DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2003/79

Feasibility of CO_2 storage in combination with geothermal plants, Denmark

A GESTCO contribution

Anders Mathiesen, Michael Larsen,
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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

G E U S

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MINISTRY OF THE ENVIRONMENT

GEUS

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1. INTRODUCTION

The potential for geological storage of CO_2 in Denmark has been investigated as part of the Gestco research project financed by the European Commision Fifth Framework Programme (Christensen 1999). The study was focused on three storage options: 1) oil and gas fields, 2) deep saline aquifers and 3) combination with geothermal energy systems. In this report we evaluate the present status for geothermal energy in Denmark and discuss the potential for storage of CO_2 in connection with geothermal systems.

In Denmark the geothermal resources are linked with hot formation water present in deep saline, porous and permeable aquifers of Mesozoic age. In the geothermal loop hot formation water is produced from the deep reservoirs and after extraction of the heat, the water is reinjected into the sandstone reservoir. The injection of return water may be combined with the injection of CO_2 either as a separate phase or in water solution. A number of studies on the feasibility of CO_2 injection in geothermal systems have been undertaken in the Paris Basin by BRGM (Bureau de Recherches Géologiques et Minières) in the Gestco project (Cortiche & Herbrich 2003).

Geothermal energy is an established technology and more than 100 plants are currently operated within Europe. In Denmark the only existing geothermal plant is the Thisted plant in northern Jylland (Fig. 1), while a second plant is under construction in Copenhagen. The Thisted plant has produced heat and injected millions of m^3 of 15% saline geothermal water without production or injection problems for nearly 20 years. The preparations to erect a geothermal plant in the Copenhagen has started. New seismic lines were acquired in year 2001 and the first well; Margretheholm-1 was drilled in 2002 (Fig. 1). The second well was drilled May 2003.

A geothermal plant can be part of a "zero emission plant", i.e. a ‘Combined Heat and Power plant (CHP), where the power and driving heat used by absorption heat pumps comes from a combined heat and power plant and where produced CO_2 is injected. The pressure in a geothermal aquifer will normally exceed both the critical CO_2 pressure and the critical temperature. Injected CO_2 will thus remain either in dense phase or be dissolved in the geothermal water. CO_2 in dense phase has, however, a lower density than water. It may thus be preferred only to store amounts that can be dissolved in the injected water, - or in the water in the immediate vicinity of the injection well where either no cap-rock exists or where it is too expensive to verify the sealing capacity of such a cap rock.

The use of geothermal energy in combination with CO_2 storage will require increase of distance between production and injection wells, will reduce the sweep or will increase material costs, - but can also reduce costs related to geological mapping and characterisation of the storage site. If CO_2 is injected together with the geothermal return water further cost reductions may be obtained throughout the injection period compared to an injection of CO_2 not associated with the injection of geothermal water.

A important note is that a combined geothermal and CHP plant with CO_2 injection can contribute to both the heat and the power supply producing heat and power at more than 100% efficiency and without emission of CO_2.

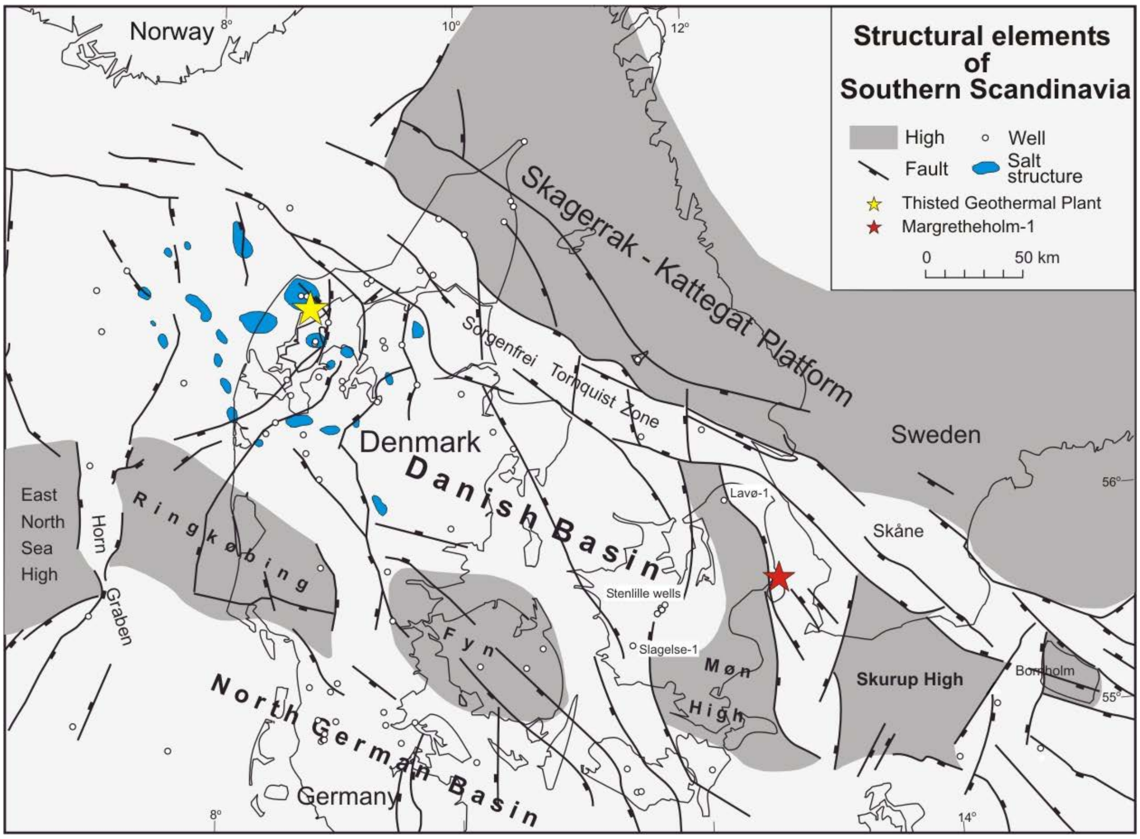

Fig. 1: *Structural elements of Southern Scandinavia and locations of the Thisted geothermal plant and the new geothermal Margretheholm-1 well.*

2. GEOLOGICAL SETTING

The Danish Basin is an intracratonic, Permian–Cenozoic structure that trends WNW–ESE. It is bounded by basement blocks of the Ringkøbing-Fyn High to the south and by the Fennoscandian Border Zone to the north-east. The Border Zone demarcates the transition to the stable Precambrian Baltic Shield and includes the Sorgenfrei-Tornquist Zone and Skagerrak-Kattegat Platform. The Sorgenfrei-Tornquist Zone is a fundamental tectonic feature that strikes NW-SE across North Jylland, Kattegat, the northern part of Øresund and through Southern Sweden (Fig. 1). It is strongly block-faulted, 30–50 km wide, with tilted Palaeozoic fault blocks unconformably overlain by thick Mesozoic deposits that show pronounced late Cretaceous–early Tertiary tectonic inversion.

The deepest regional surface mapable by reflection seismic data in the Danish Basin and Fennoscandian Border Zone is the top pre-Zechstein surface, which is a pronounced unconformity truncating tilted faults blocks in most of the area. The unconformity defines the base of the post-rift basin-fill and is overlain by a relatively complete succession of Upper Permian, Mesozoic and Cenozoic deposits that is approx. 5–6.5 km thick along the basin axis and more than 9 km locally in the Sorgenfrei-Tornquist Zone. Isocore maps of the Triassic and Jurassic–Lower Cretaceous successions show a relatively uniform regional thickness in most of the basin except for areas influenced by local faulting and halokinetic movements (Vejbæk 1989, 1997; Britze & Japsen 1991; Japsen & Langtofte 1991). Thinning of the Zechstein–Lower Jurassic and Upper Jurassic–Lower Cretaceous successions indicates a general shallowing of the basin toward the Ringkøbing-Fyn High. In early Middle Jurassic time the Ringkøbing-Fyn High, most of the Danish Basin and parts of Southern Sweden was uplifted and subjected to deep erosion. Only the Sorgenfrei-Tornquist Zone experienced slow subsidence. Southwest of this zone, the erosional unconformity, the “Base Middle Jurassic Unconformity” shows a progressively deeper truncation toward the Ringkøbing-Fyn High where the Lower Jurassic is deeply truncated. On the high the truncation reach into the Triassic succession. In late Middle–early Late Jurassic time regional subsidence gradually took over again and became more widespread as shown by a progressively younger Upper Jurassic-Lower Cretaceous onlap to the unconformity toward the Ringkøbing-Fyn High.

Geothermal resources in Denmark is mainly related to the Mesozoic succession of the Danish Basin and Fennoscandian Border Zone. This succession has been the target for exploration activities since 1935 and is known from approx. 60 deep wells drilled for hydrocarbons, geothermal energy or gas storage (Sorgenfrei & Buch 1964; Nielsen & Japsen 1991). The stratigraphic scheme applicable for the Mesozoic is based on Sorgenfrei and Buch (1964), Larsen (1966), Michelsen (1975, 1978, 1989), Bertelsen (1978, 1980), Michelsen et al. (in press) and Nielsen (in press).

3. GEOTHERMAL PROSPECTIVITY

DONG A/S (Dansk Olie & Naturgas A/S) was granted a sole concession for the exploration and production of geothermal energy in Denmark in 1978 of which part of the concession area was given back to the state in 1993. Seismic investigations were carried out and three deep geothermal exploration wells were drilled and tested. Initially it was believed that geothermal heat should be produced as hot water from deep aquifers, but due to e.g. variation in salinity and permeability gradients it was found more profitable to produce less warm water from aquifers closer to the surface.

The first national study on geothermal resources was presented by Michelsen et al. in 1981. The report compiled existing well data and seismic data from the Danish onshore areas. The study described reservoir sandstones ranging from the Late Palaeozic to Mesozoic in age, but focussed on aquifers situated between 2000 and 3000 m. The initial results were discouraging as most of the initial porosity and permeability were lost in the aquifers due to the deep burial.

Heat and power plants integrated with geothermal plants with heat pumps (primary absorption heat pumps) can be used to produce heat and power with a high efficiency. Such plants can work together with wind turbines and become an important part of an efficient system designed to cover the total need for heat and power. Geothermal plants with absorption heat pumps supplying heat to district heating networks can typically produce 5–20 times as much heat as the electricity they use to drive the plant. More power from windmills etc. can reduce the heat production from CHP plants at the district heating networks and create a need for new geothermal plants.

In 1998 the Geological Survey of Denmark and Greenland (GEUS) concluded that sufficient geothermal resources exists in sandstone aquifers to cover the need for district heating in Denmark for hundreds of years (Sørensen et al. 1998).

Niels Balling, Århus University investigated temperature gradients in greater detail and found typical gradients of around 0.03°C per meter, highest in the deeper layers (Fig. 2). Although Denmark has moderate temperature gradients, many areas and stratigraphic levels hold warm sandstone aquifers, which can be used for district heating (Sørensen et al., 1998).

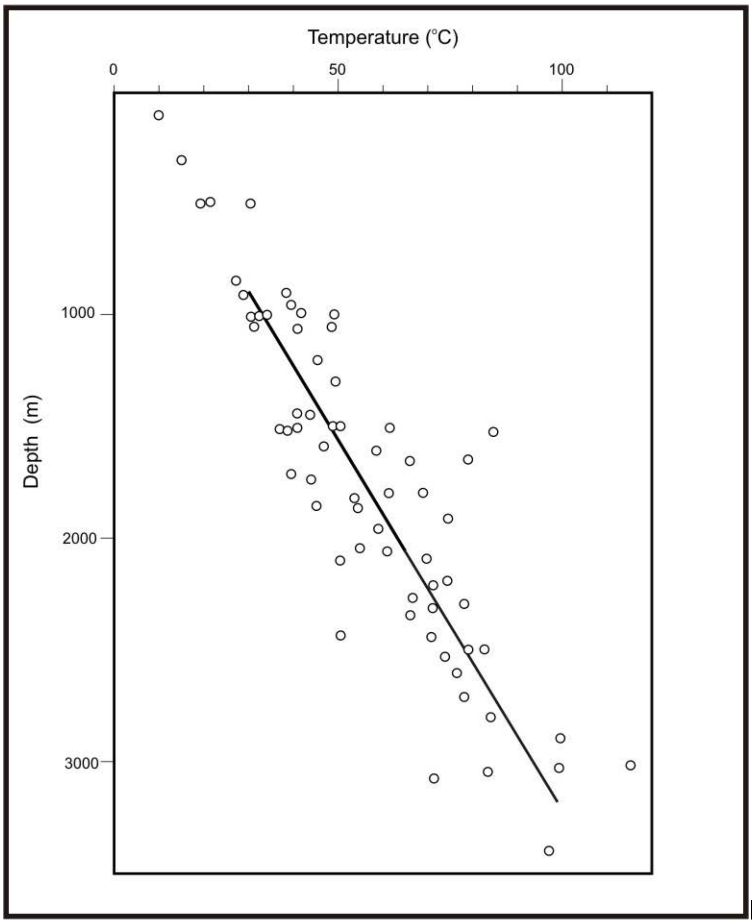

Fig. 2: *Temperature data from Danish onshore exploration wells with a regional depth relation. The temperature data has been corrected by Niels Balling, Århus University.*

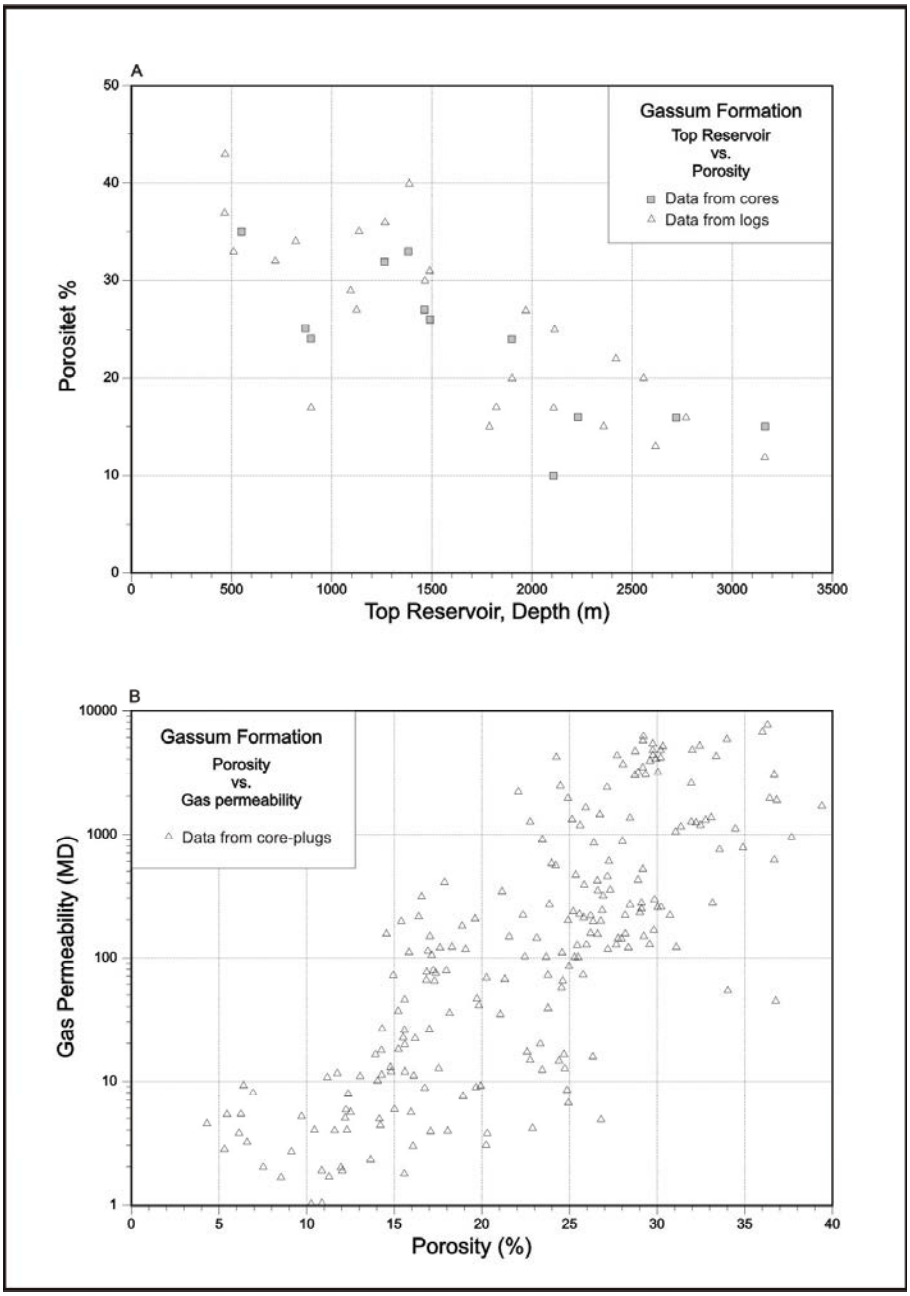

Fig. 3: *Porosity and permeability data from Danish onshore wells. A) shows the porosity as a function of depth for the Upper Triassic–Lower Jurassic Gassum formation. Each point represents an average of values in one well. B) shows permeability of gas vs. porosity in Gassum Formation. Each point represents a measurement on one core-plug.*

Both the porosity and the permeability decreases with increasing depth, but depth relations are poorly defined (Fig. 3). Furthermore, there seems to be regionally differences due to depositional environment, provenance and burial history which is not yet fully described or understood.

Thus, based on the analyses made by GEUS, Århus University and on work by DONG A/S 3 very rough roles of thumb can be used for the Danish sandstone aquifers:

- The temperature increases with 30°C per km
- The salinity increases with 10% per km
- The permeability is halved each 300 m

GEUS has contributed to the two volumes of Atlas of Geothermal Resources in the European Community (1988 and 2002) where the aim was to put together data and information for delineating areas of interest for further geothermal exploration. The latest Atlas (2002) describes the present day general knowledge on geothermal related issues within the Danish area.

In 2001, a confidential study of the geothermal potential in the Copenhagen-Malmö region was initiated on behalf of DONG A/S. The geological evaluation was conducted by GEUS and included a total interpretation of all common Danish-Swedish marine- and land seismic survey, and the study indicated promising results. This study has later served as preparations for a common drilling campaign with DONG A/S as drilling operator. This integrated geophysical and geological evaluation indicated the existence of several possible sandstone aquifers including the Gassum and the deeper Bunter sandstone aquifers known from several Danish wells and Swedish wells.

4. GEOTHERMAL RESERVOIRS

Based on regional geological studies and results from hydrocarbon exploration studies six stratigraphic units with geothermal potential are identified. These are 1) the Lower Triassic Bunter Sandstone 2) the Skagerrak Formations, 3) the Upper Triassic—Lower Jurassic Gassum Formation. 4) the Upper Jurassic Haldager Sand Formation, 5) the Upper Jurassic Frederikshavn Formation and 6) the Lower Cretaceous Arnager Greensand Formation (Fig. 4).

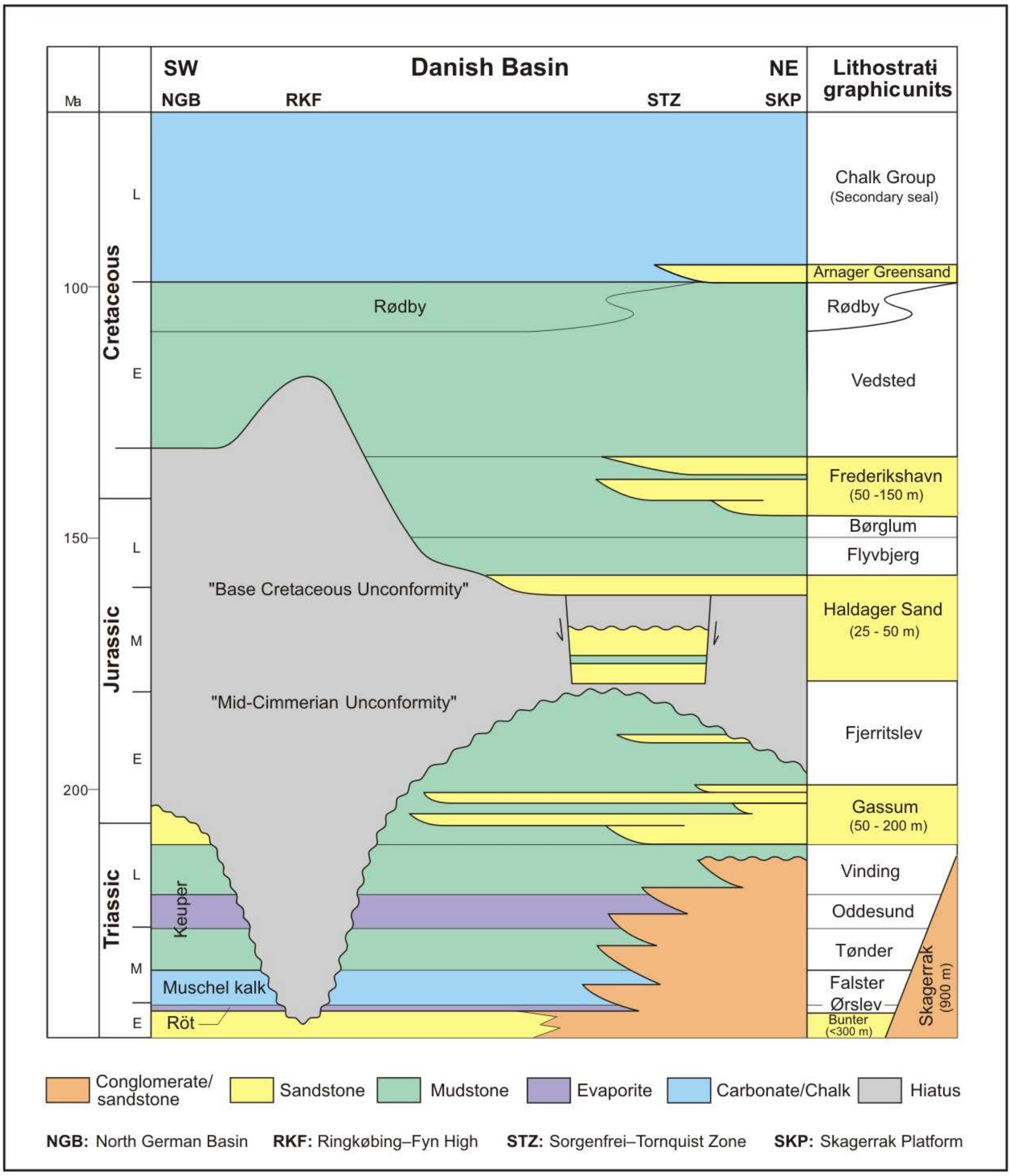

Fig. 4: *Generalised stratigraphy for the Danish area showing stratigraphic units with geothermal potential.*

Especially the Bunter and Gassum Formations have high net sand radios, occur widespread and show good porosity and permeability values. In contrast the Arnager Greensand is considered to shallow for geothermal purposes, and has a limited distribution.

4.1 Bunter Sandstone and Skagerrak Formations (Lower Triassic)

The Bunter/Skagerrak Formations are present throughout the Danish area. Sandstones of the Bunter Sandstone Formation are dominant in the south-western and central part of the Danish area and is gradually replaced by the more coarse-grained Skagerrak Formation towards the north-eastern basin margin. The Bunter Sandstone Formation represents deposition in an arid continental environment dominated by fluvial channels, aeolian dunes and marginal marine facies (Bertelsen 1980). The Skagerrak Formation is poorly known but the coarse-grained often poorly sorted lithology with claystone units and the marginal extend along the northern and northeastern basin margin suggest deposition in alluvial fans and lakes (Bertelsen, 1978,1980).

The Lower Triassic sandstone dominated succession (Bunter and Skagerrak) form units with thickness around 300 m, and may in the central part of the Danish Basin reach 900 m. The succession is thin and locally absent across the Ringkøbing–Fyn–Møn High. It is anticipated that no primary hydraulic barriers exists within the sheet sandstone (Sørensen et al. 1998). The storage potential of the Bunter Formation in the southern North Sea is evaluated in Brook et al. (2003).

Reservoir properties are poorly known and often based on estimates from petrophysic logs (Michelsen et al. 1981). The porosity estimates range from 0–24%, whereas the permeability is generally low (10–100 mD) due to the relatively deep burial depth causing diagenitic changes and cement formation.

In the north and middle Jylland, transmissibilities for the Skagerrak Formation may reach the order of 20 to 50 Dm, and in northern Jylland at more shallow depth (1000–1500 m) even higher values are expected. In the southern and south-western part of southern Jylland, transmissibilities for the Bunter Sandstone Formation are probably in the range of 5–25 Dm. Locally, the formation is thicker and the transmissibility is expected to be high. The temperatures are north of the Ringkøbing-Fyn-Møn High are 40–60^{o}C.

4.2 Gassum Formation (Upper Triassic–Lower Jurassic)

The Gassum Formation is present in the Danish Basin, Fennoscandian Border Zone, the North German Basin and on the eastern part of the Ringkøbing-Fyn-Møn High. It shows a remarkable continuity with thickness between 100 and 150 m throughout most of Denmark, reaching a maximum thickness of approx. 300 m in the Sorgenfrei-Tornquist Zone. The Gassum Formation is truncated by the base Cretaceous unconformity at the Ringkøbing-Fyn-Møn High.

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. in press). 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 the Lower-Middle part of the Formation in the Sorgenfrei-Tornquist Zone (Nielsen, in press).

Maximum net thickness of >100 m is found in the Sorgenfrei-Tornquist Zone in the area around the city of Ålborg, where the formation is shallower that 2000 m. The porosity and permeability of the Gassum sandstones are known from a number of wells and illustrate a regional, well-defined relation between reservoir properties and depth in the Danish Basin (Fig. 2). Generally the reservoir properties are excellent with porosity 18–27% and permeabilities up to 2000 mD. Transmissibilities of up to 50 Dm, locally even 100 Dm and temperatures between 40–70^{o}C may be found. Similar conditions exist over mid-Sjælland and in areas above salt structures in the Danish Basin. The permeability decreases rapidly with depth, and in the central part of the Danish Basin transmissibilities of 0.5–5 Dm are expected and temperatures between 60–110^{o}C.

4.3 Haldager Sand Formation (Middle Jurassic)

The Haldager Sand Formation is present in the central and northern part of the Danish Basin, in the Sorgenfrei-Tornquist Zone and on the Skagerrak-Kattegat Platform with depths of 1500 m and reaching a maximum net thickness of 150 m, but a marked thinning is seen southwest and northeast of the Sorgenfrei-Tornquist Zone.

The Haldager Sand Formation consists of thick beds of fine- to coarse-grained, locally pebbly sandstones intercalated with thin siltstone, claystone and coal beds. Sandstones were deposited in a range of depositional environments covering shallow marine, eastuarine, fluvial and lacustrine facies (Nielsen et al. in press). Deposition was locally affected by synsedimentary movements of faults and underlying salt structures.

The porosity varies between 12 and 33% whereas permeabilities have only been estimated in two wells having 600 and 2000 mD, respectively. Transmissibilities of up to 20 Dm and temperatures between 40–60^{o}C, and locally even 90^{o}C are found.

4.4 Frederikshavn Formation (Upper Jurassic–Lower Cretaceous)

The formation is present in the northern part of the Danish Basin and shows large variation in thickness (75–235 m) reaching a maximum thickness in the Sorgenfrei–Tornquist Zone, and in depth (500–1800 m) partly controlled by local faults and salt tectonics. The most coarse-grained parts of the formation is present in the northeast towards the Skagerrak-Kattegat Platform, whereas the formation interfingers with the fine-grained Børglum Formation towards the west (Michelsen et al. in press). The formation consists of siltstones and fine-grained sandstones forming 2–3 coarsening-upwards units separated by claystones.

Transmissibilities of up to 20 Dm but can be higher due to the shallow burial depth and temperatures between 20–45^{o}C, but may locally be higher.

5. GEOTHERMAL FAIRWAYS

Based on Michelsen et al. (1981) and Sørensen et al. (1998) geothermal fairways for each of the reservoir units were mapped. A geothermal fairway is defined as an area in which the net sand thickness of the formation is more than 25 m and the formation is present within the depth range of 1000–2000 m. The fairway map comprises the following reservoir units or regions (Fig. 5):

- Frederikshavn Fm
- Haldager Sand Fm
- Gassum Fm
- Bunter Sandstone Fm
- Höllviken Fairway

The Höllviken Fairway includes the Copenhagen-Malmö region and the subsurface in the area was unknown prior to the Margretheholm-1 test well was drilled in 2002. The Fairway is a graben structure bounded by the Sorgenfrei-Tornquist Zone to the east and the extension of the Øresund Fault zone to the west separating Sjælland in two main elements (Fig. 1 and 5). The western element belongs to the Danish Basin and shows a structural development similar to the basin, while the Höllviken Graben may be regarded as broad transition zone between the Danish Basin and the strongly faulted Sorgenfrei-Tornquist Zone.

The western element, west of the Höllviken Graben, is characterised by a number of mainly north–south trending basement faults that defines a series of fault blocks with Palaeozoic rocks showing down-throw to the west. The Palaeozoic is overlain by a Zechstein–Mesozoic succession, and Rotliegende rocks are thin or absent (Fig. 6). The old seismic lines shows that the Mesozoic succession is characterised by relatively continuous reflectors. The few faults affecting the Mesozoic show decreasing displacements upward terminating with flexures or minor throws close to the base of the Quaternary.

The Höllviken Graben is bounded to west by the Øresund Fault and its northern extension, by the Svedala Fault against the Skurup Platform to the south-east, by the Barsebäck Platform and the Sorgenfrei-Tornquist Zone to the north-east (Fig. 1). In contrast to the western part of the area of interest, the Höllviken Graben is believed to present as a series of fault blocks with Mesozoic strata that show a westward thickening and down-throw to the east. The Triassic succession is expected to be present and contain sand-prone fluvial and possible minor proportions of eolian units (Fig. 6).

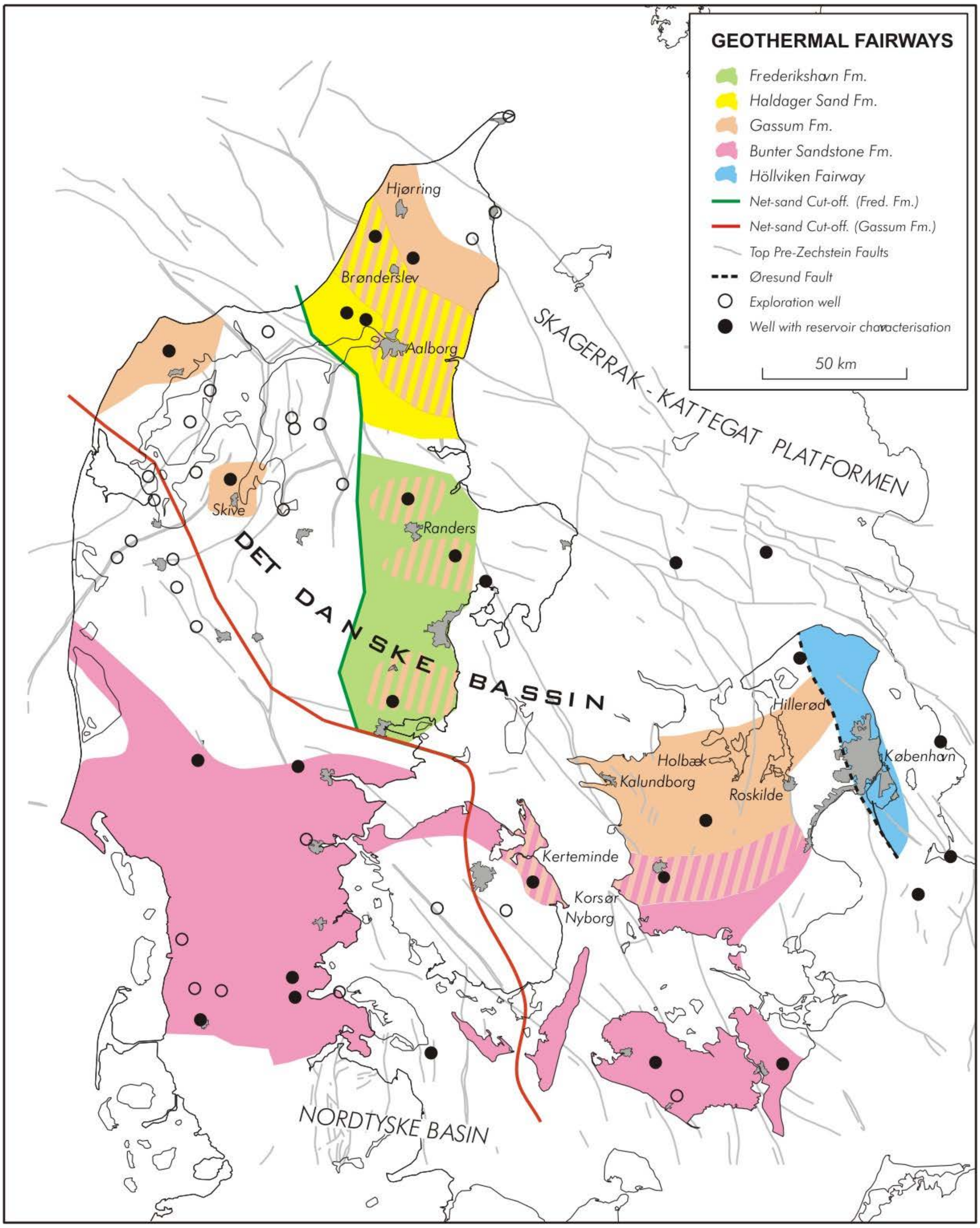

Fig. 5: *Geothermal fairways in Denmark defined as an area in which the reservoir unit is situated between 1000-2000 m and is expected to have more than 25 m net sand thickness. Overlap between fairways are marked by hachted colours. 'Net-sand cut-off' defines the western and southwestern extend of the Frederikshavn Fm Fairway and the Gassum Fm Fairway, respectively. The map is based on well data, seismic mapping and depth conversions from previous exploration surveys (from Sørensen et al. 1998).*

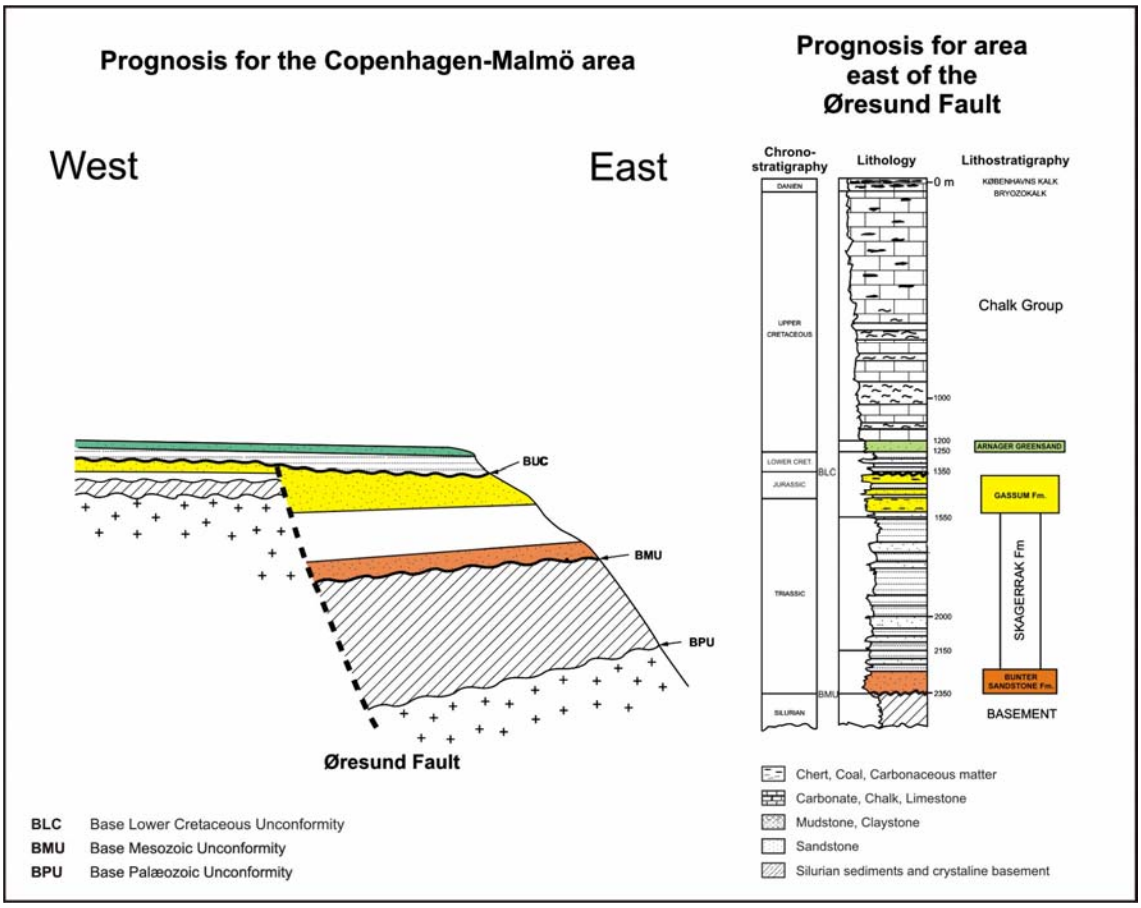

Fig. 6: *Schematic lithological prognosis for the Copenhagen-Malmö area prior to the Margretheholm-1 well. The main potential reservoirs are believed to be located on the downthown side of the Øresund Fault. The prognosis for the down-thrown side is shown to the right illustrating the expected position of possible geothermal reservoirs.*

6. METHODOLOGY OF COMBINED GEOTHERMAL SYSTEMS AND CO_2 STORAGE

A geothermal plant can be part of a "zero emission plant", where the necessary power and driving heat for absorption heat pumps at the geothermal plant comes from a combined heat and power plant, and emissions of CO_2 are recovered and injected (Fig. 7). The pressure in a geothermal aquifer will normally exceed the critical CO_2 pressure of 72.8 bar and the critical temperature of 31.1°C or 304.2 K. The combined geothermal CO_2 storage system may be operated with CO_2 in solution, or with CO_2 as a separate phase. In the latter case the reservoir integrity becomes important (see related report by Larsen et al. 2003).

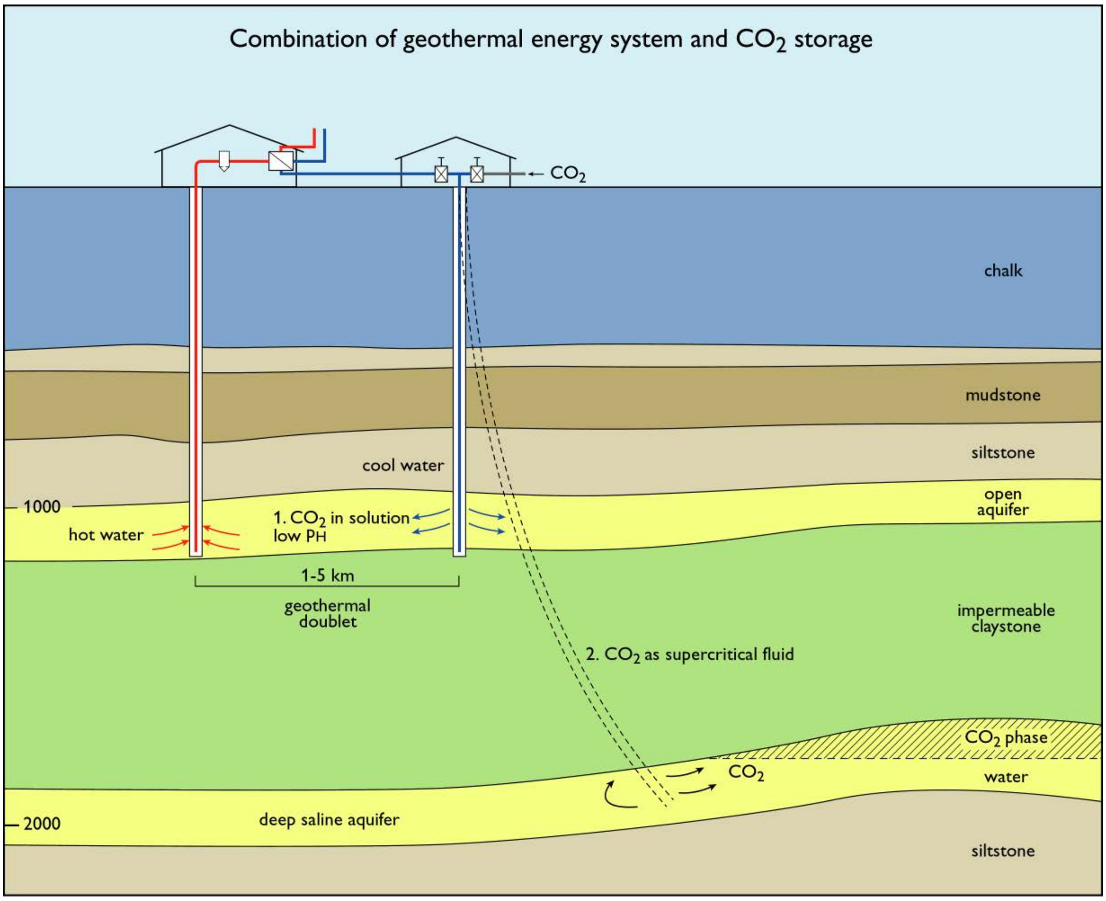

Fig. 7. *Conceptual cross-section illustrating the geothermal loop and the principle in CO_2 storage. Following production of hot water and heat absorption in the geothermal plant CO_2 is injected into the geothermal reservoirs with the cool return water. In case 1) the CO_2 is dissolved in the return water. In case 2) CO_2 injected as a supercritical fluid and acts in the reservoir as a separate phase. The CO_2 phase has lower density than the reservoir water and must thus be trapped below a tight cap rock e.g. claystone.*

6.1 CO_2 in solution

The geothermal plant is based on a water loop in which hot formation water is extracted from the reservoir, led though a geothermal plant extracting heat from the water and reinjected into the reservoir. Without CO_2 injection the distance between the production well and injection well is normally designed to maintain a constant production temperature requiring a typical well distance of 0.5–2 km depending on the flow and the reservoir properties. CO_2 may be dissolved in the cool return water and injected in the thermal reservoir. The solubility is a function of temperature and pressure. Under reservoir conditions water may contain around 3–6 wt% CO_2, as the solubility depends on pressure, temperature and salinity. The amount of CO_2 that may be injected will thus be directly linked to the volume of reinjected cooled formation water. Special concern must be given to the possible dissolution effects on minerals and cement of the reservoir rocks in order to avoid deposits and injection problems. During the migration through the reservoir some of the dissolved CO_2 may react with the reservoir formation and thereby become "permanently" trapped in the formation. However, recent studies suggest that only a minor part of the injected CO_2 may be retained and the CO_2 will eventually reach the production well (see Kervevan et al. 2003). In that case the well distance must be increased to avoid production of CO_2 contaminated water or expensive material must be used to avoid corrosion of the production system from the aggressive, low pH water. A problem with this concept is thus a reduced reservoir sweep and increased plant cost.

The storage system can benefit from the fact that reservoir characterisation, geological modelling and flow simulation is already part of the initial geothermal appraisal. Furthermore, CO_2 injection may take place through the geothermal injection well.

6.2 CO_2 as a separate phase

CO_2 may also be injected in the reservoir as a separate phase (supercritical fluid). This requires that the reservoir into which injection takes place is located below a tight cap rock and meets the criteria for CO_2 storage as set up for deep saline aquifers (Larsen et al. 2003). Storage of CO_2 as a supercritical fluid may only take place in reservoirs situated deeper than approximately 900 metres. In contrary to the geothermal reservoir a tight cap rock (e.g. mudstone or evaporite) is needed above the reservoir in order to prevent the less dense CO_2 from escaping to the surface.

In the presence of more than one reservoir unit the concept of the geothermal loop may be adjusted and hot formation water may be produced in one reservoir and reinjected into a sealed reservoir at different stratigraphic level.

7. GEOTHERMAL PLANTS IN DENMARK: THISTED

Fig. 8. *The geothermal plant in Thisted, so far the only operating plant in Denmark.*

DONG A/S was granted a concession for the exploration and production of geothermal energy in Denmark in 1978 and has worked with geothermal energy since. A geothermal pilot plant with an electric heat pump was erected in Thisted 1984 with production from and reinjection to the Gassum reservoir at 1250 m depth. The produced heat was then added to the already existing district heating network of Thisted.

The pilot plant proved a concept for avoiding corrosion and contamination of the injection well. Electricity tariffs increased and it was thus decided to install an absorption heat pump when the plant was expanded to a demonstration plant in 1988. The plant was expanded again in year 2000–2001 and both expansions was made in corporation with the district heating company, Thisted Varmeforsyning assisted by the consulting engineers Houe & Olsen A/S, who also has designed the combined heat and power plant. At present DONG A/S owns the geothermal loop and has the responsibility for its operation, while Thisted Varmeforsyning owns the rest of the plant and maintains its daily operation.

The Thisted plant has now operated for nearly 20 years and has proved, that geothermal energy can be produced as an energy efficient dependable heat source with low operating costs.

7.1 Geothermal demonstration plant

The demonstration plant in Thisted with the electric heat pump and the absorption heat pump started to operate in 1988. The difference in costs running the electric heat pump and the absorption heat pump was, however, so big, that the electric heat pump was not used in practice, and was removed from the plant in 1994. The plant was expanded further in year 2000-2001 with an additional heat pump, more filters and frequency controlled production and injection pumps.

To day the plant extracts up to 7 MW heat with the absorption heat pumps from up to 200 m^3/h of the 44°C, 15% saline geothermal water (Fig. 9). The geothermal water is produced from and reinjected in the 100 Dm Gassum sandstone reservoir at a temperature of 10-12°C. The two LiBr absorption heat pumps are driven by 150–160°C hot water from a combined heat and power incineration plant and sometimes also by heat from a gas boiler. The plant uses approx. 350 kW electricity to extract the 7 MW heat from the geothermal water.

All of the heat used to operate the absorption heat pump is recovered on the district heating network together with the extracted geothermal heat. The driving heat for the absorption heat pump is thus free of charge if the driving heat is taken from a heat supplier, which normally supply the heat directly to the district heating network. The geothermal water loop is designed with:

- Carbon steel tubes (diffusion proof and even distribution of corrosion).
- Corrosion resistant materials at selected places (e.g. balls in ball valves).
- Filtering of geothermal water to 1/1000 mm in bag and cartridge filters.
- Frequency controlled production and injection pumps.
- Avoidance of underpressures from Bernoulli effects when operating.
- Nitrogen bottles securing overpressure during stops.
- Gravel packs in production and injection well.
- Computer controlled fail safe valves.

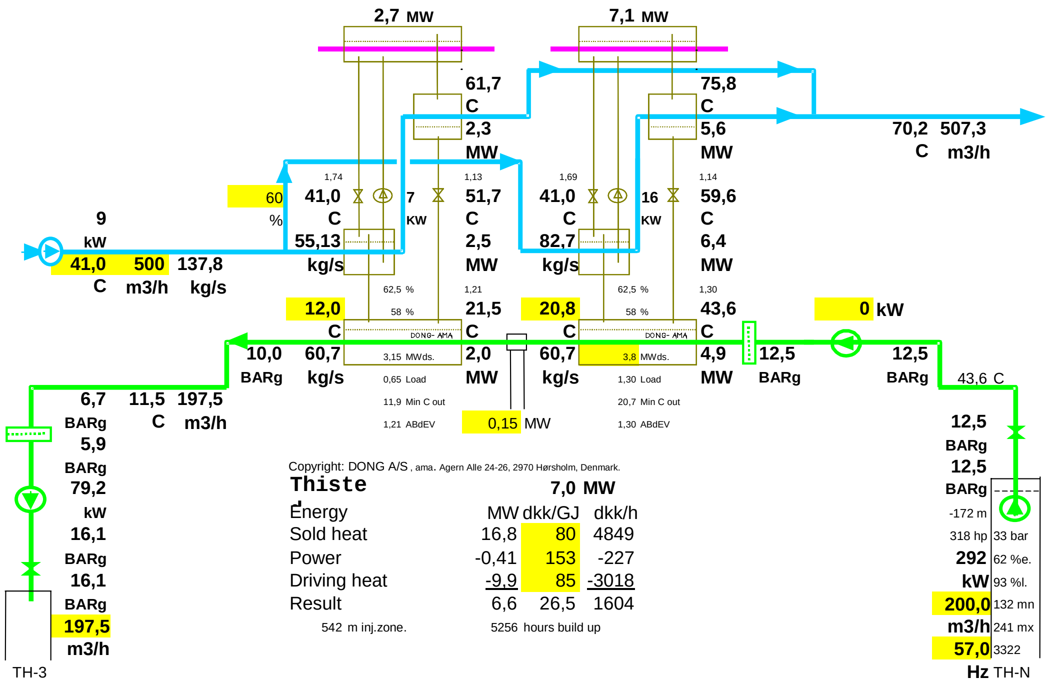

Fig. 9: *Design sheet and operating strategy for the Thisted plant.*

When the plant is started the geothermal water is produced to the sewer at the production well site where methane is removed in an aerated basin before entering the sewer. When the water is clean it is allowed to pass through the bag filters and continue to a sewer at the injection well site. The geothermal water is not allowed to enter the injection well before filter coupon tests shows that the water is clean, and it is then reinjected after being filtered in 1 micron cartridge filters.

The geothermal water is not allowed to pass through the heat pumps before the water is clean and the flow is stable in order to avoid fouling and pressure shocks in the thin titanium pipes of the evaporator. The small heat exchanger between the evaporators is used to extract additional heat form the boiler economizer. There are flanges for a booster pump in the production plant, but it has not been installed.

If the pipe pressure is falling while the plant is operating, the plant switches from flow control to pressure control of the injection valve. Nitrogen is added if the pressure becomes too low, i.e. the plant stops.

The Thisted plant has operated with very few stops. One stop occurred caused by a faulty weld and the plant did earlier stop a few times because of power failures and transients from lightening, before the control system was protected against transients. The production pump from 1988 operated for 8 years, the next pump motor broke down shortly after installation, while the present enlarged pump has operated without problems since installation.

7.2 Material selection and precipitations

Comprehensive corrosion and precipitation tests has been carried out. They included polarization resistance measurements, weight loss measurements on coupons made of different materials after long time exposure to the brine and inspection of the coupons for corrosion and precipitations.

The investigations showed that corrosion problems can be avoided by avoiding air contamination of the geothermal water. In the absence of oxygen the measured corrosion rates are at 0,06 mm/year in carbon steel and the corrosion is evenly distributed.

No precipitation takes place from the geothermal water as long as air ingress is avoided. Air ingress results in visible precipitations.

The 2 km long pipeline from the production plant to the injection well was considered made of synthetic materials, but carbon steel was chosen as corrosion rates are low. Furthermore, even very small amounts of oxygen penetrating into the brine loop by diffusion through a synthetic pipe wall material will oxidize components in the brine and cause corrosion and precipitation of scaling and corrosion products.

The general design criteria for material selection in the brine loop is:

- Base piping material : Mild carbon steel.
- Critical items (e.g. balls in ball valves) : Stainless steel type AISI 316 or equivalent.
- Weld seams : Slightly more noble material than base piping.
- Heat exchangers : Titanium plate or tubes.

The injection is protected against external corrosion by a 2 mm polyethylene coating. It was initially electrically isolated at flanges near each well to avoid corrosion from different voltage potential at wells and allow cathodic protection of the pipeline.

7.3 Filters

The inlet filters consists of a battery of bag filter units with 1 micron bags. Each filter unit has a nominal capacity of 18 m^3/h at a pressure drop of 0.2 bars (clean filters) and a filter area of 0.41 m^2. The bag filter is a surface filtrating device, i.e. particles and impurities are caught at the surface of the filters.

The injection filters consist of a battery of cartridge filter units with 1 micron cartridges each with a nominal capacity of 30 m^3/h at a pressure drop of 0.25 bars (clean filters). The cartridge filters are combined surface and depth filtration filters, i.e. particles and impurities are caught at the filter surface and very fine particles and impurities are caught inside the filter material matrix. The purity of the brine after the cartridge filters is checked regularly by filter coupon tests and always before start of injection after a stop of the geothermal water loop.

The lifetime of the filters has increased through the years and reached a level of 1-2 years per set.

7.4 Wells

The production well, Thisted-2 and the injection well, Thisted-3 are vertical and connected by a 2 km long pipeline (Fig. 10). The well spacing at 1508 m is designed to a allow a production at 200 m^3/h for 25 years before the production temperature starts to drop.

The production well is a geothermal exploration well. The original expected best reservoir, the Middle–Upper Triassic Skagerrak Formation was found to have a high content of fines and a test showed a declining permeability during the test, - possibly for that reason. The well was therefore plugged of at approx. 1300 m depth.

The Upper Triassic–Lower Jurassic Gassum reservoir at 1250 m depth was then perforated and tested with good results except for some sand production. The well is thus completed with a gravel pack and the good reservoir performance has been maintained.

The injection well is gravel-packed and equipped with injection tubing including slots for gas-lift. It has not been necessary to carry out any clean up operation of the well.

The injection tubing is designed for a much lower flow than the present flow at up to 200 m^3/h. It is thus a substantial contributor to the present injection pressure and it has been considered to exchange this tubing or remove it and thoroughly clean up the casing walls. It was, however, not found profitable to remove or exchange the tubing in the present situation, where the incineration based heat and power plant covers the whole heat demand in the summer time.

No significant pressure build up has been observed in the injection well (apart from a small increase in injection pressure when a faulty weld leaked air into the system).

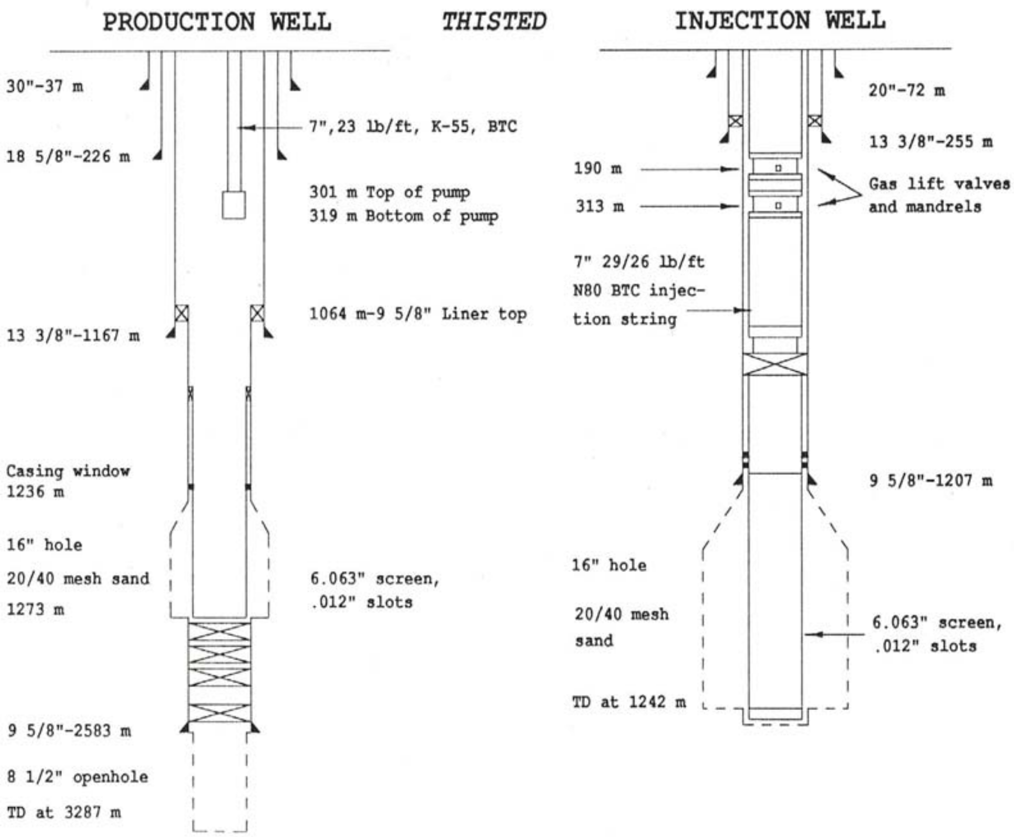

Fig. 10: *The well design used at the Thisted geothermal plant.*

7.5 Aquifer and brine data

The completed aquifer zone is 35–37 m thick (located at 1236–1273 m depth in the production well and 1207–1242 m depth in the injection well). The transmissivity and porosity is approx. 100 Dm and 28%, respectively. The permeability varies substantially in the interval, but all zones are considered connected vertically.

The geothermal 15 % saline water contains 165 g/l of total dissolved solids. The alkalinity is 0,40 meq/l, the pH is 6,1 and the density is 1100 g/l at 40^{o}C. The brine composition is:

Li^{+}	1,2	mg/l
Na^{+}	54000	mg/l
K^{+}	250	mg/l
Mg^{++}	1500	mg/l
Ca^{++}	7800	mg/l
Sr^{++}	330	mg/l
Fe^{++}	35	mg/l
Mn^{++}	16	mg/l
Cu^{++}	0.26	mg/l
Zn^{++}	0.5	mg/l
Pb^{++}	0.04	mg/l

Cd^+	0.0002	mg/l
Cl^-	101000	mg/l
Br^-	290	mg/l
NH_4^+	51	mg/l
SO_4^{--}	< 4	mg/l
SiO_2	8	mg/l

The bubble point is approx. 5.5 bar and the volume of dissolved gasses constitute around 6 vol% of the geothermal brine when it is degassed to 1 bara. The gas composition is:

CH_4	57%
N_2	41%
He	0,4%
C_2H_4	0,4%
CO_2	0,3%
H_2	0,3%
Others	0,6%

7.6 Feasibility of CO_2 storage

The geothermal plant in Thisted is in many ways comparable to geothermal doublets situated in the Paris basin concerning the operating conditions. For a typical geothermal doublet in the Paris Basin Cortiche & Herbrich (2003) evaluated a scenario with injection of CO_2 dissolved in the return water at a concentration of 10 kg CO_2 /m^3 water. The flow rate of this system was 150 m^3/h leading to an injection rate of 1500 kg/h. Given the slightly higher flow rate at Thisted an average injection of 17500 Tonnes CO_2 in solution may be estimated per year. With an expected break-through of return water to the production well head at 25 years the maximum amount of CO_2 injected in solution reaches 0.4 Mtonnes.

Introducing CO_2 to a geothermal loop, however, raises a series of problems concerning material selection and safety and will probably only be technically and economically feasible if implemented already in the planning phase of a new geothermal plant. The evaluated example from the Paris Basin thus led to a decrease in pH from 6.5 to 4.3 and thereby severely increasing the risk of corrosion.

The total investment cost for the Thisted power plant was approximately 11 million Euro (1982–2000 money) including exploration and production wells to 3.3 km and the electric heat pump plant from the pilot plant. Based on geothermal doublets in the Paris Basin Cortiche & Herbrich (2003) estimated that the investment costs would be approximately 15% higher for a system build for CO_2 injection in dissolved form and 25% higher for a system injecting CO_2 in supercritical form.

8. GEOTHERMAL PLANT IN COPENHAGEN, FUTURE PLANTS:

The largest district heating network is situated in the Copenhagen region and it has been decided to investigate the possibility of establishing a geothermal plant in the Copenhagen area. Two large transmission systems distributes heat to several local district heating networks from several CHP plants based on coal, gas and garbage, and some gas and oil based peak load boiler stations.

DONG A/S has in year 2000 formed a group together with heat and power producers and transmission companies in the Copenhagen region to prepare the establishment of a demonstration plant. A co-operation with Sydkraft Värme Malmö AB, Sweden has also been established to gain from the sharing of information and common exploration activities.

The Danish Government has granted financial support for the initial phases and the acquisition of new seismic data was made in year 2001. The subsurface of Copenhagen area is poorly known as no deep wells or seismic surveys existed prior to the 2001 survey. The nearest deep wells are Lavø-1 in northern Sjælland, the wells at Stenlille in central Sjælland, and Slagelse-1 in western part of Sjælland (Fig. 1).

A geological evaluation conducted by GEUS included a complete interpretation of all common Danish and Swedish marine and land seismic survey indicating promising results and furthermore serving as preparations for a common drilling campaign with DONG A/S as drilling operator. This integrated geophysical and geological evaluation indicated the existence of several possible sandstone aquifers including the Gassum and the deeper Bunter sandstone aquifers known from several Danish wells and Swedish wells. The new seismic data is of excellent quality and has been integrated with reprocessed old data. The combined data set has allowed a delineation of the main structures and has made it possible to assess the distribution and continuity of the sandstone reservoirs. The seismic mapping have further supported the geological model by providing information on possible facies types, and has provided essential information regarding estimates of depths and gross thickness of the reservoir units.

Two wells has been drilled on the Copenhagen project: A vertical well to 2.7 km in 2002 and a deviated well to the same depth in 2003. Around 14 MW is planned extracted from 73°C geothermal water with approx. 20% salinity with an option for expansion. The plant is expected to produce around 400 TJ heat annually or approx. 1% of the Copenhagen area total district heating demand. The plant is under construction and the CO_2 storage capacity issue has not been assessed.

9. CONCLUSIONS

GEUS has in the last decade identified widespread geothermal aquifers with sufficient heat to supply district heat to Danish towns for hundreds of years. Århus University has studied temperature gradients. DONG A/S has drilled and tested wells and compiled the following very rough rules of thumb for Danish sandstone aquifers: For each km increased depth temperature increase with 30°C, salinity increase with 10% and permeability is reduced by a factor 10. Geothermal heat can be produced at the present cost level for district heating at suitable locations. The already established combined heat and power (CHP) capacity limits the demand, but more power from wind turbines etc. will favour heat from geothermal plants.

Denmark has only one geothermal plant, which is placed in Thisted. It produces heat from 44°C, 15% saline geothermal water pumped from the Gassum sandstone aqiuifer at 1,2 km depth. The Thisted plant was erected as a pilot plant by DONG A/S in 1984 and later expanded to the present capacity at 200 m^3/h in co-operation with the district heating company. The Thisted plant has demonstrated that millions of m^3 saline brine can be injected in a sandstone aquifer for around 20 years (and expectedly much longer) without injection problems. Recently, DONG A/S has entered co-operation with power producers and district heat transmission companies in Copenhagen to establish a geothermal plant there.

CO_2 can be stored through geothermal injection wells, but the potential storage capacity is low. A perspective could, however be to establishment of a combined geothermal and CHP plant producing heat and power with more than 100% efficiency essentially without emissions.

Around 3–6 wt% CO_2 can be dissolved and stored in water depending on the pressure, temperature and salinity. The natural flow in deeper Danish aquifers is normally ignorable and the dissolved CO_2 is thus expected to stay in place. The disadvantages with this system seem manly to be the need for a bigger distance between production and injection wells to avoid production of the CO_2 (higher well connection costs, worse sweep, higher pumping costs) or alternatively more costly geothermal plants from the use of CO_2 resistant materials.

CO_2 can also be stored as a separate phase from approx. 900 m depth and downwards. It has a lower density than the water (about half) requiring a trap to keep the CO_2 in the reservoir. The existence and distribution of cap-rocks or seals has not yet been assessed neither in connection with the Thisted plant nor on a more regional basis. Thus, the present knowledge on combining geothermal and CO_2 storage as a separate phase is limited and the confirmation of a sealing rock and following control of a CO_2 phase is costly.

It is not known if dissolution effects reducing the reservoir permeability by clocking due to migrating fines will become a problem. Geothermal energy providers may also be reluctant to integrate a clean (environmentally sustainable) energy system with geological storage of CO_2 not yet fully implemented in the public opinion.

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