

Potential for brine storage near the gas storage facility at Lille Torup, northern Jylland, Denmark

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This study is based on a feasibility study for the Danish Energinet.dk to identify potential formations for brine storage near the gas storage facility at Lille Torup, northern Jylland, Denmark (Fig. 1; Hjuler *et al.* 2017).

Located on top of a salt structure, the gas storage facility comprises seven caverns, which have been washed out by circulating water in the salt dome. One cavern contains *c.* 520.000 m³ of intrusive brine that must be disposed of in order to increase the storage volume for gas. One option is to inject the brine into the subsurface if a target with appropriate storage properties can be identified, but it is a prerequisite that the stored brine does not compromise freshwater reservoirs. Due to cost considerations, the brine storage should be situated within a radius of 50 km of the gas storage facility and at a depth not exceeding 2000 m.

Based on the national geothermal research conducted during the last decade, a number of sandy formations are considered potential storage reservoirs (Fig. 2; e.g. Mathiesen *et al.* 2009; Vosgerau *et al.* 2016). Around Lille Torup, these include the Bunter Sandstone/Skagerrak, Gassum, Haldager Sand and Frederikshavn formations where the two former formations are discarded due to present-day burial depths exceeding 2000 m. In addition, the Chalk Group is considered a potential storage formation due to its importance as a hydrocarbon reservoir in the North Sea, however, due to risk of leakage to the younger sediments and risk of environmental issues, the chalk was discarded as potential storage zone.

Geological background

The Lille Torup area is located centrally in the Danish Basin, where the Upper Permian–Mesozoic succession is 5–5.5 km thick. The basin was formed in the Late Carboniferous–Early Permian with basal Rotliegendes coarse-grained clastic sediments and thick Zechstein salts overlain by Triassic sandstone, mudstone, carbonate rocks and salt (Nielsen 2003). These are followed by Lower Jurassic mudstone, Middle Jurassic sandstone, Upper Jurassic–Lower Cretaceous mudstone and siltstone with few sandstone layers. The Mesozoic succession terminates with *c.* 1200 m thick carbonate deposits.

The salt structure at Lille Torup consists of mobilised Zechstein salt penetrating the Mesozoic succession. Its top point is *c.* 250 m below the present-day surface.

The Haldager Sand Formation in the northern part of the basin is 2–150 m thick, but may exceed 200 m in rim synclines of salt structures, where sandstone commonly dominates the lithology. The Frederikshavn Formation is primarily present in the northern part of the basin and frequently includes sandstone layers. Its thickness decreases southwards from 150–300 m to a few metres. The more than 1000 m thick chalk- and limestone-dominated Chalk Group constitutes the topmost pre-Quaternary formation in large parts of the Danish Basin.

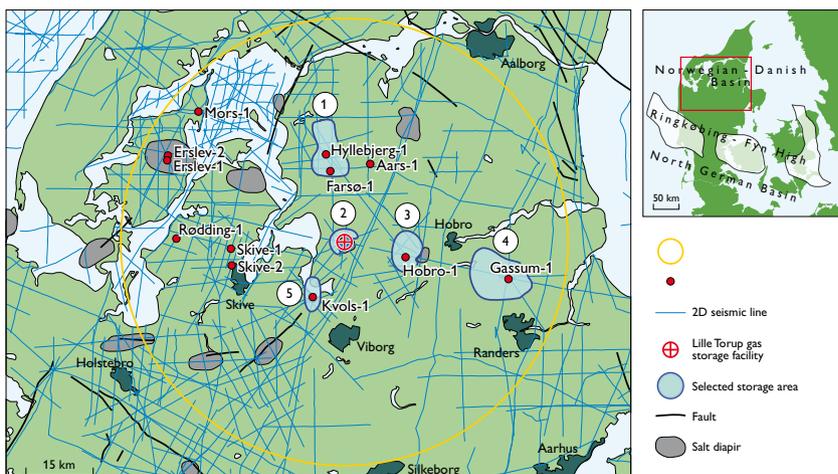


Fig. 1. The study area and selected storage areas within a radius of 50 km of the Lille Torup gas storage facility.

System	Lithostratigraphic unit	
Quaternary	Post Chalk Group	
Cretaceous	Chalk Group	Assumed seal
	Lower Cretaceous unit	Assumed seal
Jurassic	Frederikshavn Fm	Reservoir
	Børglum Fm	
	Flyvbjerg Fm	
	Haldager Sand Fm	Reservoir
	Fjerritslev Fm	Assumed seal
Triassic	Gassum Fm	Reservoir
	Vinding Fm	
	Oddesund Fm	
	Tønder Fm	
	Falster Fm	
	Ørslev Fm	
	Bunter Sandstone Fm	Reservoir
Permian	Zechstein Group	

Fig. 2. Lithostratigraphic chart showing potential reservoirs (yellow) and assumed seals (brown).

Methods

The subsurface within a radius of 50 km of the Lille Torup storage facility was screened for potential sandstone reservoirs suitable for storage. The local database comprises 11 vertical deep wells and an open grid of regional 2D seismic profiles of variable quality and resolution (Fig. 1). Some wells were excluded from the database due to location on top of salt structures (Erslev-1–2 and Skive-1–2), uncertain data quality (Aars-1) or separation from the Lille Torup storage facility by fjord water (Mors-1).

The Danish geothermal WebGIS application (Vosgerau *et al.* 2016) provided maps of formation depth, formation thickness and potential reservoir sandstone thickness as well as reservoir parameters of relevant wells. The potential reservoir sandstone thickness map was developed for assessment of the geothermal potential and is used in this study as an indicator for injection capacity.

Reservoir properties derived from well logs include the depths of formation top and base, formation thickness, gross sand thickness (i.e. cumulated thickness of all sandstone layers), potential reservoir sandstone thickness (i.e. cumulated thickness of sandstone layers with a shale content <30% and a porosity >15%), as well as averaged values of porosity, permeability and transmissivity of the potential reservoir sandstone. For uncertainty considerations, see <http://dybgeotermi.geus.dk/>.

Potential formations for brine storage

Five potential storage areas were defined based on reservoir quality assessments obtained by integration of well-log data and WebGIS data improved with locally refined seismic interpretations. Injectivity assessments were performed using ECLIPSE 100 reservoir simulation software and Petrel software. See Hjuler *et al.* (2017) for details.

The Haldager Sand Formation (Figs 3A–C) is presently buried more than 2000 m in large parts of the study area, but more shallow occurrences exist. The generally 50–150 m thick formation is dominated by sandstone known to be quartz-rich, which points to good reservoir properties. In areas of relatively shallow burial (<2000 m), the Haldager Sand Formation may constitute a storage formation.

The Frederikshavn Formation (Figs 3D–F) is buried less than 2000 m and generally more than 100 m thick; it is thickest east of Lille Torup. Several potential storage reservoirs with sufficient lateral extent can be identified. The Frederikshavn Formation constitutes a storage option.

The Chalk Group (Figs 3G, H) is buried at 100–700 m depth and is more than 1 km thick. On top of the Lille Torup salt structure, the salt movements may have fractured the c. 250 m of chalk, and increased permeability and thus reservoir quality. However, the overlying Quaternary deposits are not expected to possess sealing qualities and brine storage in the chalk could lead to environmental issues. The Chalk Group is therefore discarded as a potential storage formation.

Potential seals

The Chalk Group outside the top of the Lille Torup salt structure is expected to effectively seal off pore water from the sandy formations beneath it due to its low permeability and great thickness. In addition, the clayey Lower Cretaceous unit is assumed to be of sufficiently low permeability to prevent pressure and pore-water propagation from below.

Reservoir parameters of the formations

The Haldager Sand Formation mainly comprises sandstone layers with porosities in the 18–22% range and permeabilities in the 140–360 mD range (Table 1). Disregarding burial depth, the Haldager Sand Formation is assumed to provide suitable storage properties.

The sandstone layers of the Frederikshavn Formation have porosities in the 17–30% range, permeabilities in the 110–1500 mD range and the thickness of potential reservoir sandstone in the 6–66 m range (Table 1). In the Kvals-1 well, however, the formation seems to have little or no storage potential, assumedly because clay minerals reduce both pore

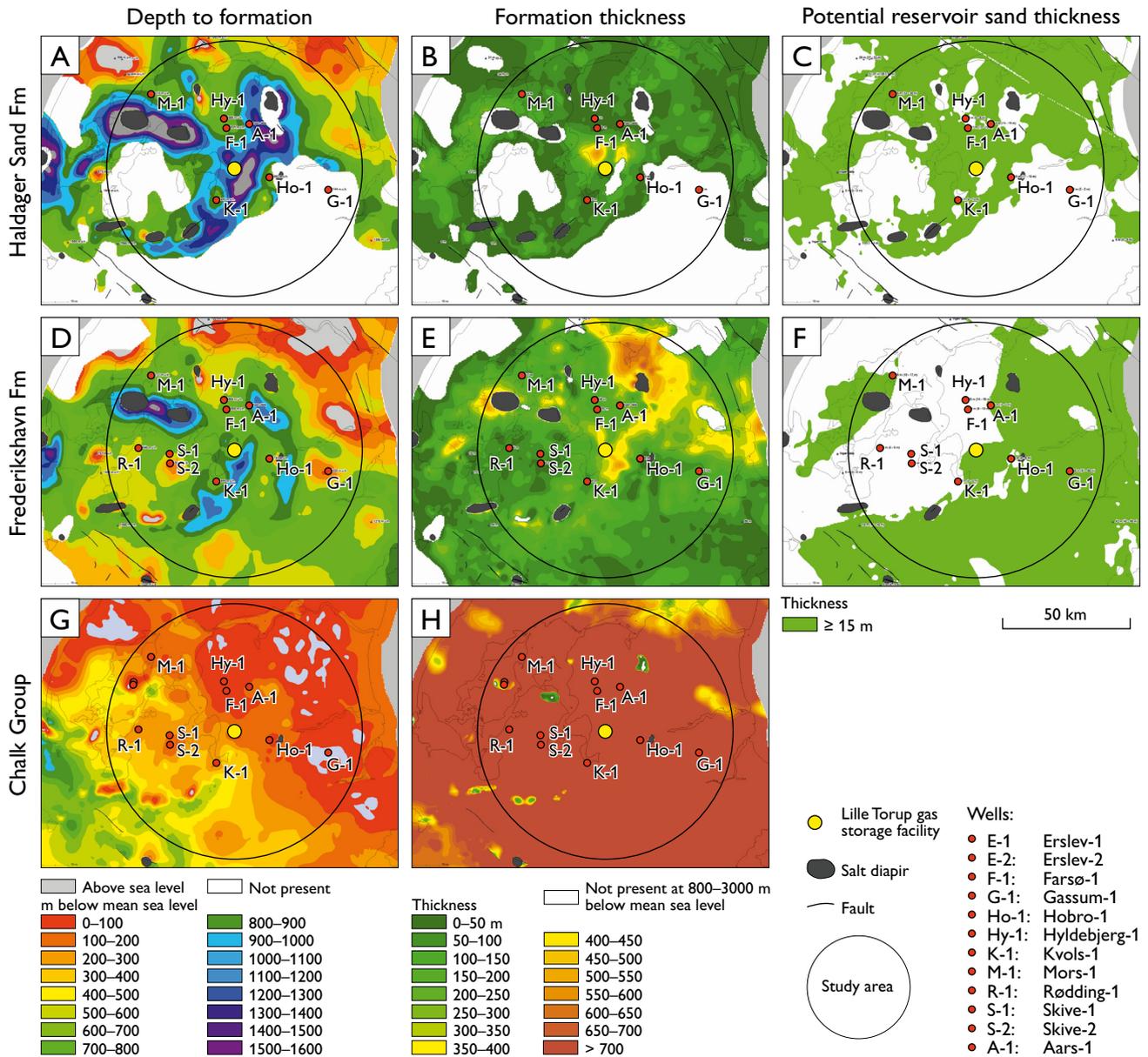


Fig. 3. WebGIS-generated maps of potential brine storage formations in the study area. Reservoir quality is assessed based on depth to formation top, formation thickness and potential reservoir sand thickness.

space and permeability. The thickness of potential reservoir sandstone decreases from east to west (Fig. 3F).

Suggested areas for brine storage

The WebGIS-based maps (Fig. 3) are suitable for assessing reservoir quality trends on a regional scale of tens of kilometres, but not on a local scale of up to a few kilometres as uncertainties will be significant. Thus, the areas suggested for brine storage cover several square kilometres (Fig. 1).

Area 1 includes the Hyldebjerg-1 and Farsø-1 wells (Figs 1, 3), in which the Haldager Sand Formation is evaluated to

provide the better storage reservoir, with higher porosities and permeabilities than the Frederikshavn Formation (Table 1). The two formations offer two storage options within a narrow depth interval.

Area 2 is situated above the rim syncline next to the salt structure beneath Lille Torup (Figs 1, 3), where the Frederikshavn and Haldager Sand formations may be up to 300–400 m thick (Figs 3A, D) and include potential reservoir sandstone units more than 15 m thick at depths shallower than 1400 m. However, existing seismic data are insufficient to confirm these thickness estimates and the formation depths may be closer to 2000 m due to deposition in the rim syn-

Table 1. Reservoir parameters of the Haldager Sand and Frederikshavn formations in five areas suggested for brine storage

Well	Formation	Thickness			Property					
		Top below mean sea level (m)	Base below mean sea level (m)	Formation thickness (m)	Gross sand (m)	Potential reservoir sandstone (m)	Average porosity (mD)	Average reservoir permeability (mD)	Reservoir transmissivity (mD)	Well injection index (m ³ /bar/day)
<i>Area 1</i>										
Farsø-1	Haldager Sand	1934	1952	18	16	11	18	138	2	
Hyllebjerg-1	Haldager Sand	1885	1894	9	9	9	22	344	3	
Average	Haldager Sand	1909	1923	14	12	10	20	241	3	
Farsø-1	Frederikshavn	1689	1839	150	25	9	17	106	1	
Hyllebjerg-1	Frederikshavn	1664	1810	146	37	15	19	188	3	
Average	Frederikshavn	1676	1824	148	31	12	18	147	2	
<i>Area 2</i>										
Average	Haldager Sand	1900	1920	20	16	12	20	255	3	
Average	Frederikshavn	1700	1756	56	33	8	15	133	1	
<i>Area 3</i>										
Hobro-1	Haldager Sand	1852	1891	39	24	18	19	175	3	
Hobro-1	Frederikshavn	1741	1806	65	12	6	19	238	1	
<i>Area 4</i>										
Gassum-1	Haldager Sand	1176	1178	2	2	2	19	188	0.5	
Gassum-1	Frederikshavn	1053	1154	101	66	65	30	1500	97	
<i>Area 5</i>										
Kvols-1	Haldager Sand	1940	1955	15	15	9	21	363	3	
Kvols-1	Frederikshavn	1856	1912	56	56	0	5	0	0	
Well average	Haldager Sand	1757	1774	17	13	10	20	242	2	9
Well average	Frederikshavn	1601	1704	104	39	19	28	406	8	27

Reservoir parameters based on the vertical wells in the suggested areas (Fig. 1). Reservoir parameters of area 2 based on average values of the Hyllebjerg-1, Farsø-1, Hobro-1 and Kvols-1 wells. For detailed descriptions of parameters and uncertainties, see <http://dybgeotermi.geus.dk/>.

cline. Thus, the estimated reservoir parameters are based on average values of the nearby wells, Hyllebjerg-1, Farsø-1, Hobro-1 and Kvols-1.

Area 3 includes the Hobro-1 well (Figs 1, 3), in which the Haldager Sand and Frederikshavn formations are estimated to offer two storage options within a narrow depth interval, the Haldager Sand Formation providing the better reservoir (Table 1).

Area 4 includes the Gassum-1 well (Figs 1, 3). The Frederikshavn Formation is more shallowly buried in this area (<1000 m; Fig. 3D) and offers the most excellent storage properties in the study area (Table 1). The Haldager Sand Formation is not present in Area 4 (Fig. 3A).

Area 5 includes the Kvols-1 well (Figs 1, 3). This well indicates good reservoir properties of the Haldager Sand Formation at a burial depth of 1940–1955 m, but also that the Frederikshavn Formation is a poor reservoir (Table 1).

Assessment of injection rate and pore pressure

Indicative injection rates (shown as a well injection index) and pore pressures for the Frederikshavn and Haldager Sand formations in the entire study area are presented in Table 1. Reservoir parameters are calculated as averages of all wells. The well injection index is assumed to correspond to the well production index; the pressure of the subsurface pore fluid in the formations is assumed to be hydrostatic.

Conclusions

The Frederikshavn and Haldager Sand formations constitute potential brine storage formations in the larger Lille Torup area and are sealed off by the Chalk Group and Lower Cretaceous unit. The Haldager Sand Formation offers the best reservoir properties but at greater depth than the Frederikshavn Formation. The well injectivity index and pore pressure indicate favourable conditions for brine storage. Five potential storage areas are suggested, compromising between burial depth and distance from the gas storage facility.

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