Executive Summary

Introduction

The Danish case study of the CO_2STORE 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 km^2 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_2equal 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 CO_2STORE 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 CO_2STORE 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 southeastern 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 CO_2STORE 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℃ 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 southeastern 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 CO_2SINK 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 CO_2STORE 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.

Øster Voldgade 10, 1350 København K - Tlf.: 38142000 - Fax: 38142050 - E-post: geus@geus.dk
Siden vedligeholdes af: webredaktøren