Carbon capture and storage (CCS) is increasingly considered to be a tool that can significantly reduce the emission of CO₂. It is viewed as a technology that can contribute to a substantial, global reduction of emitted CO₂ within the timeframe that seems available for mitigating the effects of present and continued emission. In order to develop the CCS method the European Union (EU) has supported research programmes for more than a decade, which focus on capture techniques, transport and geological storage. The results of the numerous research projects on geological storage are summarised in a comprehensive best practice manual outlining guidelines for storage in saline aquifers (Chadwick et al. 2008). A detailed directive for geological storage is under implementation (European Commission 2009), and the EU has furthermore established a programme for supporting the development of more than ten large-scale demonstration plants throughout Europe. Geological investigations show that suitable storage sites are present in most European countries. In Denmark initial investigations conducted by the Geological Survey of Denmark and Greenland and private companies indicate that there is significant storage potential at several locations in the subsurface.

The Danish perspective in storage capacity

The ten largest point sources of CO₂ emission in Denmark account for 21 mega-tonnes per year (Mt/year). From preliminary investigations of the Danish subsurface the CO₂ storage capacity in selected subsurface structures is estimated to 2500 Mt (GeoCapacity 2009a). This corresponds to more than 100 years of storage from the ten largest emission point sources. The critical parameters of this analysis are the size of the structure, thickness, continuity and quality of the reservoir and the amount of formation water that may be displaced by the injected CO₂. The estimate is calculated assuming a surrounding aquifer volume displacement of formation water, which is limited to 50 times the trap volume (GeoCapacity 2009a).

These estimates of storage capacity are uncertain and have not yet been tested in real physical storage operation. Therefore it is difficult to evaluate to what degree the volume calculations are realistic. When a specific structure is selected for storage, a number of investigative steps are necessary, including acquisition and interpretation of new 2-D or 3-D seismic data, drilling of new wells, geological and reservoir modelling and flow simulation studies. For each step of incorporating new geological data, the site model of the reservoir is updated in the process of maturing the structure towards a storage site. This stepwise approach to site characterisation gradually leads to a research-based and relatively certain capacity estimate and an evaluation of the safety and behaviour of the site under simulated conditions, including the uncertainties of the estimates.

Assessment of geological and environmental risks can be carried out at various stages in the process. Similarly, establishment of baseline studies and monitoring strategies need to be considered along with the progress of the characterisation...
tion of the storage site in order to make sure that the necessary background information is obtained before storage is initiated. In order to be reliable and operational, the baseline studies should preferably focus on measurement of conditions and properties that are stable and only show limited seasonal variations. Such studies may include groundwater-flow models and groundwater chemistry, pore water and pore gas analyses from deep wells, surface topography and natural seismicity.

A site study

Site investigations have recently been initiated of the Vedsted structure by Vattenfall A/S, with the intention of using the structure for storage of CO₂ from a nearby coal-fired power plant in Ålborg (Fig. 1; Sørensen et al. 2009). Existing data from oil exploration activities in the 1950s include one well in the centre of the structure and sparse 2-D seismic line data. The main target layer is the Triassic–Jurassic Gassum Formation at around 1800 m depth. The formation is widely distributed in the Danish Basin and has good reservoir properties (Fig. 2). It is currently used for storage of natural gas in the Stenlille structure on Sjælland and for geothermal energy in the Thisted area in northern Jylland.

Detailed sedimentological and sequence stratigraphic interpretations and correlations of the well logs and cores have established a robust stratigraphic framework for the Upper Triassic – Jurassic succession (Nielsen 2003). This framework forms the basis for the interpretation of the Vedsted-1 well section as well as predictions regarding the lithology of the potential reservoirs and seals in the Vedsted area (Fig. 3). The process has also underlined the necessity of acquisition of new data and more detailed modelling at several different scales.

At site scale, the optimal positioning of injection wells, as well as injectivity and capacity can be modelled and analysed, and the coupling between the operation of the power plant and the capture facility can be studied. The specific geological properties of the storage reservoir layers have consequences for the propagation and distribution of the injected CO₂ and for the storage mechanisms in the specific reservoir. Most reservoirs show both vertical and horizontal heterogeneities that will influence the distribution of the CO₂.

The preliminary reservoir model for the Vedsted structure has been investigated by simulating an injection well on its south-eastern flank and using injection rates realistic for power-plant supply rates (Frykman et al. 2009). After ten years of constant injection, the CO₂ distribution is as seen in Fig. 4, which clearly shows the subdivision of the migrating front into several sub-layers due to intraformational sealing layers with low permeability that also have high capillary entry pressures. The layering in the model has maximum lateral continuity, which probably overestimates the segregation to be found in real cases, but any intra-reservoir sealing layers will have such an effect on the distribution. Since this filling pattern influences the capacity, it is necessary to analyse further the properties and the continuity of the intraformational sealing layers.

CO₂ can be trapped by several mechanisms, including structural trapping under an overlying sealing formation, dissolution of CO₂ in formation water, capillary trapping in the pore network and mineral trapping by reactions between CO₂ and mineral phases in the reservoir rock. These trapping mechanisms work on different scales both in space and time and need to be studied by designing appropriate models and experiments.

For large-scale injection of CO₂ displacing saline porewater, the propagation of the pressure field during injection outside the immediate site area is of interest. Modelling of this pressure distribution will serve to predict the amount of over-pressure building up locally within the storage site, and can be used to suggest possible means of management.

Fig. 2. Distribution of the Triassic–Jurassic Gassum Formation in the subsurface at depths between 800 m and 2400 m (yellow), the depth interval in which CO₂ exists as a supercritical phase and where burial diagenesis has not yet provoked significantly lowered porosity. At the supercritical phase the volume of CO₂ is much less than that of the CO₂ gas at the surface.
The scale of the challenge and future perspective

The first detailed pan-European assessment of CO₂ storage capacity in the framework of the EU research project Geo-Capacity has resulted in a geographic information system (GIS) database of CO₂ emissions, storage capacity estimates and geological information. The database includes information on reservoirs with a total storage capacity of 360 000 Mt CO₂, with 326 000 Mt in deep saline aquifers, 32 000 Mt in depleted hydrocarbon fields and 2000 Mt in unmineable coal beds: 116 000 Mt are onshore, and 244 000 Mt offshore (GeoCapacity 2009a). Some of the estimated storage capacity is associated with structural traps, but a very large part is in regional deep saline aquifers without identified specific traps. Almost 200 000 Mt of the total storage capacity in the database are located offshore Norway. These estimates date back to 2003 and have not been updated within the GeoCapacity project. An attempt to provide a more cautious and conservative European estimate has yielded a storage capacity of 117 000 Mt with 96 000 Mt in deep saline aquifers, 20 000 Mt in depleted hydrocarbon fields and 1000 Mt in coal beds, and with approximately 25% located offshore Norway. This must be compared to a total of 2000 Mt of CO₂ emission from large point sources, i.e. point sources emitting more than 0.1 Mt/year within Europe.

In order to illustrate the scale of the technology and infrastructure that has to be established if CCS is to become an active industry, we can look at the amount of CO₂ produced by the ten largest point sources in Denmark. There are 43 large point sources emitting more than 0.1 Mt/year within Europe. In order to illustrate the scale of the technology and infrastructure that has to be established if CCS is to become an active industry, we can look at the amount of CO₂ produced by the ten largest point sources in Denmark. There are 43 large point sources emitting more than 0.1 Mt/year within Europe.
tions this corresponds to 11 billion \((11 \times 10^9)\) m\(^3\) CO\(_2\) gas. The annual production of natural gas from the Danish part of the North Sea amounts to 10 billion \((10 \times 10^9)\) m\(^3\) (Danish Energy Agency 2008), which is transported in pipelines and tankers and processed at plants and refineries. The comparable size of the potential volume of CO\(_2\), to be moved around at surface and injected into the subsurface (although compressed to smaller volumes at depth), points to the large scale at which a CCS-related processing and transporting industry has to be established.

**Concluding remarks**

The CCS activities described here related to large-scale storage operations will involve significant physical resources and manpower. Fortunately, the work with storage-related items does not have to begin from first principles, because much of the experience already exists in the oil and gas industry, which can provide methods and tools for immediate use. The skills of geoscientists and engineers are needed in the investigation and characterisation of the sites and the subsurface conditions for storage of CO\(_2\), and a whole new infrastructure and industry may be established. Geoscience and geo-engineering will play a major role in the analysis of the geological foundation, the assessment of site performance, and will be critical in securing the safety of the operations.

Initial investigations of the Danish subsurface indicate that suitable structural traps with a significant storage potential are present at several locations, and that the structures can accommodate the CO\(_2\) produced from several or most of the large Danish point sources. Thus, geological storage of CO\(_2\) may contribute considerably to the reduction of the Danish CO\(_2\) emission, if we can be assured about safety issues, and if political and public acceptance can be obtained.

**References**


**Authors’ address**

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