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Selection of the best CO_2 storage sites in the Nordic region

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SUMMARY:

Selection of the most prospective sites from each country in the Nordic with saline aquifers storage sites were done in relation to the known overall storage potential for each country and 10 sites in Norway, 5 sites from Denmark and 3 from Sweden were selected and ranked in a all Nordic hierarchy of the most prospective storage sites and areas.

KEYWORDS: aquifers, ranking, CO_2 storage, prospectivity

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Selection of the best CO_2 storage sites

1. Introduction

Parts of the Nordic region have previously been screened for potential storage sites within the EU co-funded GESTCO (2004) and GeoCapacity (2009) projects and by the Norwegian Petroleum Directorate in the Norwegian CO_2 storage atlas (2011-2014). However, these previous mapping projects only covered Norway and Denmark. During 2013 and 2014 new storage formations, units and traps were mapped and included in the Nordic CO_2 storage site GIS-database.

Denmark has mapped 4 formations, 1 aquifer unit and 20 traps, hereof 12 new sites not evaluated in previous projects. In Norway, 28 formations and 151 traps have been identified in the Norwegian part of the North Sea, the Norwegian Sea and Barents Sea. In Sweden, two areas with potential for geological storage of CO_2 have been identified in the South-east Baltic Sea and in South-west Scania. Sweden has mapped 8 storage units and 1 trap within 7 defined formations and one undefined unit, all new data.

Iceland has a very different geological setting with young igneous, mainly basaltic rocks. Iceland has mapped porous onshore basalt formations potentially suitable for CO_2 storage. Finland has only shallow sedimentary basins not suitable for CO_2 storage.

In summary 36 formations (note that some formations are present in more than one country making a difference between counting for each country and overall counts of storage sites), 8 storage units and 172 traps in saline aquifers, together with an area of 34000 km^2 with porous basaltic rocks in Iceland, have been mapped as potentially suitable for geological storage of CO2 in the Nordic region (Figure 1).

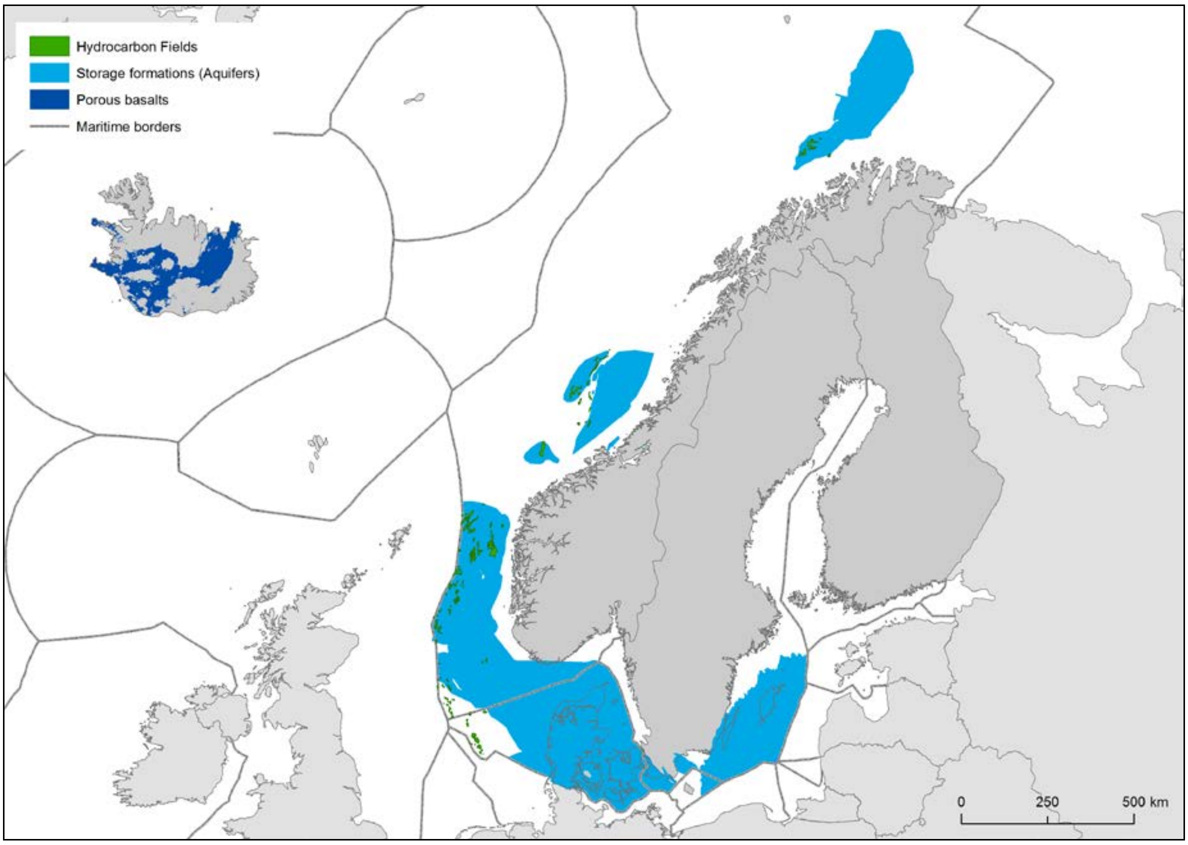

Figure 1. All mapped potential Nordic CO_2 storage sites.

To facilitate future CO_2 storage operation, the most prospective CO_2 storage sites and formations for safe and permanent storage in the Nordic region have been ranked and selected. This memo summarises the storage site characterisation, the ranking procedure and results of the overall Nordic ranking.

2. Storage site characterisation and ranking procedure

An evaluation of several methodologies used in other screening projects such as "Best practice for the storage of CO_2 in saline aquifers" (Chadwich et al. 2008), GeoCapacity (Vangkilde-Pedersen at al., 2009), IEA-GHG CCS site characterisation criteria (Bachu et al. 2009), The Queensland CO_2 Geological Storage Atlas (Bradshaw et al. 2010), CO_2 Storage Atlas for the Norwegian North Sea (Halland et al. 2011) have been the basis for the Nordic CO_2 storage site characterisation and ranking criteria (Table 1).

The ranking criteria were divided into 4 main groups: reservoir properties, seal properties, safety and data coverage (maturity) and each criterion could fall within 3 categories: preferred, questionable and caution (Anthonsen et al. 2014).

The ranking has not considered parameters like economy, distance to shore or transport of CO2 as this present ranking was focused on geological parameters.

Reservoir properties	Optimal - 3 point	Questionable – 2 point	Caution – 1 point	Remarks
Depth	>800m-2500m	600-800m	<600m	Case specific depending on temperature gradient in the area
Porosity	>20%	10-20%	<10%	
Permeability	>100 mD	10-100 mD or extrapolated from closest well drilled through the reservoir	<10 mD or no data	Indicate gas or fluid measurements
Heterogeneity	Low N/G>0.4 Existents of uniform high porosity layers with thickness above 5 meter	Moderate N/G 0.1-0.4 Alternating high/low porosity layers. Layer thickness below 5 meter	High N/G<0.1 Highly alternating thin high/low porosity layers or channel sands with low connectivity. Diagenesis	Since heterogeneity is hard to quantify it advisable to give a remark about interpreted depositional environment and if the area has known diagenesis
Pore pressure	Hydrostatic or lower		Overpressure	
Thickness (Net sand)	>50m	15-50m	<15m	
Seal properties	Optimal	Questionable	Caution	
Thickness	>50m	20-50m	<20m	
Fault intensity	Low No mapped faults through reservoir or seal	Moderate Minor faults through reservoir or seal	High Large faults through reservoir and/or seal. Bounding faults	
Lateral extend	Continuous	Unsure about existence of a continuous seal. Seal locally thinner than 20 meter	Not continuous	
Multiple seals	More than one	Only one	Unsure if a seal exists	
Lithology of the primary seal	Homogeneous clay, mud or evaporites	Chalk	High content of silt or sand	
Safety/risk	Optimal	Questionable	Caution	
Seismicity	Low	Moderate	High	Both frequency and magnitude. Subjective, give argument for this category if moderate or high is chosen.
Risk of contamination of groundwater	No	Unsure	Yes	
Maturity/data coverage	Optimal	Questionable	Caution	
Wells	Well though the actual trap or storage unit	Well(s) though equivalent geological formations	No well data	
Seismic survey	3D seismic	2D seismic younger than 1970	2D seismic lines older than 1970 or sparse data	

Table 1. The Nordic CO_2 storage site characterisation and ranking criteria for saline aquifers.

The selection and ranking of the most prospective Nordic storage sites have been carried out on basis of table 1.

It has to be stressed that the selection and ranking are a result of the present available knowledge from the Nordic storage atlas GIS-database in 2014. This means that new geological knowledge and future research can change this order of succession, about which storage sites and areas that are the most prospective.

3. Results

Selection of the most prospective sites from each country with saline aquifer storage sites were based on the known overall storage potential for each country. Ten sites in Norway (table 2), five sites from Denmark (table 3) and three from Sweden (table 4) were selected and ranked in a Nordic hierarchy (table 5)(figure 2 and 3). If more than one storage sites reached same ranking level (scour) they were ranked according to storage capacity.

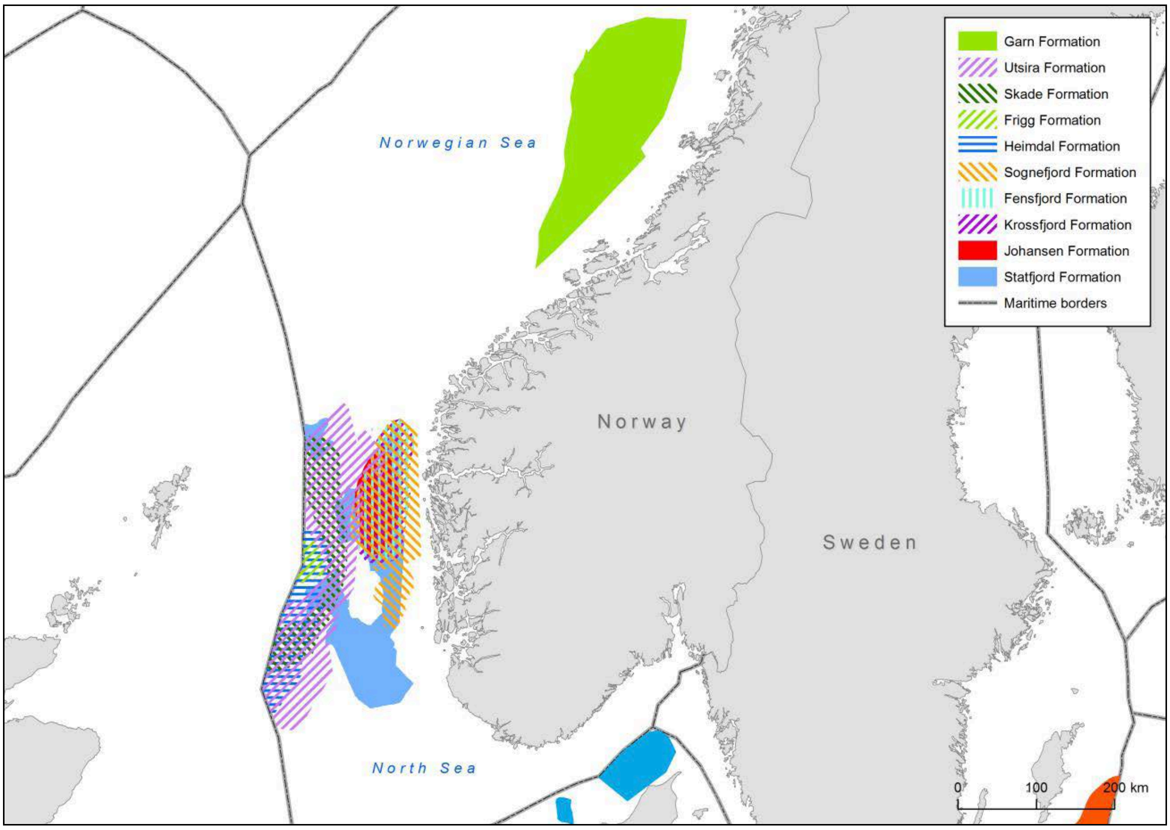

Figure 2. Location of the Norwegian ranked storage formations.

Of the 27 mapped and characterized Norwegian storage formations (table 2), the ten most promising were selected (see figure 2). For the Norwegian storage formations, no upper limit as e.g. 800 meters has been used, resulting in a larger storage capacity for some of the formations than realistically can be utilized for CO_2 storage.

Selection of the ten most promising storage units was not based on the ranking score only. Several storage formations had the same ranking, and only small differences in the reservoir properties could have change the site from good to not good. Originally, several units from the Barents Sea such as the Stø Formation and Tubåen Formation were among the top ten, having a ranking score of 42 and 43 respectively. However, it is well known both from exploration and from Statoil's injection campaign at the Snøhvit Field, that the reservoir properties of these sandstones at 2.5-2.6 km burial are not as good as expected. The sediments have previously been buried deeper and experienced quartz cementation causing reduction in porosity and permeability. The later uplift for the Snøhvit reservoir was about 1 km. Due to these condition they have not been included in this ranking.

Many formations offshore Norway have large storage capacities. One unit with large storage capacity is the Gassum Formation, but this only gets a ranking score of 39. For this unit, there is some uncertainty related to pore pressure, since no overpressure is measured in the eastern wells and overpressure is observed in the western area. From the ranking and the storage capacity, it seems that three of the best formations for large scale industrial storage would be the Utsira Formation, Sognefjord Formation or the Skade Formation. They all have storage capacities >10 000 Mt, shallow burial < 2 km, and high porosity and permeability values.

The most prospective site in Denmark based on the ranking procedure and storage capacity is the Gassum aquifer; see table 3 and figure 3. This is a large open dipping aquifer with a modelled storage capacity of 3700 Mt (Bergmo et al., 2013), but existence of only 2D seismic surveys and no wells through the storage unit make the data more uncertain. The Havnsø and Gassum sites are anticlinal structures with no major faults cutting through the structures, and they have a theoretical capacity of respectively 926 and 630 Mt. The Gassum structure has a higher heterogeneity and lower permeability than the Havnsø structure, but the advantage of an exploration well drilled on top of the Gassum structure makes data more reliable.

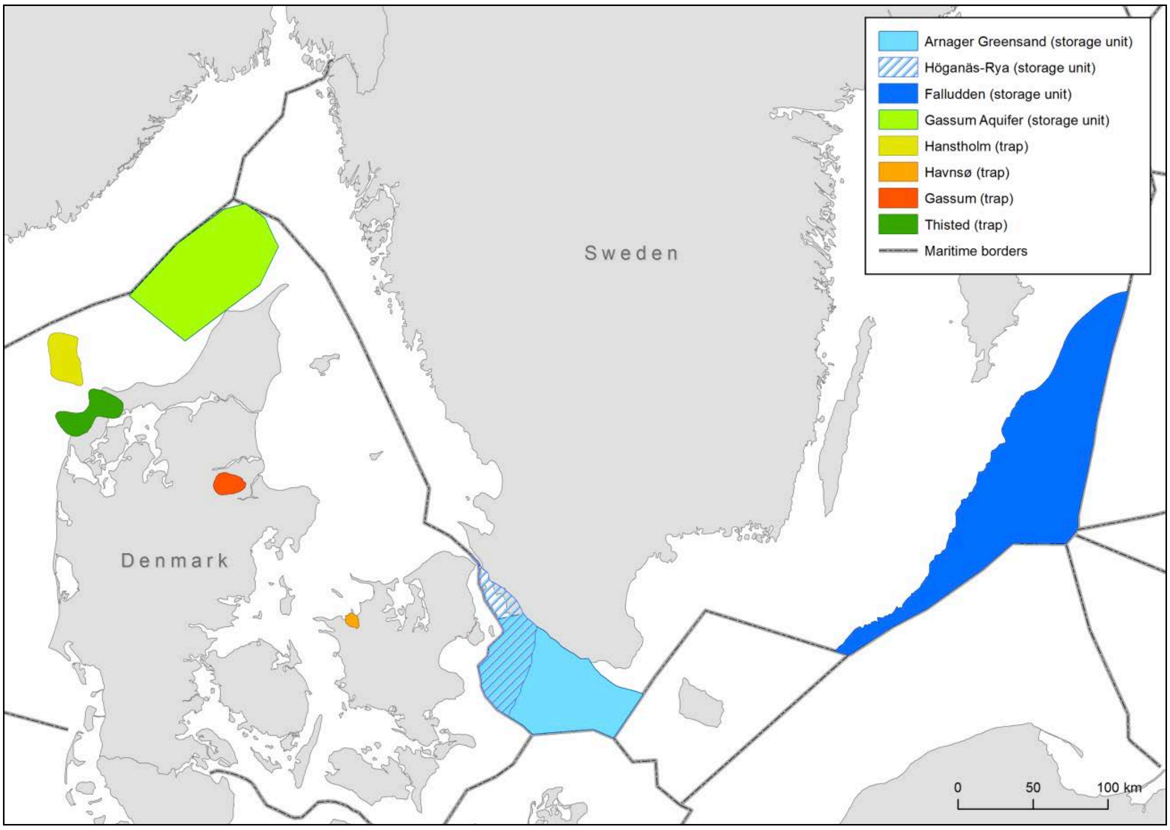

Figure 3. Location of the ranked Danish and Swedish storage sites.

The Thisted and Hanstholm structures are large anticline structures, with theoretical capacities of 11039 and 2753 Mt respectively. The Hanstholm structure has a higher porosity than Thisted, but on the other hand, data from the Thisted structure is based on four wells drilled through the northern part of the structure, and

Hanstholm has only one well placed on the flank of the structure, possibly not representative for the whole structure.

Hydrocarbon exploration in Denmark is concentrated in the Central Graben in the Danish North Sea. Exploration outside the Central Graben has been less intensive and consequently the data coverage generally has a lower density, resulting in a lower ranking for the Danish storage sites compared to the Norwegian sites.

Of the eight storage units and one trap that were identified in the southernmost part of Sweden (table 4), the three most prospective storage sites are the Faludden sandstone, the Arnager Greensand and the Höganäs-Rya sequence (see figure 3). More detailed information is shown in table 4. The Faludden sandstone is a stratigraphic confined, open saline aquifer forming a large lens-shaped weakly east-south-east dipping aquifer. The Faludden sandstone is a very homogeneous sandstone and the estimated theoretical storage capacity is 745 Mt. The Arnager Greensand in south-west Scania represents a weakly north-east dipping large open saline aquifer. The Arnager Greensand displays a very high porosity and permeability, and has an estimated theoretical storage capacity of 521 Mt. The Höganäs-Rya sequence represents a weakly north-east dipping semi-closed saline aquifer and has an estimated theoretical storage capacity is 543 Mt.

Limited hydrocarbon explorations were conducted in Sweden through the 1970s resulting in 2D seismic and a few deep drillings in the Baltic Sea and south-west Scania and adjacent sea. Hence, the Arnager Greensand and the Faludden sandstone have old, but somewhat good, data coverage, whereas data for the Höganäs-Rya sequence is more limited.

Storage unit (u) or trap (t)				Reservoir properties						Seal properties					Safety/Risk		Maturity/data coverage	
Name	Location	Storage capacity in Mt	Total Score	Depth	Porosity	Permeability (gas)	Heterogeneity	Pore pressure	Thickness/ Net sand	Thickness	Fault intensity	Lateral extend	Multiple seals	Lithology	Seismicity	Ground-water	Well data	Seismic surveys
Sognefjord Formation	North Sea	11465	45	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Krossfjord Formation	North Sea	3977	45	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Utsira Formation	North Sea	30000	44	3	3	3	3	3	3	3	3	3	2	3	3	3	3	3
Skade Formation	North Sea	10696	44	3	3	3	3	3	3	3	3	3	3	2	3	3	3	3
Heimdal Formation	North Sea	5112	44	3	3	3	3	3	3	3	2	3	3	3	3	3	3	3
Fensfjord Formation	North Sea	4100	44	3	3	3	3	2	3	3	3	3	3	3	3	3	3	3
Frigg Formation	North Sea	1164	44	3	3	3	3	3	3	3	3	3	3	2	3	3	3	3
Ula Formation	North Sea	2193	43	3	3	3	3	1	3	3	3	3	3	3	3	3	3	3
Tubaen Formation	Barents Sea	1240	43	3	2	3	3	3	3	3	2	3	3	3	3	3	3	3
Brent Group	North Sea	2740	42	2	2	3	3	2	3	3	3	3	3	3	3	3	3	3
Are Formation	Norwegian Sea	2533	42	3	3	3	3	3	3	3	3	3	3	3	3	3	1	2
Statfjord Formation	North Sea	1850	42	2	2	3	3	2	3	3	3	3	3	3	3	3	3	3
Sto Formation	Barents Sea	1342	42	3	2	3	3	2	3	3	2	3	3	3	3	3	3	3
Johansen Formation	North Sea	861	42	2	2	3	3	2	3	3	3	3	3	3	3	3	3	3
Fruholmen Formation	Barents Sea	260	42	2	2	3	3	3	3	3	2	3	3	3	3	3	3	3
Rogn Formation	Norwegian Sea	51,6	42	3	3	3	3	3	3	3	3	3	3	3	3	3	1	2
Garn Formation	Norwegian Sea	8003	41	3	3	3	2	3	3	3	3	3	3	3	3	3	1	2
Ile Formation	Norwegian Sea	3576	41	3	3	3	3	3	2	3	3	3	3	3	3	3	1	2
Cook Formation	North Sea	639	41	2	2	3	3	2	2	3	3	3	3	3	3	3	3	3
Hugin Formation	North Sea	1939	40	3	2	3	3	2	2	3	1	3	3	3	3	3	3	3
Tilje Formation	Norwegian Sea	1750	40	3	3	3	2	3	2	3	3	3	3	3	3	3	1	2
Gassum Formation	North Sea	17631	39	3	2	3	3	1	3	3	2	3	3	3	3	3	2	2
Nordmela Formation	Barents Sea	490	39	3	1	2	2	3	2	3	2	3	3	3	3	3	3	3
Sandnes Formation	North Sea	16216	38	2	2	3	3	1	3	3	2	3	3	3	3	3	2	2
Sleipner Formation	North Sea	870	38	2	2	3	2	2	2	3	1	3	3	3	3	3	3	3
Skagerrak Formation	North Sea		37	3	2	2	3	1	2	3	2	3	3	3	3	3	2	2
Bryne Formation	North Sea	9417	36	3	2	2	2	1	2	3	2	3	3	3	3	3	2	2

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Table 1. Ranking of Norwegian storage units and traps (Aagaard et al. 2014).

Storage unit (u) or trap (t)			Reservoir properties						Seal properties					Safety/ risk		Maturity/data coverage	
Name	Storage capacity in Mt	Total Score	Depth	Porosity	Permeability (gas)	Heterogeneity	Pore pressure	Thickness/ Net sand	Thickness	Fault intensity	Lateral extend	Multiple seals	Lithology	Seismicity	Groundwater	Well data	Seismic surveys
Gassum (t)	630	43	1460	25	300	0,32	<hs	53	320	low	con	yes	ms	low	no	1	2D
Hanstholm (t)	2753	42	900	20	-	0,4	<hs	92	500	low	con	yes	cs	low	no	1	2D
Havnsø (t)	926	43	1500	22	500	0,67	<hs	100	260	low	con	yes	ms	low	no	0	2D
Pårup (t)	91	40	1550	10	300?	0,23	<hs	30	300	low	con	yes	ms	low	no	0	2D
Rødby (t)	152	41	1125	24	75	0,18	<hs	45	160	low	con	yes	cs/ep	low	no	2	2D
Thisted (t)	11039	42	1166	15	10-100	0,47	<hs	449	240	low	con	yes	cs	low	no	4	2D
Tønder (t)	91	42	1615	20	>100	0,17	<hs	35	180	low	con	yes	evap	low	no	5	2D
Vedsted (t)	162	42	1898	20	2000	0,74	<hs	103	525	mod	con	yes	cs	mod	no	1	2D
Voldum (t)	288	39	1757	10	-	0,38	<hs	30	334	low	con	yes	cs	low	no	1	2D
Gedser (t)	245	41	852	18	108	0,18	<hs	56	>150	low	con	yes	ep/ls/cs	low	no	0	2D
Femer Bælt (t)	305	41	1078	19	137	0,23	<hs	72	>150	low	con	yes	ep/ls/cs	low	no	0	2D
Langeland nord (t)	26	39	1326	14	36	0,17	<hs	44	>150	low	con	yes	ep/ls/cs	low	no	0	2D
Langeland (t)	328	40	992	14	36	0,29	<hs	75	>150	low	con	yes	ep/ls/cs	low	no	0	2D
Langeland syd (t)	149	40	1491	14	36	0,3	<hs	81	>150	low	con	yes	ep/ls/cs	low	no	0	2D
Ærø nord (t)	51	40	1288	14	36	0,2	<hs	52	>150	low	con	yes	ep/ls/cs	low	no	0	2D
Ærø (t)	263	40	986	14	36	0,18	<hs	52	>150	low	con	yes	ep/ls/cs	low	no	0	2D
Kegnæs (t)	188	41	1544	15	31	0,18	<hs	51	215	low	con	yes	ep/ls/cs	low	no	1	2D
Rømø (t)	135	39	1904	15	-	0,21	<hs	41	>150	low	con	yes	ep/ls/cs	low	no	0	2D
Horn Graben (t)	1458	39	1375	15	-	0,46	<hs	144	>150	High	con	yes	ep/ls/cs	low	no	0	2D
Erik (t)	98	41	2719	15	-	0,46	<hs	235	>500	low	con	yes	ep/ls/cs	low	no	1	2D
Gassum Aquifer (u)	3700	43	1000	23	210	0,5	<hs	50	>100	low	con	yes	ms	low	no	0	2D

Table 2. Ranking of Danish storage units and traps (Aagaard et al. 2014). The five most prospective sites are marked in blue.

Storage unit (u) or trap (t)			Reservoir properties						Seal properties					Safety/ risk		Maturity /data coverage	
Name	Storage capacity in Mt	Total Score	Depth	Porosity	Permeability (gas)	Heterogeneity	Pore pressure	Thickness/	Thickness	Fault intensity	Lateral extend	Multiple seals	Lithology	Seismicity	Groundwater	Well data	Seismic surveys
Faludden (u)	745	40	3	2	3	3	2	2	3	3	3	3	2	3	3	3	2
Arnager Greensand (u)	521	39	3	3	3	3	3	2	3	2	3	2	2	3	2	3	2
Höganäs-Rya (u)	543	39	3	3	3	3	3	2	3	2	3	3	2	3	2	3	1
L.Cretaceous sands, unit A (u)	330	39	3	3	3	3	3	2	3	2	3	3	2	3	2	3	1
Dalders structure (t)	22	38	3	2	2	3	2	2	3	3	3	3	2	3	3	3	1
När (u)	426	37	3	2	2	3	3	2	3	3	1	3	2	3	3	3	1
Bunter Sandstone (u)	165	37	3	2	2	3	3	2	3	2	3	3	2	3	2	3	1
Viklau (u)	553	36	3	1	2	3	3	2	3	3	1	3	2	3	3	3	1
L.Cretaceous sands, unit B (u)	115	36	3	3	3	3	3	3	3	2	3	3	2	2	1	3	1

Table 4. Ranking of Swedish storage units and traps (Aagaard et al. 2014).

Name	Ranking score	Storage Capacity in Mt	Country
Sognefjord Formation	45	11465	NO
Krossfjord Formation	45	3977	NO
Utsira Formation	44	21300	NO
Skade Formation	44	7560	NO
Heimdal Formation	44	5112	NO
Fensfjord Formation	44	4100	NO
Frigg Formation	44	1164	NO
Garn Formation	43	8003	NO
Gassum Aquifer (model area)	43	3700	DK
Havnsø (trap)	43	926	DK
Gassum (trap)	43	630	DK
Thisted (trap)	42	11039	DK
Hanstholm (trap)	42	2753	DK
Statfjord Formation	42	1850	NO
Johansen Formation	42	861	NO
Faludden (unit)	40	745	SE
Höganäs-Rya (unit)	39	543	SE
Arnager Greensand (unit)	39	521	SE
Total capacity		**86249**	

Table 5. The overall Nordic ranking of the 18 selected storage sites most prospective storage sites.

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