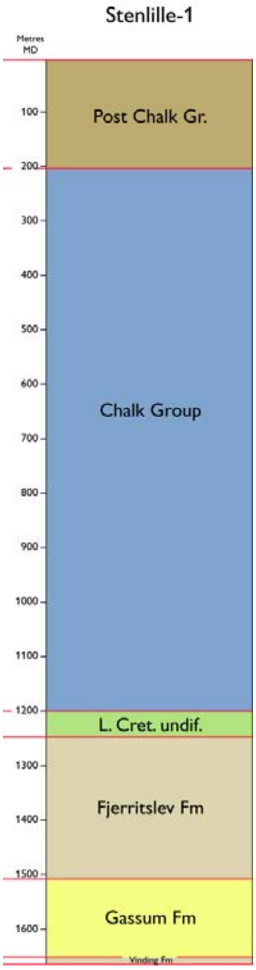


Figure 11. *Stratigraphic depth section of the Stenlille-1 well showing the lithostratigraphic units and their thickness. The main reservoir in sandstones of the Gassum Formation. The lithostratigraphic units and definition of formation boundaries in the deep wells are based on Nielsen & Japsen (1991).*

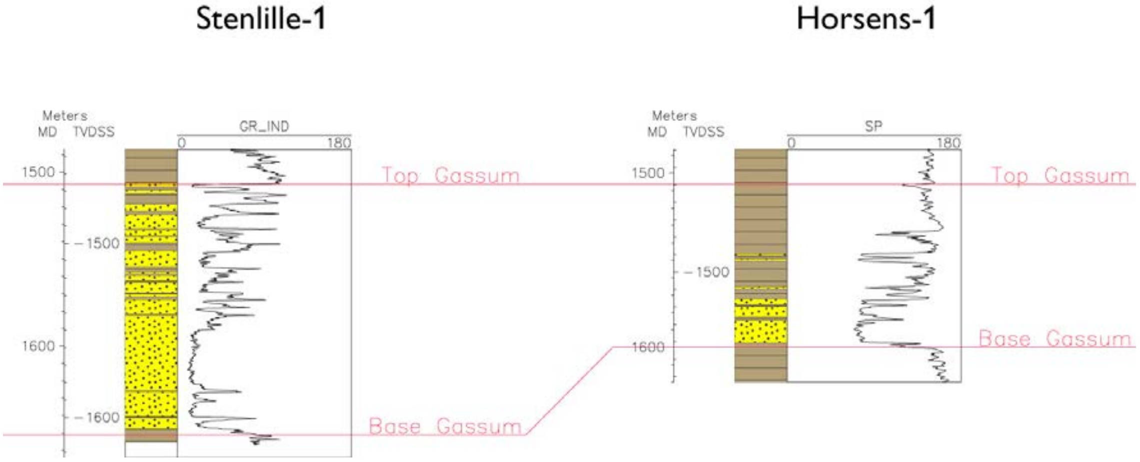


Figure 12. *Petrophysical well logs of the Stenlille-1 and Horsens-1 wells showing the interpreted sand/shale ratios and lateral variability of the primary reservoir unit. The top and base of the reservoir is based on interpretations given in Nielsen & Japsen (1991).*

Havnsø	**Stratigraphic units with possible reservoirs**				**Reservoirs**					
Wells	Name		Depth Interval MD m	Gross Reservoir Thick. M	SAND Cut-off Value	Net Reservoir Thick. M	Sand/Gross Ratio	Porosity %	Permeability mD	Temp. °C
Horsens-1		Lower Cretaceous undiff.	1,111-1,168	57						
	Gassum Fm	Gassum Fm:	1,449-1,543	94	90 API SP	25	0.26	S-31, C-25	G-500	
Stenlille-1		Lower Cretaceous undiff.	1,158-1,205	47	GR=56	1	0.02			
	Gassum Fm	Lower Jurassic 2; TS 10 - TS 11	1,326-1,398	72	GR=56	9	0.13			
		Lower Jurassic 1; TS 7 - TS 10	1,398-1,465	67	GR=56	6	0.09			
		Gassum Fm; Base Gassum - TS 7	1,465-1,609	144	GR=56	110	0.76	20-25		60-70

Table 5. *Table listing the closest wells and reservoir characteristics of stratigraphic units with potential for storage of* CO_2 *. The porosity values are given by F: porosity based on FDC log, C: porosity measured on core. The permeability values are given by G: air permeability measure on core, L: liquid permeability measured on core. Based on Michelsen (1981)*

Storage quality

Lithologically the aquifer is expected to be roughly similar to that described for the Gassum Formation at the Stenlille gas storage facility were the basal part records a thick, relatively coarse-grained sandstone unit (Fig. 12 and Table 6). This unit is followed upwards by four sequences containing fine-grained sandstones and mudstones (Nielsen *et al.* 1989). The porosity varies between the different reservoir units but an average of 22% has been applied for the storage calculations. The permeability of the Havnsø structure is unknown, but is estimated to be comparable to the values seen in Stenlille where the Gassum Formation occurs at similar depth, having average permeability around 500 mD. The high permeability is important for obtaining high injection rates of CO_2.

Subsurface storage capacity

Based on the reservoir information from the Stenlille natural gas storage and the north-westwards facies changes of the Gassum Formation, the gross thickness is estimated to be 150 m with a net/gross of 0.67 leading to approximately 100 m of net sand. No information exists on the actual reservoir pressure and temperature and hydrostatic pressure and regional temperature gradients have been applied in the storage calculations. The structure has previously been calculated to hold 923 Mt CO_2. A more detailed model for the reservoir is presented by Bech & Larsen (2003, 2005) and suggests 846 Mt CO_2.

Compartment no.	Reservoir model layer(s)	% of total pore volume	Pore volume (km^3)	Storage capacity (Mt)
1	1	5.7	0.21	48
2	2	1.3	0.05	11
3	3 – 7	14.9	0.55	126
4	8	1.2	0.04	10
5	9 – 15	76.9	2.85	651
Total reservoir	1 – 15	100.0	3.70	846

Table 6. *Definition, pore volume and estimated storage capacity of the five reservoir compartments in the Havnsø structure. From Bech and Larsen (2003, 2005).*

Seal

The structure is sealed by a thick package of marine mudstones of the Fjerritslev Formation (Figs. 8, 11). Laboratory experiments and full-scale test at the Stenlille natural gas storage facility suggests that the claystones form a tight seal. The integrity of the claystones towards CO_2, however, has not been tested in the laboratory. Geochemical modelling of the seal/CO_2 reactions were performed by BRGM as part of the CO2STORE project and are presented below.

Reservoir simulation

A simulation model using Eclipse 100 has been made for the Havnsø structure. The calculations are reported in Bech & Larsen (2005) and show that the rock properties in the reservoir would allow injection of 200 kg CO_2/sec equal to the average daily emission rates of Asnæsværket. The CO_2 may be injected through a single injection well perforated over a length of 200 m. The simulation was run for a period of 100 years.

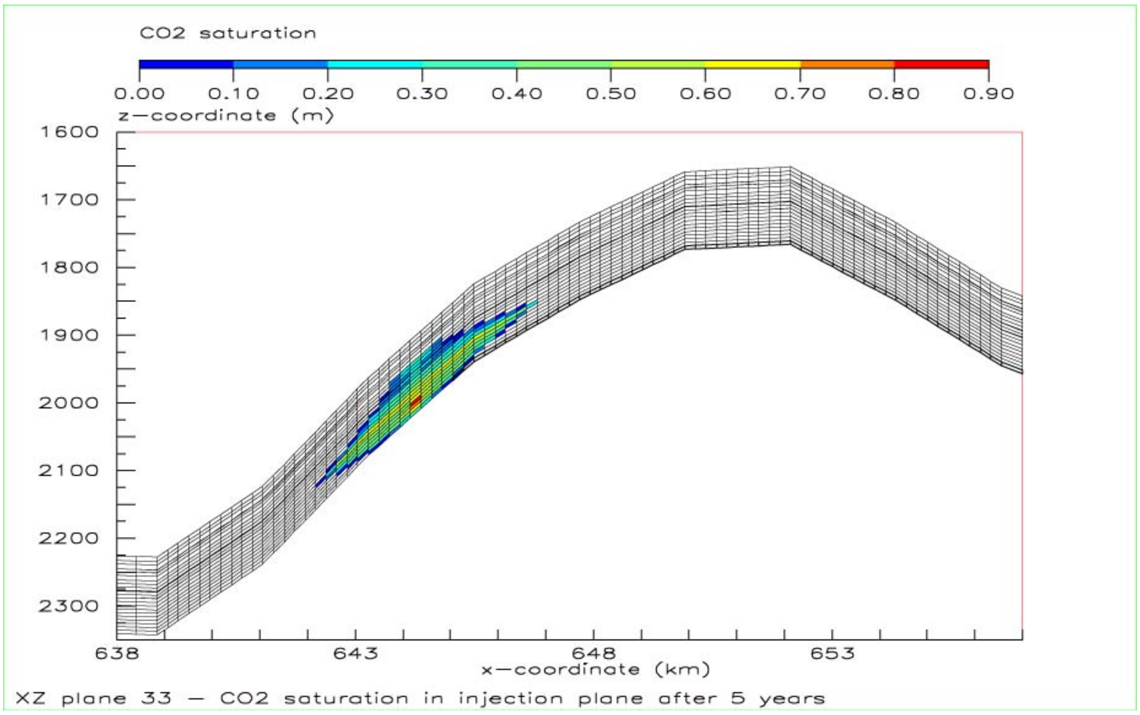


Figure 13. *Vertical distribution in injection plane of CO_2 saturation in the Havnsø structure after 5 years of injection. The injection rate was 200 kg/sec or 6 million tons/year in 100 years.*

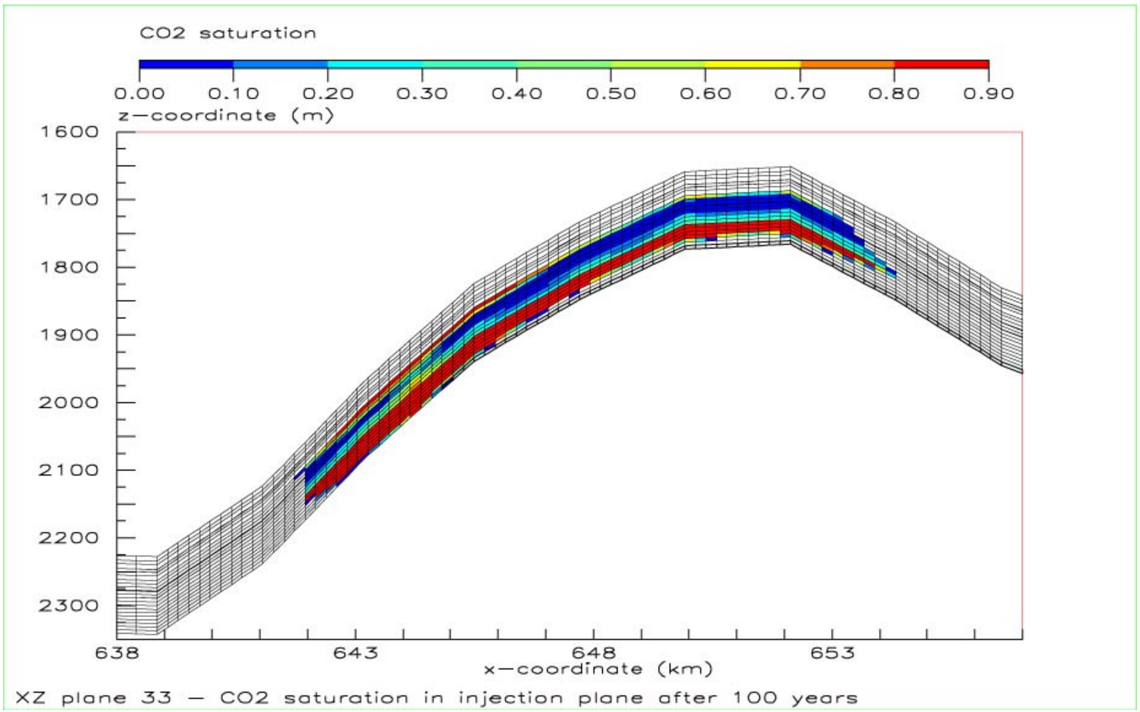


Figure 14. *Vertical distribution in injection plane of CO_2 saturation in the Havnsø structure after 100 years of injection. The injection rate was 200 kg/sec or 6 million tons/year in 100 years.*

The Havnsø reservoir is divided into five compartments, which means that it is necessary to inject the CO_2 at five different locations to fully exploit the available total storage volume which is estimated to 846 million tons of CO_2. However, the largest of the five compartments contains 77% of the total storage volume corresponding to 651 million tons of CO_2 and the present simulation study demonstrates that this is large enough to hold the emission from the Asnæs power plant and nearby refinery at Kalundborg for 100 years. That emission is 6 million tons of CO_2 per year (1994–1999) corresponding to 200 kg/sec or 630 million tons over 100 years. The CO_2 is injected into the reservoir through a horizontal well 8 km long and completed over a length of 200 m. The maximum permissible injection pressure of 300 bar is reached, but only during the first few days.

The injected CO_2 migrates to the top of the reservoir compartment while partly dissolving in the water.

The CO_2 will eventually escape by molecular diffusion, but it will take more than one million years before the CO_2 reaches the surface.

Geochemical modelling

Long term geochemical modelling was performed by BRGM as part of the CO2STORE case study. It was decided to focus the modelling on the role of the low permeability clay layers on the geochemical interactions, the geochemical interactions in the cap rock and the impact of a difference between the temperature of the injected CO_2 and the reservoir temperature. The study is reported by (Durst & Gaus 2005) and the summary given below is an extract from this report.

Scenario 1 - Diffusion in the cap rock

In this scenario long term diffusion modelling of CO_2 loaded brine is performed using a 1D-coupled model taking into account the caprock mineralogy in order to assess the potential porosity changes at the base of the caprock. Data incorporated in the model: temperature, pressure, cap rock mineralogy, porosity and brine composition

Scenario 2 – Impact of CO_2 on shale layers in the reservoir when supercritical CO_2 is assumed to flow through the shale (open geochemical system)

In this scenario, CO_2 loaded brine is supposed to flow through some weak zone of a shale layer and the 1-D modelling is aimed to determine if the geochemical reactions are likely to prohibit the flow or to enhance it. Data incorporated in the model: temperature, pressure, shale layer mineralogy, reservoir mineralogy below and above the shale layer, porosities, brine composition.

Scenario 3 – Impact of CO_2 on shale layers in the reservoir when it is assumed that only diffusion of dissolved CO_2 through the shales occurs

The reservoir is interbedded with shale layers with very low vertical permeability that can act as local “cap rock” and possibly help trapping the CO_2. This scenario investigates the behaviour of the shale layer when no fluid flow can go through. A 1-D modelling of the diffusion of the CO_2 in the shale and in the reservoir above it is performed to assess the potential porosity changes as well as the time needed for the CO_2 to break through the shale.
Data incorporated in the model: temperature, pressure, shale layer mineralogy, reservoir mineralogy below and above the shale layer, porosities, brine composition.

Below is given a conceptual diagram of scenario’s 1–3.

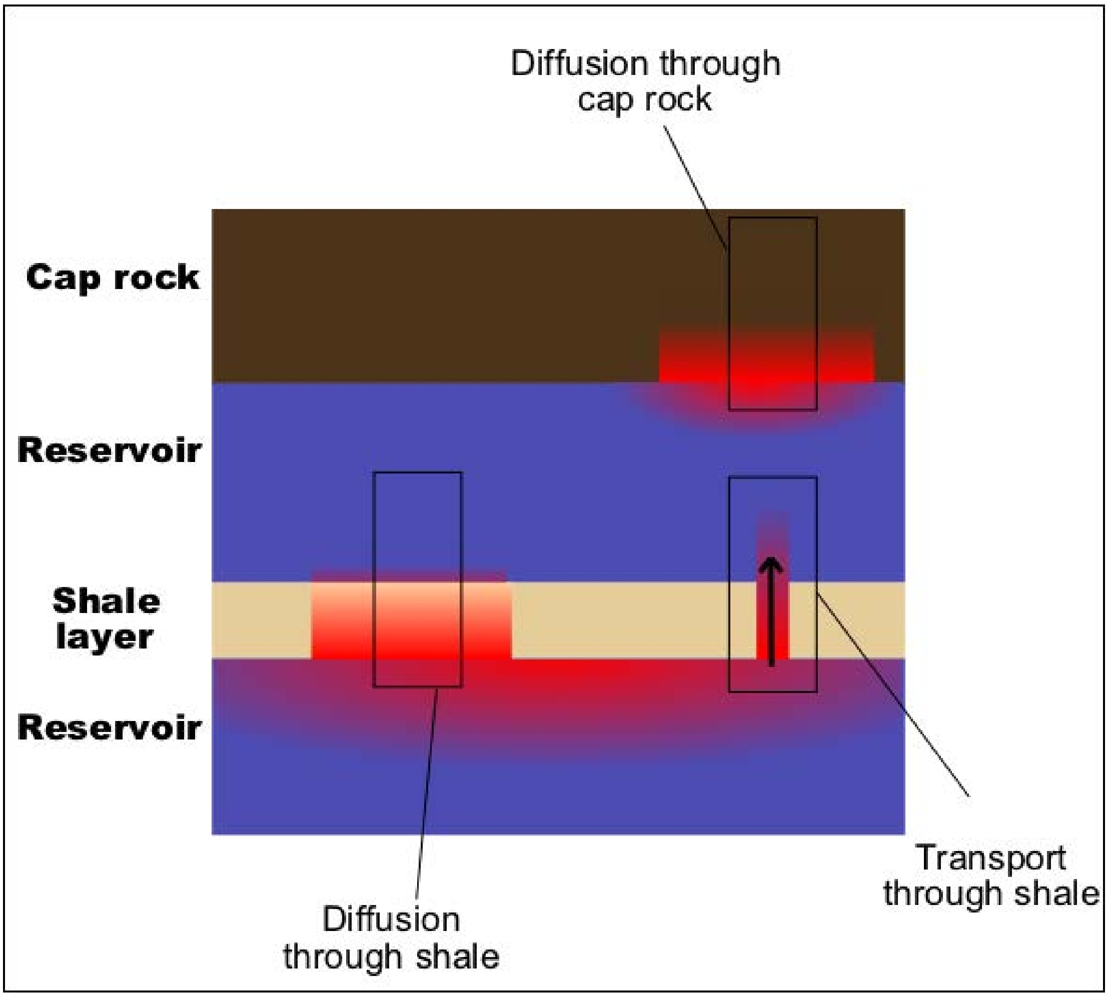


Figure 13. *Conceptual diagram of scenario's 1–3 modelled by BRGM (Durst & Gaus 2005).*

Scenario 4 – Impact of geochemical interactions when the injected CO_2 has a different temperature from that of the reservoir temperature

When the injected CO_2 has a different temperature compared to the reservoir temperature then this might have an impact on the geochemical interactions mainly during the injection period. A 1D model simulating a near well environment is set up for the whole injection period and a sensitivity analysis with respect to the injection temperature is carried out (in the range 30°C-90°C). Data incorporated in the model: injection temperature, reservoir temperature, pressure at injection, injection rate, reservoir mineralogy, porosity, brine composition.

The study concluded that dissolution and precipitation will occur as a result of the acidity of dissolved CO_2. However the geochemical reactions are not expected to cause severe damage to the cap rock. Below is given the results of modelling in scenario 1 showing the rate of CO_2 diffusion through the cap rock; after 4,500 year, the CO_2 has entered the first 15 m of the cap rock (Fig 14).

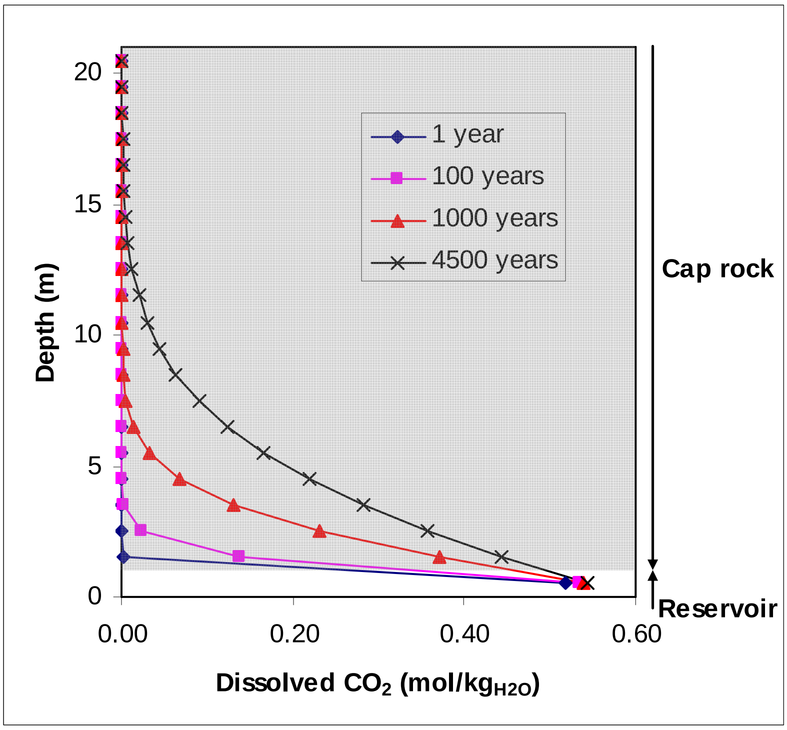


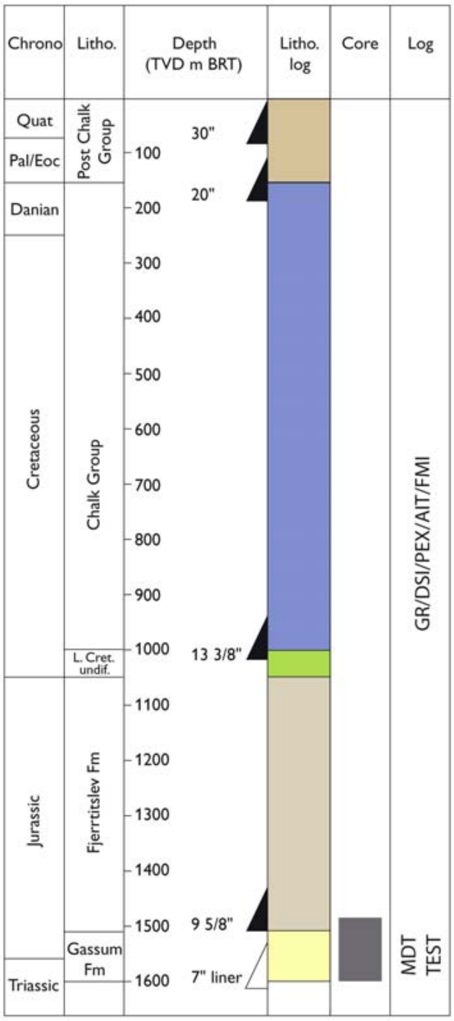
Figure 14. *Evolution of the dissolved CO_2 concentration in the cap rock during 4500 years of diffusion. (From Durst & Gaus 2005).*

Data acquisition programme

As part of the case study a fictive data acquisition programme has been formulated. This includes an exploration well positioned close to the top of the structure. A well prognosis for this well is given below.

Level +20 m	
Depth (m)	Expected geological succession
0-35	Quaternary till
35-70	Quaternary fluvial sand
70-155	Paleocene/Eocene clay
155-250	Danian Chalk
250-1000	Upper Cretaceous Chalk
1000-1075	Lower Cretaceous mudstone
1075-1365	Fjerritslev Formation marine mudstone
1365-1369	Fjerritslev Formation sandstone **monitoring zone**
1400-1500	Fjerritslev Formation marine mudstone **main seal**
1500-1531	Gassum marine sandstone compartments 1-4 **Top Reservoir**
1531-1600	Gassum marine sandstone compartment 5 **main injection zone**

Table 7. *Well prognosis Eskebjerg (top structure)*



Log	Objective
GR	Correlation log
AIT	Resistivity for reservoir quality
PEX	Density for porosity Neutron for porosity Density Neutron for lithology RHOZ for permeability
DSI	Compressional velocity, porosity Shear velocity Rock mechanics, Seismic attribute analysis
FMI	Borehole geometry Structural/stratigraphic dip Borehole image Faults and fractures
MDT	Formation Pressure Mobility Fluid Sample (PVT quality)
CMR	Porosity Permeability

Figure 15. *Well prognosis and suggested logging programme for the first exploration well on the Havnsø structure.*

Capture

This paragraph is prepared by ENERGI E2 an focuses on the potential of CO_2 capture from Asnæs Power Station and on the required permissions, necessary for establishing a capture plant at Asnæs Power Station. The scenario does not go into technical details regarding integration of the capture plant with the power plant, although this is an area where large potential savings are expected to be found. It shall be stressed that the described scenario is a constructed case study and does not reflect the strategic plans of ENERGI E2.

CO_2 capture plant

This case study focuses on a post combustion CO_2 capture plant to be used to clean CO_2 from the flue gas.

Type of capture

As the capture unit is planned to be used both for retrofit to unit 5 and for a new unit 6 it has been decided to focus on conventional post combustion capture.

The plant will however be prepared for integration with unit 6 in order to achieve the lowest energy consumption possible. In addition, it is expected that more energy-efficient absorbents will be developed in the coming years (e.g. within another EU-project CASTOR).

Flue Gas Rate

Flue gas rate from unit 5 at full load of 640 MW_{el} is 575 Nm^3/s (dry, 6% O_2) equal to round 1,900,000 Nm^3/h (wet, act. O_2).

Flue gas rate from unit 6 at full load of 700 MW_{el} is 523 Nm^3/s (dry, 6% O_2) equal to round 1,700,000 Nm^3/h (wet, act. O_2).

Both unit 5 and unit 6 are base load plants. Unit 5 operates with annual equivalent full load hours of 6,200 hours per year, while design data for unit 6 is 6,800 full load hours per year.

Composition of Flue Gas

The composition of the flue gas varies with the coal type used. In general, the coal used is a mix of different types.

Unit 5 is equipped with both desulphurization and $deNO_x$ plants, and the composition of the coal and the flue gas (after 95% $deNO_x$ and desulphurization) is within the ranges shown in Table 8.

The data are also used as design data for the new unit 6.

Capture Rate

An average capture rate of 90% is anticipated.

Purity of captured CO_2

When the captured CO_2 leaves the stripper in the capture plant it contains other species than CO_2.

Dependent on the requirements for purity of the CO_2 it may be necessary to clean the CO_2 by means of different CO_2 purification equipment.

In principle, it is possible to reach a very high CO_2 purity – but it may be very costly.

In this case study, the captured CO_2 is anticipated to be stored in the aquifer formation of Havnsø. The final CO_2 product should therefore fulfil the purity requirements for pressurization, pipe transportation and aquifer storing. However, there are no standards for CO_2 purity for different applications.

Coal	Units	Value	Range
C	wt-%	62.17	61.0 – 73.0
O	wt-%	8.00	3.8 – 10.2
H	wt-%	3.44	3.3 – 5.0
N	wt-%	1.38	1.2 – 1.9
S	wt-%	0.65	0.4 – 2.4
Cl	wt-%	0.01	0.0 – 0.2
H_2O	wt-%	12.70	5.2 – 13.5
Ash	wt-%	11.65	5.5 – 17.3
Sum	wt-%	100.00	–
LHV	MJ/kg	24.14	23.4 – 29.0

Flue gas	Units	Value	Range
N_2	vol-%	73.5	71 – 72
CO_2	vol-%	14.6	13 – 15
H_2O	vol-%	7.7	9 – 11
O_2	vol-%	3.3	3 – 4
Ar	vol-%	0.9	0.8 – 0.9
Sum	vol-%	100.0	–
SO_2	ppm	29	0 – 40
NO_x	ppm	19	0 – 30
CO	ppm	50	0 – 50
HCl	ppm	0	0 – 10
Temperature	°C	46	44 – 48

Table 8. *Composition of design coal and a range of typical used coals at Asnæs Power Station and the corresponding flue gas after desulphurization, entering the CO_2 absorption plant.*

In other on-going EU-research projects (ENCAP and CASTOR) CO_2 purity requirement is an area of investigation.

The provisional results from these projects prescribe purity for aquifer storage less restrictive than for e.g. Enhanced Oil Recovery purposes or for ship transportation.

From the project, ENCAP, the following limits are defined for the design case, corresponding to pipeline transport and aquifer storage:
H_2O < 500 ppm
CO_2 > 90%
H_2S < 1.5 vol%
The sum of condensable gasses (CO, Ar, O_2, N_2, H_2, CH_4) < 4 vol%

It is anticipated that these purity requirements for pipeline transport and for aquifer storage can be reached quite easily. On-going research may however define more restrictive limits as more information becomes available.

CO_2 delivery condition for transport
Depending on how the captured CO_2 should be transported to its storage the delivery condition of the CO_2 varies.

According to the EU-project ENCAP most international studies prescribe a CO_2 delivery pressure of 110 bar, and ENCAP defines furthermore CO_2 delivery temperature of max. 30°C.

CO_2 Flow Rate
The flow rate of the pressurized CO_2 is 137 kg/s for unit 5 and 125 kg/s for unit 6.

Equipment Dimension
As the capture plant has to treat a flue gas rate of up to 575 kg/s a large capture plant is needed.

Dimensions of the absorber and stripper towers are expected to be 30 – 40 meters in height and 20 – 23 meters in diameter. Alternatively, the absorber and stripper towers can be divided into two towers each. Other related equipment, like pumps, heat exchangers etc. will be installed in a separate machinery building.

Layout

Due to the large size of a capture plant, an important criterion when selecting a site is to find a site large enough for the capture plant.

Another important criteria is to place the capture plant close to the flue gas duct between the desulphurisation plant and the stack in order to minimise costs.
In Figure 16 a possible site for the future unit 6 and the capture plant is shown.

From the main plant the flue gas passes the electrostatic precipitator and the desulphurisation plant. Without CO_2 capture, the flue gas would then continue to the stack to be emitted to the atmosphere.

With CO_2 capture, however the flue gas will go into the two parallel absorber towers where the CO_2 will be captured by the absorbent. From the absorber the CO_2-free flue gas will then go to the stack to be emitted.

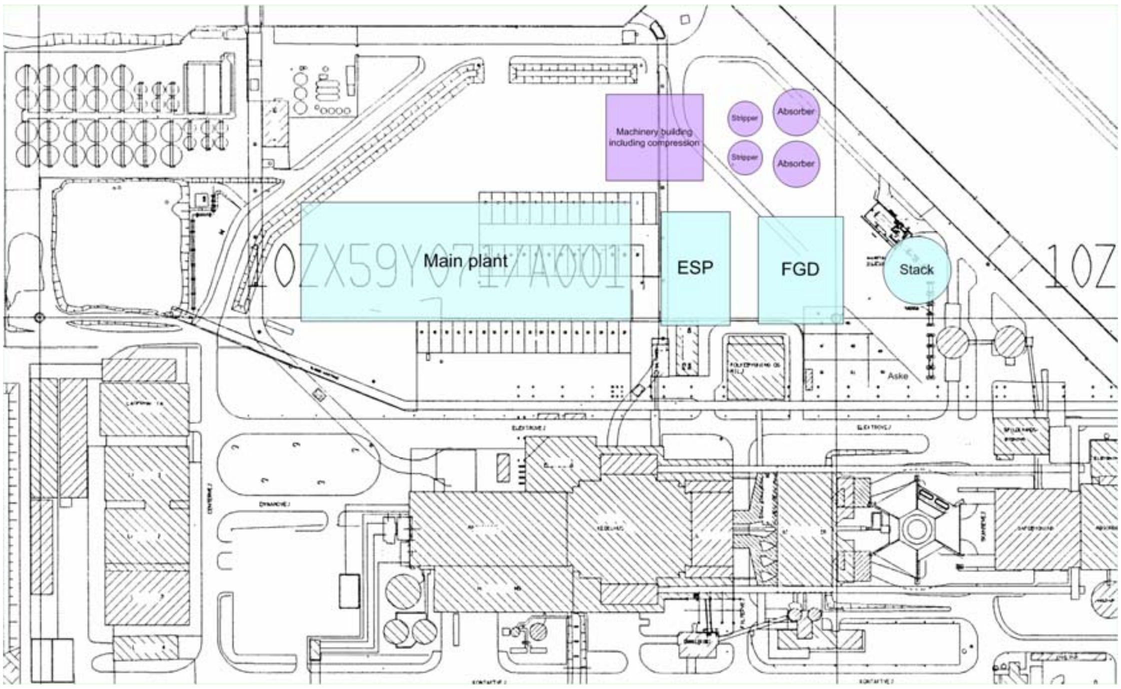


Figure 16. *Possible site for the CO_2 absorption plant north of the planned unit 6. Both the absorber and the stripper are divided into two towers.*

Surface transport

The requirements and costs for a surface pipeline was evaluated by Statoil ASA (Berger 2005). The calculations are based on transport of maximum of 6 million tonnes CO_2 per year delivered at the power plant site and injected at the south-eastern flank of the structure. The transport will be in a specifically designed pipeline with estimated total length of 15 km. It is anticipated that the pipeline may be dug into the quaternary cover with a surface coverage of minimum 0.9 m. The cost estimate is a ”best guess” and no geotechnical analysis have been made concerning the practicality of pipeline route and ground stability.

Pressure requirements

Onshore gas pipelines are often operated at 80 bar pressure in contrast to offshore (long distance) pipelines which are operated at higher pressure in order to minimise the costs. The dimensions of a CO_2 pipeline is adjusted to keep the pressure high enough to keep the CO_2 in dense fluid phase. The lowest allowable pressure in the pipeline is set to 60 bars. If pressure drops below this value the CO_2 may change to gas phase. This will result in low density and high flow velocities in the pipeline.

Dimension of the pipe

The pipe dimension has been calculated for different inlet pressure. The outlet pressure is set to minimum 60 bars. The temperature in CO_2 and surroundings are set to 10°C in the calculations.

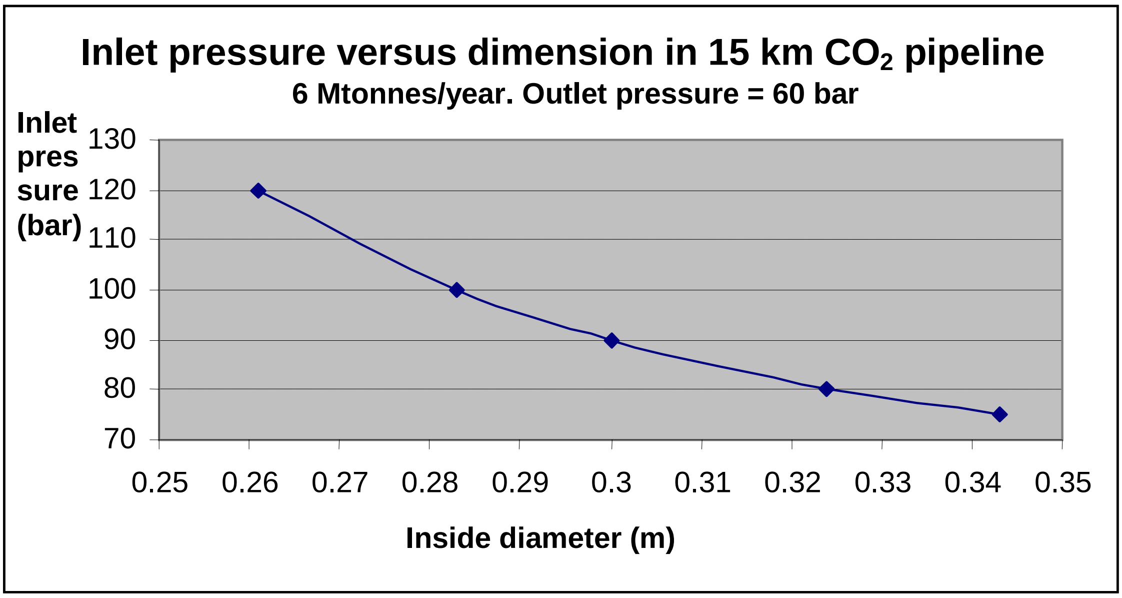


Figure 17. *Dimensions of the proposed 15 km long CO_2 pipeline.*

The calculations show that an inlet pressure of 80 bars will require a minimum inside diameter of 0.324 m (12.76”). From the figure it is evident that a change in inlet pressure from 80 bars to e.g. 120 bar will not cause a dramatic change in diameter. The costs will thus not change significantly if a higher operating pressure is chosen.

For the Kalundborg case an inside diameter of 0.330 m (13”) is preferred.

Route:
The calculations are based on a tentative pipeline route as indicated in Fig. 18.

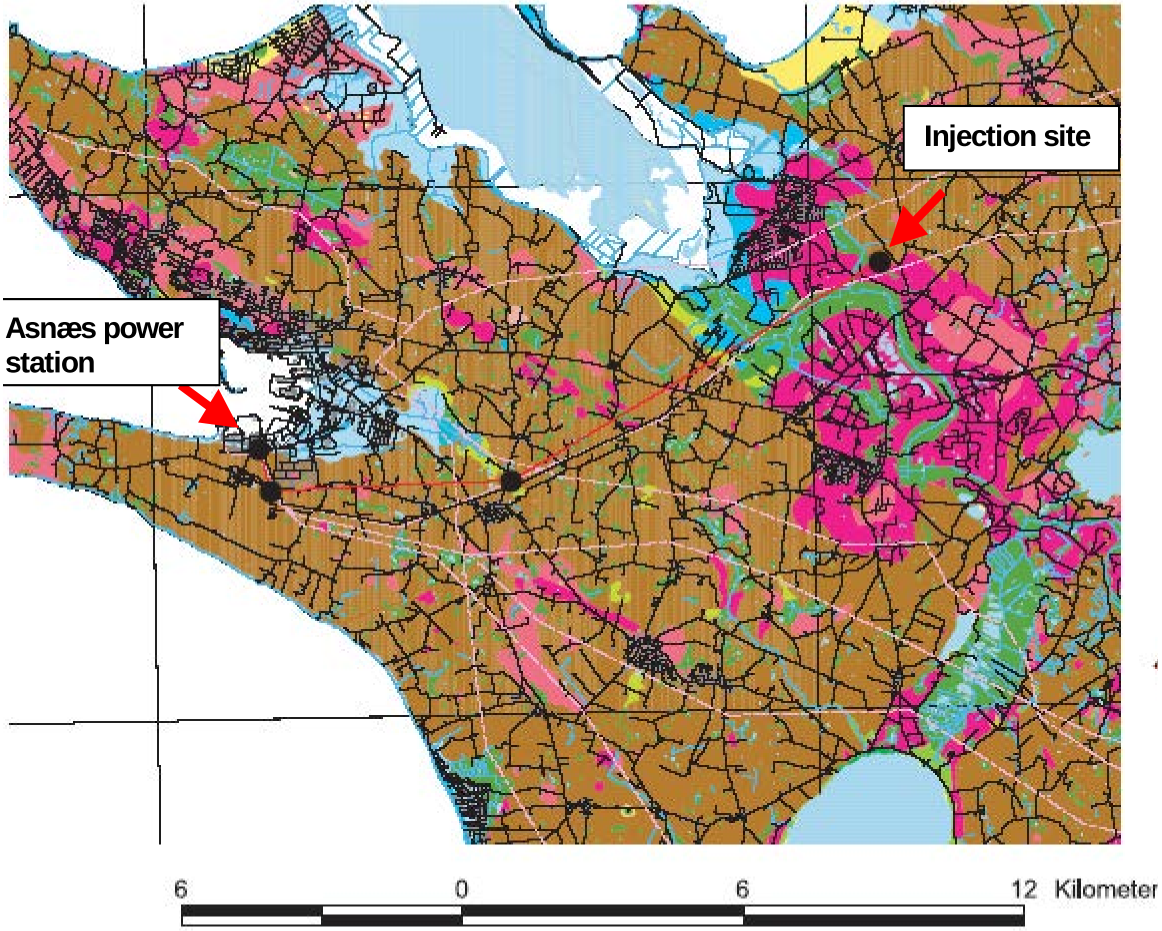


Figure 18. *Pipeline route use in the calculation of transport costs from the Asnæs power station to the injection site at Eskebjerg.*

The pipeline route is chosen to avoid densely populated areas and where possible to follow existing pipelines and high voltage cables (black line). The colours on the background map indicate the nature of the uppermost 1 m. Brown: Glacial till, Green: freshwater clay, Red: Glacial alluvial sand and gravel. It is anticipated that the soil types will not present major problems to the pipeline construction.

The cost estimate is made only on the main pipeline and does not include connection lines from the power plant or the refinery.

Cost evaluation

The calculation is based on a construction cost of 625 – 750 € per metre for a 13” (0.330 m) pipeline. The pipeline will be dug into the ground and covered. The total construction costs for a 15,000 m pipeline will thus amount to 9.4 – 11.3 Mill. €

The cost evaluation includes:

- Gas pipeline, valves and spare parts
- Digging of trench and covering of pipeline
- Reestablishment of vegetation, road pavement etc.
- Signal cable and warning strips
- Surface markings
- Pressure tests
- Detailed building project
- Building planning and surveillance
- 10% additional costs

The cost estimate does not include the following:

- Expropriation costs to landowners
- Project costs covering the period from draft project to start of detailed building project (e.g. Environmental Impact Assessment (EIA) from authority West Zealand County).

It is most likely that the capture plant will need an EIA and it is almost certain that the transport- and especially the storage systems will require an EIA. Consequently, it is most likely that the entire CCS-system will be evaluated together as one system.

The EIA process will include several public hearing phases. As this CCS-system will be the first system in Denmark of its kind some public involvement can be expected. It is expected to take about 18 months to get an approval.

The cost estimate is based on Statoil’s experience from construction of onshore pipelines, “best guess” and a number of general assumptions. It does not included specific site studies.

According to normal procedures it is anticipated that the pipeline will be surrounded by a 25 metres wide security zone. This zone will exist on both sides of the pipe line and will be given strict restriction concerning buildings and general use. The cost estimate assumes that the pipeline including the security zone can be constructed without conflicts with existing buildings.

Injection wells

According to the reservoir model the Havnsø structure may be filled by one injection well, however, to obtain the best injection control it is foreseen that three wells may be needed. One of these should be reuse of the data acquisition well.

Monitoring

In order to securely store CO_2 underground a monitoring system should be set up. This should be able to:

1. Acknowledge the CO_2 credits by proving that the injected CO_2 stays in the subsurface
2. Monitor that no CO_2 leaks to the surface and thereby pose a risk to the environment, animals and humans

The design of the monitoring system should be made in dialogue with the authorities and the listing below is only given as an example.

Seismic

4-D seismic surveys although extremely expensive have proven successful to image the injected CO_2 at the Sleipner Field. In an onshore setting as the Havnsø case repeated seismic surveys may, however, not be a feasible solution.

Wells

A number of shallow monitoring wells may be used to detect any CO_2 migrating out of the storage structure. The methods are applied with success at the Stenlille gas storage.

Other

A number of geophysical methods have been suggested for underground storage sites and will be tested in the CO2SINK project in Berlin. The methods include cross-hole seismic and geoelectric measurements. It is anticipated that a best practice manual will be issued on the monitoring possibilities.

Economic modelling

The economics in the Kalundborg case was evaluated as part of the GESTCO project (Hendriks & Egberts 2003) using the assumptions that 6 millions tons CO_2 would be stored per year. The calculations using the GESTCO DSS module showed that the total costs would amount to 32 €/ton CO_2 avoided. The capture costs (using retrofitting on the existing power units) would amount to (22 €/Mg CO_2) contributing with 2/3 of the total costs.

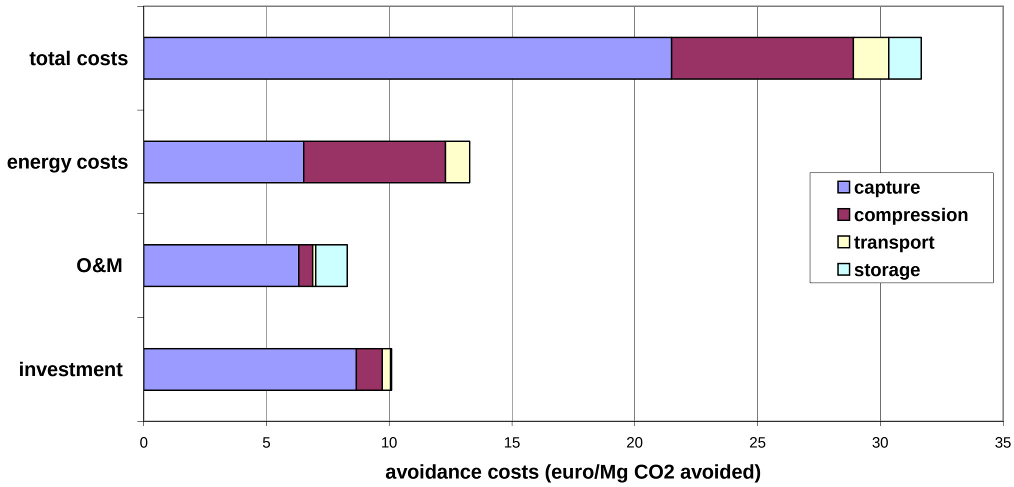


Figure 18. *Figure showing the costs and investment related to the Havnsø-Asnæs sequestration system. The total avoidance costs is 32 €/ton CO_2 avoided). Note the relative high capture costs (22 €/ton CO_2) contributing with 2/3 of the total costs. The sequestration system was modelled for 30 years (Hendriks & Egberts 2003).*

As part of the present study Jakobsen (2005) made a new economic evaluation using a modified version of the GESTCO DSS. Jakobsen used a bench-mark scenario and compared the Net Present Value of the system as a function of a number of variables (Table 9).

	Net Present Value		
	Benchmark scenario	5.000 production hours/year Minor efficiency improvements	6.000 production hours/year Major efficiency improvements and falling coal prices
Fixed quota price 5 Euro per ton CO_2	-2.91	-3.18	-2.67
Quota price 10 Euro, increasing 1% per year	-2.62	-2.75	-2.15
Quota price 13 Euro, increasing 5% per year	-2.02	-1.88	-1.11

Table 9. *Kalundborg scenario Net Present Value (Billion Euro) (From Jakobsen 2005)*

The conclusions from this study was that very high capture costs (40 €/ton captured CO_2) would make the Kalundborg scenario uneconomic.

Most studies have reported present costs of 40 – 50 €/ton captured CO_2, foreseeing reduction of capture costs to about 20 €/ton captured CO_2. For the economic calculations capture costs of 15 – 40 €/ton captured CO_2 was used (Fig. 19).

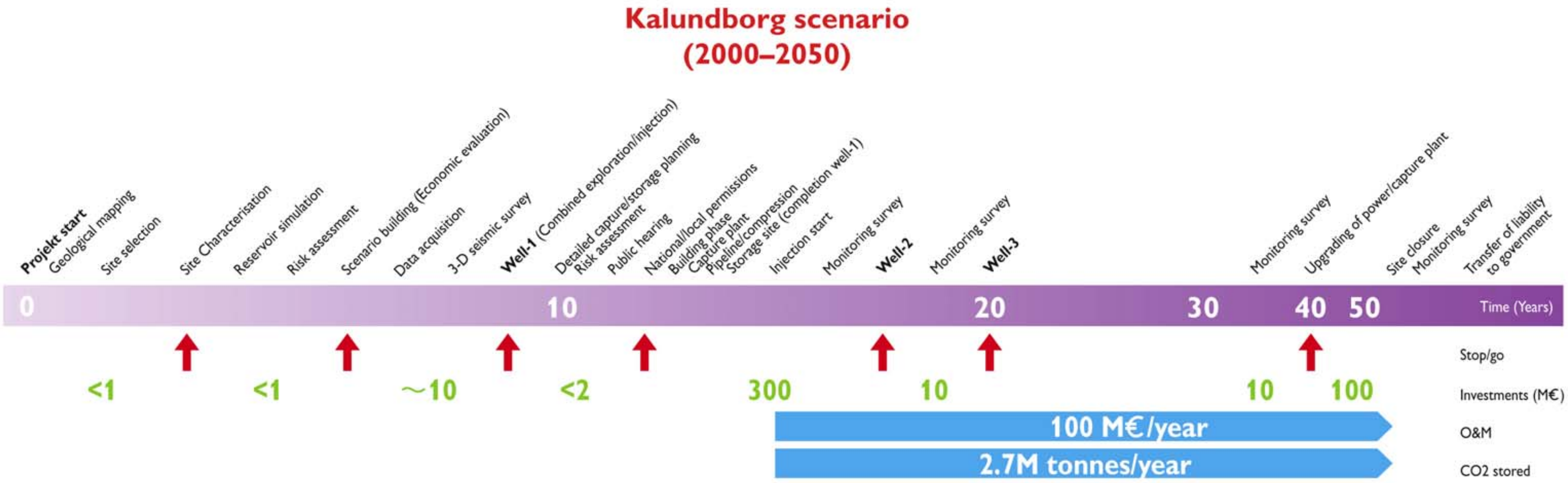


Figure 19. *Timeline showing the Kalundborg scenario (2000–2050) and the expected investments.*

Legal regulations on CO_2 emissions and storage

International

Emission reduction targets are linked to the Kyoto agreement adopted in 1997 and taking force in March 2005. The EU thus aimed at reducing greenhouse gas emissions by 8% relative to base year 1990. The Danish contribution according to the EU´s burden-sharing agreement is 21% to be met in the period 2008-2012. The agreement is intended to form the basis for far bigger reductions during the remainder of the 21^{st} century.

Danish power plants mainly burn coal; in recent years also natural gas, and to a minor extent, biomass. The existing plants are among the world's most energy efficient plants. Switching from coal to natural gas has already enabled the United Kingdom – as one of the few EU countries – to achieve real reduction of CO_2 emissions. In the longer term, growing pressure and higher prices of natural gas are to be expected and at the same time, shifting to natural gas is not sufficient to attain the long-term reductions expected in the period after expiry of the Kyoto agreement in 2012.

The short-term national plans are mostly linked to the EU burden-sharing agreement for reaching the Kyoto goals. The EU Emission Trading Scheme (ETS) commenced in January 2005. The ETS system opens for trading and exchange of CO_2 allowances and thereby sets a market price for CO_2. This system works along the lines of the national systems that have been applied to Danish power plants and industry since January 2005. According to the national system each CO_2 emitter is allowed a specific CO_2 emission based on the record of previous years. The amount is fixed for each year and excess CO_2 emission is taxed and should be "paid back" next year in the sense that any excess CO_2 emission in one year should lead to corresponding reduction of CO_2 emission in the following year. In addition the excess emission is taxed in 2006-2007 by 40 €/ton rising to 100 €/ton in 2008 and onwards.

The Danish Greenhouse gas emissions are 62 Mt/year, of which approximately 80% are CO_2. The national reduction targets of 21% would thus correspond to a reduction of approximately 12 million tonnes of CO_2 per year. Storing CO_2 from Asnæsværket and the Statoil refinery in the Havnsø structure could obtain half of this reduction. The current need for reductions is around 6 Mt/year (according the Danish Energy Agency DEA, 2005).

OSPAR

In general the OSPAR convention regulates the use of the maritime areas and prevents any disposal of waste. A workshop was held in Trondheim, Norway 26–27 October 2004 in order to address the possibilities for CO_2 storage in geological structures in the maritime area and associated problems. As 1/3 of the Havnsø structure is situated offshore the OSPAR convention may come into force if a decision for underground storage of CO_2 is made. The main conclusion from the workshop was that any project should be planned in accordance with national regulations and international agreements. In addition the risks of leakage from an underground storage should be evaluated against the effects of atmospheric CO_2 on the marine environment. The workshop also discussed the learning from the Sleipner storage site.

EF bird protection and special habitat areas; EU RAMSAR

The Havnsø structure is situated partly within an EF bird protection and special habitat area and EU RAMSAR area (Figs 20–21). These areas are regulated by international laws to prevent destruction of bird and animal life. It is anticipated that the underground storage facilities will not be in conflict with these regulations, however, pre-injection site surveys and monitoring surveys e.g. shooting seismic may pose a problem. It is recommended that contact is made with the authorities early in the planning phase.

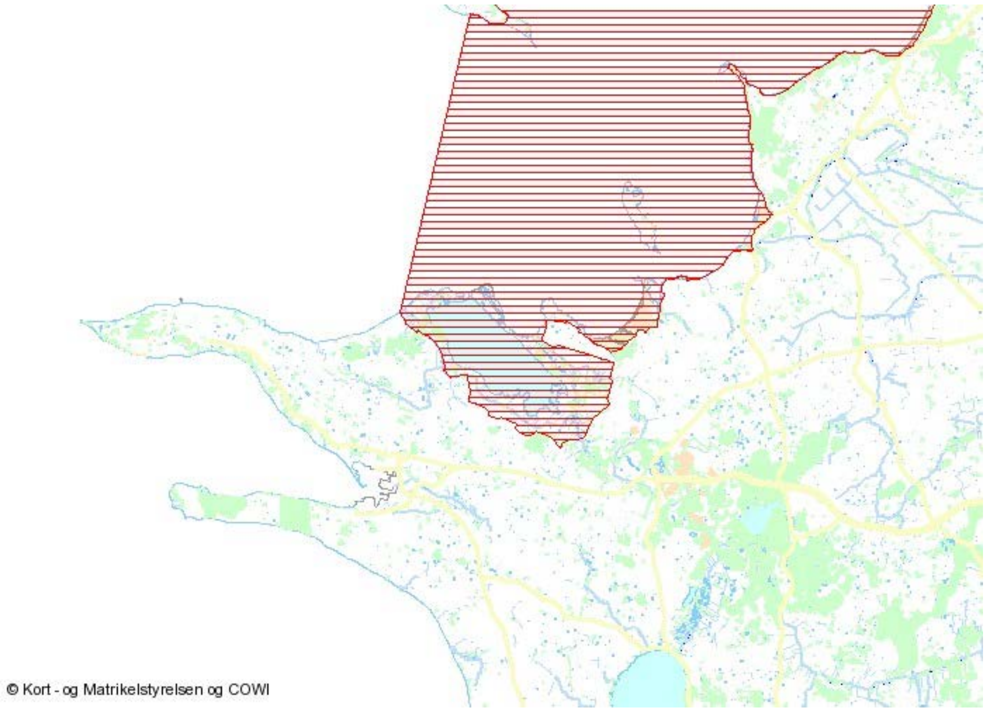


Figure 20. EF bird protection and EU RAMSAR area (Hatched area). Reproduced from www.Vestsjællandsamt.dk

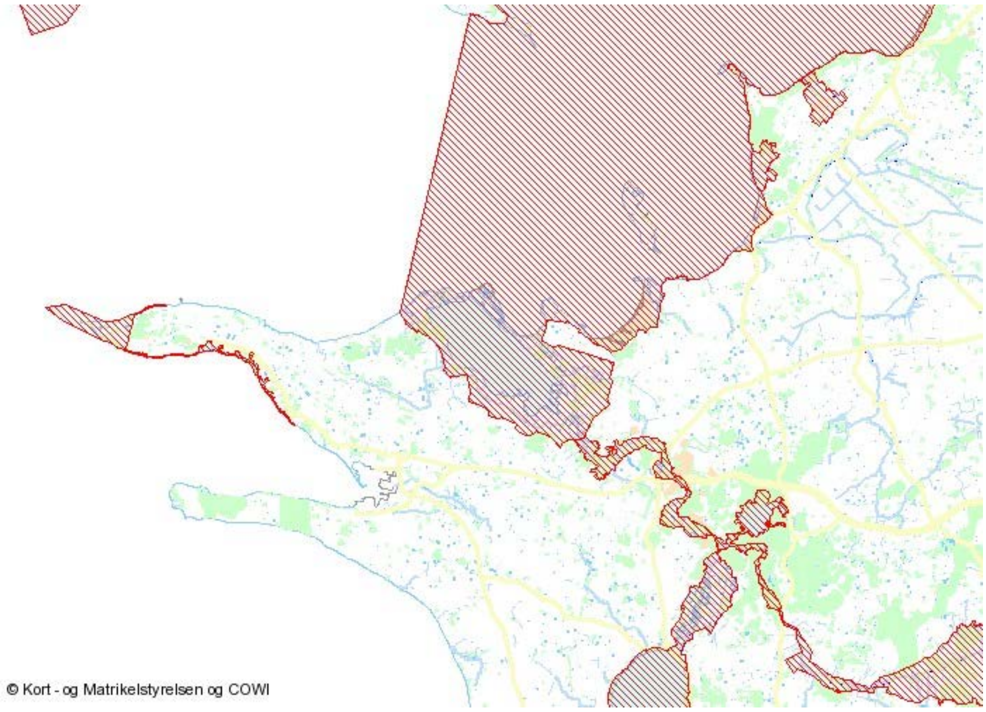


Figure 21. EF Habitat areas. Reproduced from www.Vestsjællandsamt.dk

Permission requirements for the capture plant

When building a CO_2 capture, transportation and storage system (CCS) a number of permits will be required. As CCS will be a new technology in Denmark it is expected that the requirements from the authorities regarding environmental investigations and documentation will be rather high.

Regarding permission requirements for the capture plant itself, this will most likely include the following permissions:

- Expression from the county whether an Environmental Impact Assessment (EIA) will be necessary or not
- Most likely an EIA from the County
- Environmental permission from the Community.
- Building permission from the Community
- Technical approval of some parts of the installations, like erection permissions from the Factories Inspectorate

Environmental Impact Assessment

When building new, large facilities or plants, the authority must be contacted for an expression of whether an Environmental Impact Assessment (EIA) will be necessary.

An EIA is an evaluation of the influence on the overall environment including evaluation of different alternatives. For Asnæs Power Station the authority is West Zealand County.

It is most likely that the capture plant will need an EIA and it is almost certain that the transport- and especially the storage systems will require an EIA. Consequently, it is most likely that the entire CCS-system will be evaluated together as one system. The EIA process will include several public hearing phases. As this CCS-system will be the first system in Denmark of its kind some public involvement can be expected. It is expected to take about 18 months to get an approval.

Environmental permission

The existing environmental permission for the power station given by the local authorities will have to be adjusted to include the capture plant. The local authorities are in this case West Zealand County.

The focus of the renewed environmental permission will most likely be on five topics:

1. use and handling of any chemicals
2. changes in noise
3. changes in emissions
4. waste water
5. changes in cooling water

1) The capture plant will introduce two new chemicals to the power plant: absorbent and inhibitor, and increase the use of cooling water, active carbon as filter material and NaOH for cleaning besides an increase in use of process steam and electricity.

With regard to the environmental permission it is important whether the selected absorbent and inhibitor are listed in Appendix 1 in the Risk Order from the Danish Environment Department or not. If any of the chemicals are included in the list a special detailed risk evaluation has to be performed.

The traditionally used absorbent, Monoethanolamine, MEA is not included in the list – other potential new absorbents may be included.

2) It is not anticipated that a capture plant will contribute significantly to an increase in the noise level from the power plant.

3) In the Environmental Permission it is anticipated that there will be requirements to the emissions from the plant.

In the Guidelines No. 2, 2002 from the Danish Environment Department B-values for emission concentrations are given for ethanolamine, MEA. The B-value is set to 0.01 mg/m^3.

If another absorbent will be used it is anticipated that a B-value for this absorbent specifically will have to be prepared.

For a pilot capture plant the estimated escape of absorbent through the stack from the absorber and the stripper is 50-200 ppm, equal to the escape in similar industrial facilities. For full size capture plants this will be a matter to investigate more carefully.

4) In normal operation there will be no additional waste water from the plant. The capture plant will produce two kinds of disposals in form of filter material (used active carbon) and disposal from the re-claimer. Both kinds of disposals will be disposed as any other disposal.

5) Traditionally, a considerable amount of cooling water is needed for operation of a capture plant. At present, cooling water for the existing plant is taken from the fjord and from different reservoirs. It is anticipated as the capture plant will be integrated with the new unit 6 that the amount of cooling water will be considerably reduced, and it is expected that cooling water will be no problem.

Besides this, concerns about risk for leakage to the ground and to the ground water will have to be evaluated and also an evaluation of use of BAT (Best Available Technology) will have to be included.

The appliance for the environmental permission can be done in parallel with the appliance for the Environmental Impact Assessment, and the total time for the two permissions is expected to be about 18 months.

Building permission

All buildings established have to be reported to and approved by the local authorities, in this case Kalundborg Community. Getting a building permit is a standard procedure and as the plant will be built on an existing power plant site no special considerations are foreseen in this case. Appliance for the building permission will take place after the environmental permissions have been obtained but the time needed for obtaining the building permission is anticipated to be negligible.

In planning of the surface installation (pipeline, and injection site) special attention should be made to the national Danish protection laws (Naturbeskyttelsesloven §33) that designates areas of special interests. No conflicts, however, is anticipated for the installations described in the CO2STORE scenario (Fig. 22).

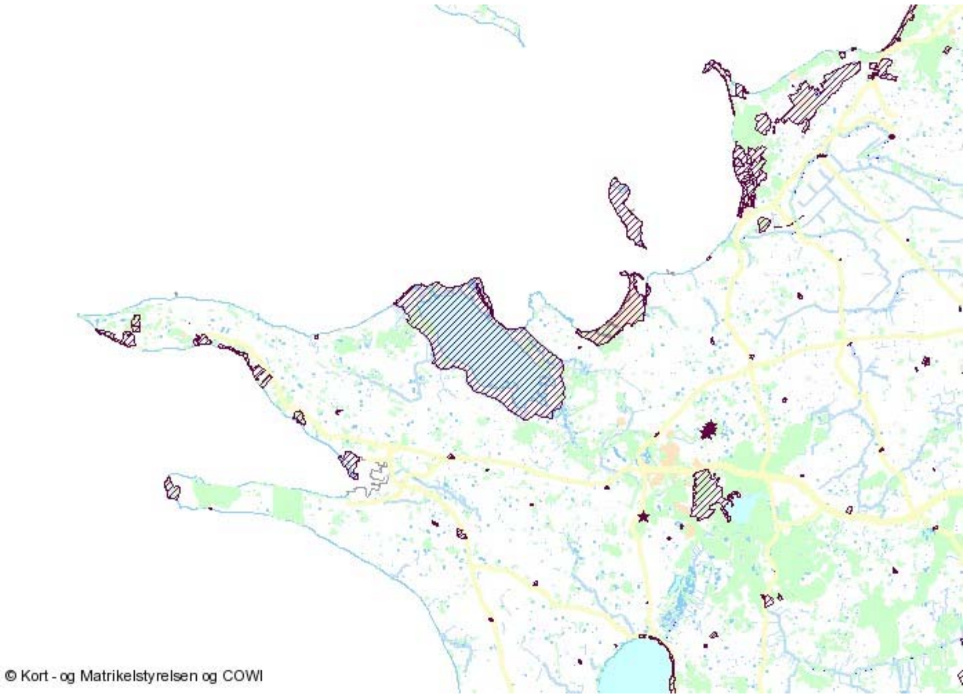


Figure 22. Areas with restricted use due to their environmental and/or cultural values (hatching and stars) according to the national Danish protection laws (Naturbeskyttelsesloven §33). Reproduced from www.Vestsjællandsamt.dk

Erection permits

Certain types of installation have to be approved by the Factories Inspectorate. As long as the rules are fulfilled this is no delaying process and no special considerations are anticipated.

Risk assessment

Underground storage of CO_2 is a measure to reduce human impact on the global climate, however the storage site may in worst case cause damage to the local environment, humans and animals. In order to properly address the risks related to underground storage of CO_2 the Kalundborg case study used the Quintessa FEP database (Features, Events and Processes http://www.quintessa.org/consultancy/index.html?co2GeoStorage.html which is made available through the IEA Greenhouse Gas Programme. The risk assessment involved analysis of all relevant FEPs, identification of the most important FEPs, and development of some geological scenarios incorporating the major FEPs that could be modelled using numerical reservoir simulation. Global effects of leakage from the storage site will also be shortly discussed in the paragraph on international regulations (control of CO_2 benefits etc.).

All FEPs that might affect the underground storage of CO_2 in the Havnsø aquifer are listed in Appendix 2. Individual FEPs are categorised and risks identified based on their perceived applicability to the current target reservoir. The most important FEPs resulting from the auditing are summarised below.

Group 1: Geological features

- Overpressuring – reservoir characteristics
- Effects of pressurisation of reservoir on cap rock
- Undetected features, faults at top of reservoir

Group 2: Long term fate of CO_2

- Reversibility - Fingering leading to CO_2 escaping the trap

Group 3: Impact on society and humans

- Lifestyles – public opposition to storage project
- Impacts on humans - health effects of CO_2

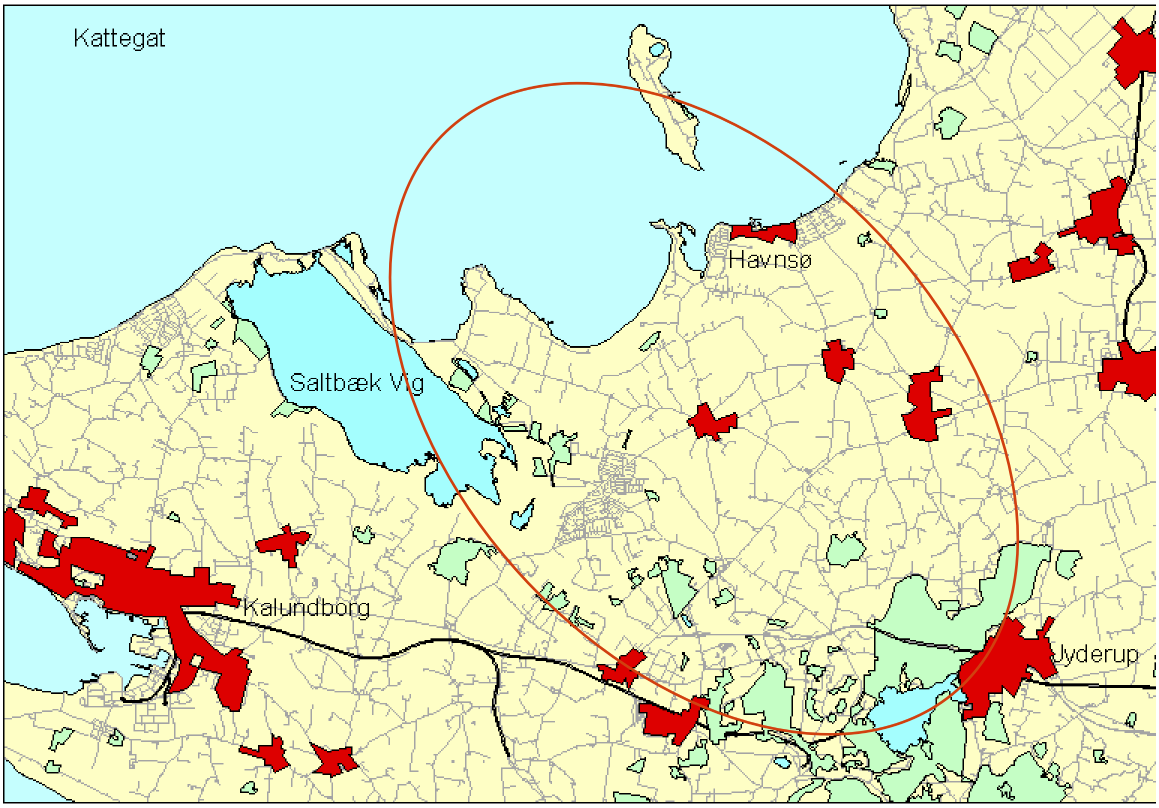


Figure 23. *The areal extent of the Havnsø structure shown relative to towns (red), forest (green) and open land (light yellow). Infra structure (roads) and isolated buildings are shown in grey.*

Project risks

In addition to the risk assessment performed through the Quintessa database a number of project risks should be considered (Figure 24). These are risks that would put a hold on the project and eventually lead to exclusion of the storage site. Several of the risks listed are related to projects costs.

Risk Assessment		
Risk	**Mitigation**	**Issues**
Geological		
Seal	3D seismic	Feasibility Permitting Cost
	Analogue	Access to gas injection project data
	Drilling wells and testing	Feasibility Permitting Cost
Capacity	Monitoring of aquifer	Seal integrity during injection
Reservoir	Drilling coring and testing	
Low level leaks	Monitoring of soil/water	Management of a monitoring project Feasibility, locations
Monitoring	4D seismic	Feasibility Permitting Cost
	Monitoring wells	Feasibility Permitting Cost location
Injectivity	Testing Analogue data	
Well leak	Good drilling practise	

Figure 24. Summary of project risks.

Conflicts of use

Geothermal energy

The geothermal energy resources have been evaluated for the major Danish towns (Sørensen *et al.* (1998). The survey included Kalundborg which was ranked as 7 on a list of 23 potential sites for geothermal energy recovery (Table 10).

Geothermal prospect	Reservoir	Temperature Celcius	Resource TJ/km^2	Area Km^2	Specific ressource TJ	Specific demand TJ/year
Kalundborg	Gassum	52	7171	50	359000	846

Table 10. *The geothermal potential in the Kalundborg area (From Sørensen et al. 1998)*

The geothermal potential, however, is not considered of commercial interest due to the fact that excess heat is currently produced from the coal fired power plant. The possible conflict of use will thus lie in plans for geothermal energy systems after close down of the power plant.

Gas storage

The Havnsø structure was evaluated as natural gas storage reservoir in 1973, but was excluded due to its large size. The Danish natural gas company DONG established the Stenlille gas storage 45 km southeast of Havnsø using the same reservoir formation. The pore volume of the Stenlille structure is estimated to 0.247 km^3 compared with 3,670 km^3 in the Havnsø structure. It is considered unlikely that the Havnsø structure will be considered for gas storage in the future.

Hydrocarbon

Several of the structures that form potential CO_2 storage sites in Denmark have been evaluated and drilled for hydrocarbon exploration. However there are until date no hydrocarbon finds in structures east of 12°E. The explanation is lack of mature source rock units (Thomsen *et al.* 1981). Although petroleum exploration through history has presented unexpected discoveries the Havnsø structure is assumed only to hold saline water.

Drinking water

No conflict is expected with drinking water production, which takes place from Quaternary sandstone reservoirs at depths down to a few hundred metres (Fig. 25). Diffusion of CO_2 through the cap rock and overburden has been modelled by Bech & Larsen (2005). This study shows that it will take more than 1 million years before the CO_2 will reach the surface. Escape of CO_2 along faults is not considered likely.

Drinking water may, however, be contaminated if CO_2 escape along linings of injection or observation wells. The well integrity thus presents a problem that needs special attention in the storage project (see appendix 2).

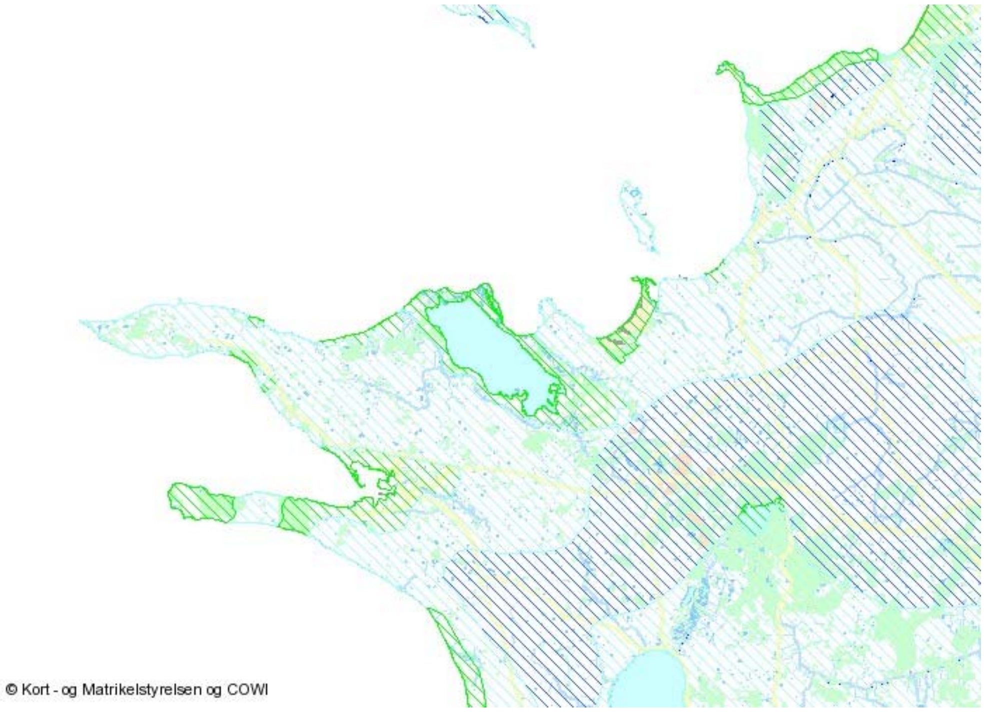


Figure 25. Classification of areas concerning their importance for drinking water resources. Dark blue hatches: important drinking water resources; light green hatches: drinking water resources; dark green hatches: limited drinking water resources. Reproduced from www.Vestsjællandsamt.dk

Recommendations

Indications are that the Havnsø geological structure is very suitable for storage of CO_2 – it is large, simple and most likely possess good reservoir and seal properties. The structure is probably one of the best in Denmark – possibly in Europe.

With two large CO_2 emission point sources located in the nearby city of Kalundborg, a source – storage scenario with injection of 4-6 Mt CO_2 per year would be feasible, with the possibility of adding similar amounts of CO_2 transported in pipeline from sources in the greater Copenhagen area, less than 100 km to the east.

In order to investigate and mature the Havnsø structure to become the first Danish saline aquifer CO_2 storage facility, a step-wise approach is envisaged.

The following steps are recommended:

1. Data acquisition

In order to properly map the structure and assess the quality of the reservoir and seal, new 3D seismic data and a well to approx. 2.000 m will be needed. The work should include geological analysis, modelling of reservoir/cap rock (seal) behaviour and on-site dynamic flow test using small amounts of CO_2 for injection.

2. Site demonstration facility

When the structure, reservoir and seal have been sufficiently mapped, analysed and modelled an injection demonstration facility should be established. Injection of up to 100,000 ton CO_2 per year for a number of years should take place in order to test the structure. The demonstration facility should also include monitoring systems. The CO_2 could be transported to the injection site by train and/or truck.

3. Industrial storage

The final step will be developing the facility into an industrial storage of CO_2 with injection of several million tonnes of CO_2 per year. The CO_2 should be transported from the source(s) by pipeline and/or could be injected into the structure directly from the capture plant using a deviated well.

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Appendix 1

This appendix contains background information for the eleven aquifer traps mapped in the GESTCO project and the present study. The estimate of the CO_2 storage capacity given for each structure is based on a number of generalisations and assumptions described below:

- Area: The outline of the closures was digitised and plotted using ArcView 8.0 (Lambert Conformal Conical Projection of the WGS84 ellipsoid). The area is automatically given by the GIS system.
- Temperature: The reservoir temperature of undrilled structures and wells without temperature data is calculated from the regional geothermal gradient 50°C+(30°C /1000m)(depth msl – 1500m) (Niels Beck, GEUS pers.com 2003).
- Pressure: The aquifers are considered to react as open reservoirs meaning that the reservoir pressure is assumed to equal the hydrostatic pressure, P_{hyd} = g x row x depth (g=9.81 m/sec^2 and row = density of water ~1000 kg/m^2)
- The lithostratigraphic units and definition of formation boundaries in the deep wells are based on Nielsen & Japsen (1991).
- Porosity and permeability data are sparse for the Danish onshore area. Measured values are referred to in the text. In structures without well data values are extrapolated from nearby wells or calculated using a regional porosity/permeability plot (Sørensen et al. 1998). Difference in vertical versus horizontal permeability values is not taken into account.
- The net/gross values are estimated by the use of a well specific cut off value for the gamma (GR) or spontaneous potential (SP) log. This method only allows separation of sand (reservoir) and shale (nonreservoir) units and does not account for poor reservoir sand quality etc.
- The storage volumes are based on the physical pore volume present in the trap. It is assumed that reaction between reservoir rock and CO_2 is negligible.
- Reservoir density of CO_2 is calculated by the use of PVTsim (Calsep 2000) as a function of pressure and temperature.
- The diffusion of CO_2 into the formation water has not been taken in to account when calculating the maximum storage volume. Diffusion would increase the volume of CO_2 that can be stored in a given structure.
- Unfaulted, thick units of claystones or evaporites seal the traps. The integrity of the cap rock to CO_2 has not been questioned.

Appendix 2

The Quintessa FEP database (Features, Events and Processes) http://www.quintessa.org/consultancy/index.html?co2GeoStorage.html was used as a basis for the assessment. The risk assessment involved analysis of all relevant FEPs, identification of the most important FEPs.

All FEPs that might affect the underground storage of CO_2 in the Havnsø aquifer are listed below.

FEP Category	FEP Class	FEP	Audit
0 The assessment basis	0.1 Purpose of the assessment		Assess risks of the proposed underground storage of CO_2 emitted from Asnæs power plant and Statoil refinery in the Havnsø structure (see main report)
	0.2 Endpoints of interest		Constrained to considering the degree of containment within the subsurface, i.e. amount, location and timing of any leakage not impacts
	0.3 Spatial domain of interest		Overburden and surface areas in the near surroundings of the Havnsø structure. The domain includes farmland, recreational areas, small communities and shallow marine areas. The Risk assessment does not include the city of Kalundborg situated 15 km southwest of the storage site.
	0.4 Timescales of interest		5,000 years
	0.5 Sequestration assumptions		The risk assessment is carried out for a fictive storage scenario including CO_2 captured at the coal fired power plant Asnæs and the Kalundborg Statoil refinery. The amount of CO_2 stored will be 40 years emissions from the Asnæs power station (~3.0 million tonnes CO_2 per year) and the refinery (0.5 million tonnes per year). The CO_2 will be stored in a saline aquifer at 1500 m depth situated 15 northeast of the power plant. The reservoir consists of marine clastic sandstones of the Upper Triassic–Lower Jurassic Gassum Formation. The system is modelled as an unconfined aquifer where CO_2 is trapped within a 4-way

			domal closure. The domal structure is caused by rising salt from the underlying Zechstein Group. The CO_2 will be stored as a dense phase fluid at the lower western flank and it is assumed that the formation pore fluid will be expelled from the structure whereas buoyancy forces will result in CO_2 migrating upwards to the top of the structure. Over time (>5000 years) the CO_2 will dissolve in the formation water and sink to the bottom of the reservoir. The cap rock consists of marine mudstones and silty mudstones, including some carbonate beds of the Fjerritslev Formation.
	0.6 Future human action assumptions		It is assumed that the injection wells will be sealed and abandoned after the injection period according to prevailing regulations and subsequently the site will be closed by agreement between the regulator and operator. Thereafter human actions will be limited to monitoring and remediation if necessary.
	0.7 Legal and regulatory framework		The Havnsø structure is situated partly onshore and partly below the inshore marine basin Kattegat. Any CO_2 storage offshore would have to be legal under the OSPAR and London Conventions. These bodies are currently (as of Sept 2005) considering the status of offshore underground CO_2 storage. Assuming that these bodies agree that CO_2 storage under these circumstances is legal, it would be subject to regulation by national or supranational bodies, presumably the Danish government. Onshore storage will be governed by National regulations. No such laws exists for CO_2 storage, however Denmark has two operating LNG storage sites that may form a guide for future regulations. The LNG storage sites are regulated by the Ministry of Energy. It is assumed that after site closure has been agreed, liability will be with the Danish State. Building permissions and environmental impact assessments will be regulated by the local authorities. Part of the spatial domain is classified as EF habitat, EF bird-

			protection and EU RAMSAR areas protecting wildlife and plants. Special rules may apply.
	0.8 Model and data issues		Data, including regional data, is sparse. Old, poor quality 2D seismic data exists for the structure. The structure has not been drilled but well data is extrapolated from wells in mid Zealand (Stenlille) and Jutland (Horsens). The reservoir is modelled as homogeneous marine sandstone bodies separated by thin siltstone units. The injection model is based on Eclipse 100 and 300 (Bech & Larsen 2005)
1 External factors	1.1 Geological factors	1.1.1 Neotectonics	No faults are observed on the structure. However, the nearby Røsnæs structure seems to be affected by neotectonics resulting from salt movement.
		1.1.2 Volcanic and magmatic activity	There has been no recorded volcanic or magmatic activity since at least Mesozoic times and the chances of any in the next 5,000 years are considered negligible.
		1.1.3 Seismicity	No seismicity above 4 open Richter scale has been registered
		1.1.4 Hydrothermal activity	No hydrothermal activity is known in the spatial domain of interest and the chances of any are considered negligible because of the lack of any effective geological heat source
		1.1.5 Hydrological and hydrogeological responses to geological changes	These are likely to be negligible as the spatial domain of interest is hydrostatically pressured
		1.1.6 Large scale erosion	Large scale erosion is not likely on the time scale of interest. Glaciation is possible, but not considered likely as global warming is predicted.
		1.1.8 Bolide impact	Destruction of the seal by a bolide impact is not considered a significant risk. The results of a bolide impact of the size necessary to destroy the seal would far outweigh any impacts of the release of the stored CO_2.
	1.2 Climatic factors	1.2.1 Global climate change	Global warming and the accompanying sea-level rise may lead to flooding of parts of the domain of interest and possibly (1000 year perspective) the injection site (+20 m.a.sl.). The underground

			storage itself, however, will not be affected.
		1.2.2 Regional and local climate change	Not considered relevant compare with 1.2.1
		1.2.3 Sea level change	Sea level rise might occur in the time frame of interest and may affect surface installations. No effects on the underground storage repository are expected. See 1.2.1
		1.2.4 Periglacial effects	The spatial domain of interest is not in a periglacial environment
		1.2.5 Glacial and ice sheet effects	Not likely to be important as global warming not cooling is predicted
		1.2.6 Warm climate effects	See 1.2.1 above
		1.2.7 Hydrological and hydrogeological responses to climate change	The storage site is located in a low relief area outside any major fluvial systems. The effects are likely to be minimal as fluid flow probably very slow and not likely to be seriously affected by base level changes
		1.2.8 Responses to climate change	The storage site is not likely to be affected by any climate changes see 1.2.1
	1.3 Future human actions	1.3.1 Human influences on climate	Human activities is predicted to cause global warming see 1.2.1
		1.3.2 Motivation and knowledge issues	Societal memory of CO_2 storage is assumed but probably not necessary as human intrusion by deep drilling is not likely to take place in the area (no natural resources). Eventually this would not result in significant leakage of CO_2 because it would be held in the reservoir by the pressure exerted by the drilling mud in the well.
		1.3.3 Social and institutional developments	Breakdown of society is not likely to adversely affect the storage site.
		1.3.4 Technological developments	Technological developments are likely to lead to better monitoring of the distribution and saturation of CO_2 in the spatial domain of interest, and to better remediation techniques in the event of a leak.
		1.3.5 Drilling activities	Future drilling activities are not expected in the spatial domain of interest. However drilling for hydrothermal resources may present a conflict of use see 1.3.6. Drilling through the reservoir should not interfere with storage providing the correct mud weight to retain the CO_2 in the

			reservoir is used and any wells are drilled, sealed and abandoned appropriately.
		1.3.6 Mining and other underground activities	Drilling for hydrothermal resources may take place in the future. The target will either be the Gassum Formation (CO_2 reservoir in which case CO_2 may escape with the hot recycled water) or the deeper Bunter Sandstone Formation. Drilling through the reservoir should not interfere with storage providing the correct mud weight to retain the CO_2 in the reservoir is used and any wells are drilled, sealed and abandoned appropriately. Production of drinking water takes place in the area, but drilling does not exceed 100 m depth and will not affect the storage reservoir nor cap rock. Mining is not expected as there are no known appropriate subsurface resources in the spatial domain of interest.
		1.3.7 Human activities in the surface environment	Building activities and other human activities (apart from 1.3.5 and 1.3.6) will not affect the deep storage site
		1.3.8 Water management	Drinking water resources are present in the spatial domain of interest. Production takes place in Quaternary and Neogene/Paleogene strata; however drilling does not exceed 100 m and will not affect the storage reservoir nor cap rock. Future water production may include the underlying Chalk Group, but will not affect the storage site.
		1.3.9 CO_2 presence influencing future operations	No hydrocarbon interests in the spatial domain. The lack of hydrocarbons is explained by absence of mature source rocks in the Danish Basin east of 6 degrees W (Thomsen et al. 1998).
		1.3.10 Explosions and crashes	No explosions or crashes are likely to affect this deep storage site
2 CO_2 Storage	2.1 Pre-closure	2.1.1 Storage concept	Inject CO_2 through three wells into sandstones of the Gassum Formation. The concept assumes that 1) CO_2 will be stored in dense phase; 2) that injected CO_2 will be trapped within the domal structure; 3) that the system acts as an unconfined aquifer allowing pore fluids to be displaced outside the trap.
		2.1.2 Storage quanti-	Injection will be through 3 wells placed

		ties, injection rate	on the flank of the structure. 3.5 million tonnes of CO_2 will be injected per year for the lifetime of the project, simulated as a nominal 40 years. Injection is planned to take place in the lower, high permeable zone of the Gassum Formation.
		2.1.3 CO_2 composition	The CO_2 is assumed to follow the recommendations given by ENCAP and CASTOR e.g. free of water vapour, SO2 and NOx. Minor components may be present; however it will be possible to clean the CO_2 stream according to National specifications.
		2.1.4 Microbiological contamination	Not considered to be a risk as should not be contaminated before injection
		2.1.5 Schedule and planning	Not yet known as the modelled scenario is fictive. The project consists of 1) site screening (3 years); 2) site characterisation (3 years); planning and public hearing phase (2 years); building phase (3 years); Injection phase 40 years.
		2.1.6 Pre-closure administrative control	Not known : Likely to be the responsibility of the project operator
		2.1.7 Pre-closure monitoring of storage	Monitoring will be a prerequisite for onshore storage. It will most likely include continuous pressure surveillance, monitoring wells and soil gas / isotopic characteristics. Other methods like seismic data and geoelectrical methods may be considered.
		2.1.8 Quality control	CO_2 quality likely to be controlled at wellhead (flow rate, temperature and pressure). Gas quality likely to be monitored by Gas Chromatograph
		2.1.9 Accidents and unplanned events	Should be dealt with by best oilfield practice. Remediation plan needed for unplanned emissions, problems underground

Potential Risk		2.1.10 Overpressuring	This is a risk if the reservoir characteristics or sand distribution is unfavourable. Reservoir simulation has been performed with parameters known from nearby wells. Although a pressure increase is predicted the pressure appears to remain within bounds. Sensitivity studies on reservoir distribution needed. Pressure control may be achieved by injection through more than one well and injection into different reservoir compartments to prevent unwanted pressure rise and fingering. Final conclusions can only be made after drilling and injection test of first well.
	2.2 Post-closure	2.2.1 Post-closure administrative control	Assumed to rest with the State as closure assumed to be with agreement of the Regulator (which doesn't yet exist)
		2.2.2 Post-closure monitoring of storage	Assumed to be responsibility of State
		2.2.3 Records and markers	Assumed to be the responsibility of the State
Potential Risk		2.2.4 Reversibility	Fingering leading to CO_2 escaping the trap may occur in which case CO_2 may not be recovered. In the event of unintended migration or overpressuring, the injection wells could be opened up and allowed to flow and return the reservoir to its initial pressure. Given that a high proportion of the CO_2 would be above the level of the well perforations it is unlikely that much of the CO_2 would be recovered.
		2.2.5 Remedial actions	In case of political or technical demands for recovery of injected CO_2 a remediation well drilled at the top of the structure may allow for parts of the injected CO_2 to be brought to the surface. After some time (hundreds of years) CO_s will be dissolved in the formation water and will start sinking to the bottom of the reservoir – remediation actions will then be difficult. See also 2.2.4.
3 CO_2 properties, interactions and transport	3.1 CO_2 properties	3.1.1 Physical properties of CO_2	The CO_2 is assumed to be stored as a separate component in dense phase. Simulation predicts long term dissolution of CO_2 into formation water. After 5000 years parts of the CO_2 will be dissolved.
		3.1.2 CO_2 phase	Predicted by phase diagram and equa-

		behaviour	tion of state. Only dense phase CO_2 likely to be present due to the +1500 m depth of the reservoir. In long term perspective also dissolved CO_2.
		3.1.3 CO_2 solubility and aqueous speciation	Considered using reservoir simulation.
Potential Risk	3.2 CO_2 interactions	3.2.1 effects of pressurisation of reservoir on cap rock	Simulation of the injection history has shown that a maximum pressure of 1.5 times the hydrostatic pressure will be reached within the first few days of injection, after this pressure will decrease. Given a maximum pressure of 300 bars fracture and break-trough of the cap rock is unlikely to occur. Cap rock test has been performed at the Stenlille gas storage site although not against CO_2. Final conclusions can only be made after drilling of first well and pressure testing of the cap rock.
		3.2.2 Effects of pressurisation on reservoir fluids	Native pore fluid is highly saline water – no serious effects likely apart from displacement and increased solubility of CO_2
		3.2.3 Interactions with hydrocarbons	Based on regional assessment of petroleum systems no hydrocarbons are expected to be present. The lack of hydrocarbons is governed by lack of mature source rocks in the Danish Basin.
		3.2.4 Displacement of saline formation fluids	The storage system is modelled as an unconfined aquifer assuming that displacement of pore fluid takes place. The reservoir formation is mapped within the Danish Basin and the North German Basin and does not reach the surface. Displaced pore fluid is thus expected to be trapped within the reservoir formation. In case of break-through of the cap rock pore fluid may migrate through the overburden following pressure gradients. The unfaulted nature of the overburden with flat-lying, interbedded sandstone layers, tight mudstone layers and a more than 1 km thick Chalk successions will probably prevent saline pore fluid from reaching the near surface within the timescale of interest.

		3.2.5 Mechanical processes and conditions	See 3.2.1
		3.2.6 Induced seismicity	Not perceived as a serious risk
		3.2.7 Subsidence or uplift	Not likely to occur within timeframe of interest
		3.2.8 Thermal effects on the injection point	Temperature of injected CO_2 is different from the formation temperature. Simulation has been carried out by BRGM showing increasing chemical dissolution of reservoir rock leading to increasing porosity near injection point with rising temperature. The dissolution effects should be taken into account during the construction phase of the injection wells.
		3.2.9 Water chemistry	Data extrapolated from nearby wells. Pore fluid highly saline.
		3.2.10 Interaction of CO_2 with chemical barriers	Chemical barriers not relevant for the reservoir and primary seal. Interaction of CO_2 and carbonate rock may occur if CO_2 is leaking and reach the base of the chalk Group (1000 m depth). Dissolution is expected to take place in the lower few metres depending on fracturing. Outside this zone precipitation and mineral trapping of CO_2 is expected.
		3.2.11 Sorption and desorbtion of CO_2	Effects have not been studied
		3.2.12 Heavy metal release	Unknown whether any potential for this in the reservoir rock. Heavy mineral placers may occur in the shoreface sandstones.
		3.2.13 Mineral phase	Information on reservoir and cap rock geochemistry extrapolated from nearby wells. Sandstones are arkoses and subarkoses (quartz, K-feldspar and Plagioclase and feldspars with minor calcite, dolomite, siderite, pyrite and clay minerals) caprock mainly quartz, illite, kaolinite, K-feldspar, Albite and smectite.
		3.2.13.1 Mineral dissolution	Simulation has been carried out by BRGM. Dissolution of albite and siderite. Precipitation of chalcedony, kaolonite, dawsonite K-feldspar and siderite. Reactions towards the cap rock are very slow.
		3.2.13.2 Ion exchange	Diffusion through the cap rock has been modelled. After 5000 years 41% of the

			injected CO_2 has escaped the reservoir. However, diffusion through the overburden is slow CO_2 will not reach the surface within 1 million year
		3.2.13.1 Desiccation of clay	The low content of water in the injected CO_2 may lead to dry-out and shrinking of clays followed by cap rock desiccation. The process is likely to be restricted to the lower few metres of the caprock. The problem is common with gas injection sites. At Stenlille no serious damage to the cap rock has been encountered.
		3.2.14 Gas chemistry	Precise gas chemistry of injected fluid not yet known – see 3.1.1
		3.2.15 Gas stripping	Unknown
		3.2.16 Gas hydrates	Should not develop in well or pipeline (CO_2 dry) reservoir is outside hydrate stability envelope
		3.2.17 Biogeochemistry	Not enough data available to assess importance
		3.2.18 Microbial processes	Not studied. Microbial activity likely to be lowered near injection point and limited by scarcity of other nutrients in reservoir as a whole.
		3.2.19 Biomass uptake of CO_2	Likely to be limited as microbial activity likely to be limited by scarcity of other nutrients.
	3.3 CO_2 transport	3.3.1 Advection of free CO_2	Assessed using numerical reservoir simulation.
		3.3.1.1 Fault valving	Faults not recorded at the storage structure
		3.3.2 Buoyancy-driven flow	Assessed using numerical reservoir simulation. See 3.3.1 above. Approximately 10% of the CO_2 will dissolve during the time frame of interest.
		3.3.3 Displacement of formation fluids.	see 3.2.4
		3.3.4 Dissolution in formation fluids	Assessed using numerical reservoir simulation. Approximately 10% of the CO_2 will dissolve during the time frame of interest. Dissolution rates may be higher but will depend on effective driving force (see 3.3.2) permeability and the ratio of the free CO_2/water surface.
		3.3.5 Water medi-	Assessed using numerical reservoir

		ated transport	simulation. Not important from escape perspective as simulations indicate CO_2 dissolved in brine is transported downwards
		3.3.6 CO_2 release processes	According to the reservoir simulations, most likely release is as a free gas through injection or monitoring wells. May be avoided by best practice drilling and completion of wells. CO_2 escape by diffusion through the cap rock and overburden has been modelled. The results show that after 1 million years 41% of the injected CO_2 has escaped the reservoir, but has not yet reached the surface.
		3.3.6.1 Limnic eruption	Not likely to occur. Escaping CO_2 may be temporarily stored in the shallow standing body of water; Saltbæk Vig. In event of a limnic eruption CO_2 would spread towards the coast and would not affect populated areas. However, wildlife may be affected but the event is not likely to occur.
		3.3.7 Co-migration of other gases	Likely that impurities in CO_2 stream will also be released if CO_2 is released
4. Geosphere	4.1 Geology	4.1.1 Geographical location	Havnsø structure, Northeast of Kalundborg, Denmark
		4.1.2 Natural resources	None within reservoir and cap rock formations – predicted by basin modelling and tested in nearby wells
		4.1.3 Reservoir type	Marine shoreface sandstones
		4.1.4 Reservoir geometry	The reservoir consists of widespread shallow marine sandstones of the Gassum Formation. The sandstones were deposited from repeated progradation of shoreface and deltaic units. Net sand decreases towards the northwest. Local facies variations may reflect shoreface, barriers, spits and lagoonal deposits.
		4.1.5 Reservoir exploitation	The reservoir formation is used for natural gas storage at the DONG site 45 km southeast of Havnsø. Hydrothermal energy is produced from the formation at Thisted in northern Jutland 130 km northwest of Havnsø.
		4.1.6 Cap rock or sealing formation	Marine mudstones of the Jurassic Fjerritslev Formation. Predominantly silty mudstones with thin carbonate beds. The Formation is more than 500 metre

			thick in the region.
		4.1.7 Additional seals	Chalk Group carbonates may act as a secondary chemical seal
		4.1.8 Lithology	The reservoir consists of fine- to medium, locally coarse-grained sandstones interbedded with heteroliths, claystones and thin coal beds.
		4.1.8.1 Lithification/diagenesis	The sandstones have undergone diagenesis and are cemented mainly by quartz. Detailed studies are available (Friis 1987).
		4.1.8.2 Pore architecture	The porosity is excellent ranging from 18–27% (maximum 36%) and permeabilities up to 2000 mD. Linear correlations exist for both porosity and permeability versus depth (Priisholm 1983; Sørensen et al. 1998).
		4.1.9 Unconformities	“Mid-Cimmerian Unconformity” “Base Cretaceous Unconformity”
		4.1.10 Heterogeneities	The reservoir is predicted to consist of laterally continuous sandstone bodies separated by heterolithic beds, claystones or coal beds. Facies changes may occur and will control local variation in porosity and permeability. Risk of fingering through highly permeable zones.
		4.1.11 Fractures and Faults	No faults mapped at structure. See 4.1.12
Potential Risk		4.1.12 Undetected features	Minor faults may be present at top of structure, but are unlikely to extend through the cap rock
		4.1.13 Vertical geothermal gradient	For reservoir and geochemical modelling, assumed to be 30°C per km, surface temperature 10°C.
		4.1.14 Formation pressure	Initial pressure not known. Assumed to be hydrostatic e.g. 200 bar. Pressure during and post-injection assessed via numerical reservoir simulation.
		4.1.15 Stress and mechanical properties	Not known. Leak-off pressure of overburden assumed to be 150% of hydrostatic (Bech & Larsen 2005).
		4.1.16 Petrophysical properties	Unknown at storage site. Data extrapolated from nearby wells (core and well logs). Reservoir is assumed to be water-saturated porous and permeable sandstone.
	4.2 Fluids	4.2.1 Fluid properties	Data extrapolated from nearby wells –

			pore fluid consists of highly saline water. Major components are: CL, Na, Ca, K, Mg with some additional Br and SO4. Injection assumed to be pure CO_2
		4.2.2 Hydrogeology	Not known or modelled. Assumed to be very slow (negligible) flow in aquifer
		4.2.3 Hydrocarbons	None predicted from basin modelling and negative results from exploration campaigns
5 Boreholes	5.1 Drilling and completion	5.1.1 Closure and sealing of boreholes	Injection wells to be abandoned according to best practice for regulatory requirements
		5.1.2 Well lining and completion	According to best practice for regulatory requirements
		5.1.3 Workover	None planned for injection wells
		5.1.4 Monitoring wells	Monitoring wells would probably extend down to 1400 m below surfaces. Well completion in intra Fjerritslev Fm sandstones would detect any CO_2 escaping through the cap rock.
		5.1.5 Well records	Within the geological database at GEUS
	5.2 Borehole seals and abandonment	5.2.1 Closure and sealing of boreholes	Not yet known for injection wells - will be according to prevailing regulations
		5.2.2 Seal Failure	Risk of poor cement bond to poorly lithified strata. Leakage will probably be slow, but may cause CO_2 to migrate across internal seals separating different reservoir compartments. May increase risk of fingering. See 2.1.10
		5.2.3 Blowouts	Not likely to occur. The mudstones of the cap rock will to some extend be self sealing.
		5.2.4 Orphan wells	No deep wells present in the area. GEUS holds the record of deep wells in Denmark. Registration since 1848.
		5.2.5 Soil creep around boreholes	Not considered a risk in stable flat location
6. Near-surface environment	6.1 Terrestrial Environment	6.1.1 Topography and morphology	The deep storage site is not likely to be affected by future geomorphological processes
		6.1.2. Soils and sediments	Geochemical effects may occur if CO_2 leaks. Analysis not performed due to lack of data.
		6.1.3 Erosion and deposition	Low relief area no major changes expected. The deep storage site is not likely to be affected
		6.1.4 Atmosphere	Not assessed

		and meteorology	
		6.1.5 Hydrological regime and water balance	The underground storage will not be affected by changes in the hydrological regime
		6.1.6 Near surface aquifers and surface water bodies	CO_2 is not expected to be released to the surface. However, if CO_2 escapes potential damage needs to be assessed. Part of the spatial domain is classified as EF habitat area protection wildlife and plants. Special rules may apply. Freshwater streams and the shallow are regulated by national environmental laws (Naturbeskyttelsesloven)
		6.1.7 Terrestrial flora and fauna	CO_2 is not expected to be released to the surface. However, if CO_2 escapes potential damage needs to be assessed. Part of the spatial domain is classified as EF habitat area protection wildlife and plants. Special rules may apply.
		6.1.8 Terrestrial ecological systems	CO_2 is not expected to be released to the surface. However, if CO_2 escapes potential damage needs to be assessed. Part of the spatial domain is classified as EF habitat area protection wildlife and plants. Special rules may apply.
	6.2 Marine Environment	6.2.1 Coastal features	The coastline is a low energy inshore coastline. No major changes (except flooding, see 1.2.3) are likely to occur. Storage not likely to be affected
		6.2.2 Local Oceanography	The coastline is a low energy inshore coastline. No major changes (except flooding, see 1.2.3) are likely to occur. Storage not likely to be affected
		6.2.3 Marine sediments	CO_2 is not expected to be released to the surface. However, if CO_2 escapes, potential damage needs to be assessed. The possibility of CO_2 retention in the near surface sediments has not been examined.
		6.2.4 Marine flora and fauna	CO_2 is not expected to be released to the surface. However, if CO_2 escapes, potential damage needs to be assessed. Damage to sediment-dwelling organisms and sea-bed benthos may be a potential risk. CO_2 released to the free watermass is not considered a risk.
		6.2.5 Marine ecological systems	See 6.2.4. Part of the spatial domain is classified as EF bird protection and EU RAMSAR area. Special rules may apply.

	6.3 Human behaviour	6.3.1 Human characteristics	Not likely to be affected
		6.3.2 Diet and food processing	Not likely to affect diet and food processing
Potential Risk		6.3.3 Lifestyles	Public opposition may be expected. Construction and operation of the storage site may probably make people feel uneasy. This may influence real estate prices and recreational activities. The effect is likely to diminish within a few years of (successful) operation of the storage system. The risk should be avoided by careful and honest information prior to project start.
		6.3.4 Land and water use	Onshore CO_2 pipeline will have a 25 m wide protection zone on each side. No buildings or other activities will be allowed in this zone. The injection facilities will be private property of the operator. Effects/restrictions in other areas not expected.
		6.3.5 Community characteristics	CO_2 capture and storage may expand the lifetime of energy production at the Asnæs power plant and thus secure job opportunities and industrial production in the Kalundborg community. Although sparsely populated, the storage area has great recreational interests. Small human community and scattered farm houses is present at storage site. Public opposition may be expected
		6.3.6 Buildings	The storage and monitoring system should be planned such that no special requirements are needed for buildings in the domain of interest. Pipeline and injection platform would need to be maintained until site closed. Monitoring wells etc would need to be maintained in a longer period depending on system performance.
7. Impacts	7.1 System performance	7.1.1 Loss of containment	The storage system will be designed to retain CO_2 within a geological timeframe. Experiences from natural accumulations of CO_2 and from oil and gas fields prove that this assumption is valid. In case of unintended leakage the systems shall be able to detect (monitoring) and remediate the leakage. Unintended impacts on nature and humans should be evaluated

			through the risk assessment and major risks identified.
	7.2 Impacts on the physical environment	7.2.1 Contamination of groundwater	Leakage to shallow, fresh water aquifers are not expected, but may be a potential risk (see 3.3.6)
		7.2.2 Impacts on soils and sediments	Not studied
		7.2.3 Release to the atmosphere	Possible if system leaks. Will reduce the benefits of the storage scenario. Could require purchase of emissions certificates on open market.
		7.2.4 Impacts of exploitation of natural resources	None likely
		7.2.5 Modified hydrology and hydrogeology	Injection would modify hydrogeology. Adverse effects not expected.
		7.2.6 Modified geochemistry	Injection will modify reservoir rock and cap rock only slightly – see geochemistry section of final report
		7.2.7 Modified seismicicty	The Danish area is a low seismicity area. No effects expected.
		7.2.8 Modified surface topography	The reservoir is situated at 1500 m depth at 200 bars hydrostatic pressure. Although pressure will increase as a function of injection no significant effects are expected at the surface.
		7.2.8.1 Sinkhole formation	In the case of release of CO_2 from the reservoir it is expected to be slow – sinkhole formation is not expected
	7.3 Impacts on flora and fauna	7.3.1 Asphyxiation effects	If the system leaks CO_2 may accumulate in topographic depressions and lead to asphyxiation of wildlife. In the marine environment it could impact on sediment-dwelling organisms and sea bed benthos.
		7.3.2 Effect of CO_2 on plants and algae	In case of long term leakage to the surface CO_2 may influence the vegetation. The effects will depend on CO_2 concentrations in the soil and surface waters. It could also affect marine algae.
		7.3.3 Eco-toxicology of contaminants	Not considered as injected CO_2 will be clean, see 2.1.3
		7.3.4 Ecological effects	If system leaks long term effects may occur, see 7.3.1 and 7.3.2
		7.3.5 Modification of microbiological sys-	Not assessed due to lack of data

		tems	
Potential Risk	7.4 Impacts on humans	7.4.1 Health effects of CO_2	If system leaks CO_2 may accumulate in surface depressions and cellars/building and cause asphyxiation of humans. Any such effects should be avoided by planning and careful risk assessments. Risk to human health (acute or chronic) cannot be accepted and will stop the storage project.
		7.4.2 Toxicity of contaminants	Not expected as injected CO_2 will be clean see 2.1.3
		7.4.3 Impacts from physical disruption	During construction and operation all Health and Safety regulations should be observed to prevent any accidental injuries. Pipeline (CO_2 at 80 bars) may be accidentally disrupted. Hypothetical physical disruption of the reservoir and caprock (faulting) will not lead to sudden release of the stored CO_2.
		7.4.4 Impacts from ecological modification	Long term, continuous leakage of CO_2 may influence the ecological system through changes in vegetation and wildlife.

FEP audit for CO_2 storage in the Havnsø aquifer northeast of Kalundborg.