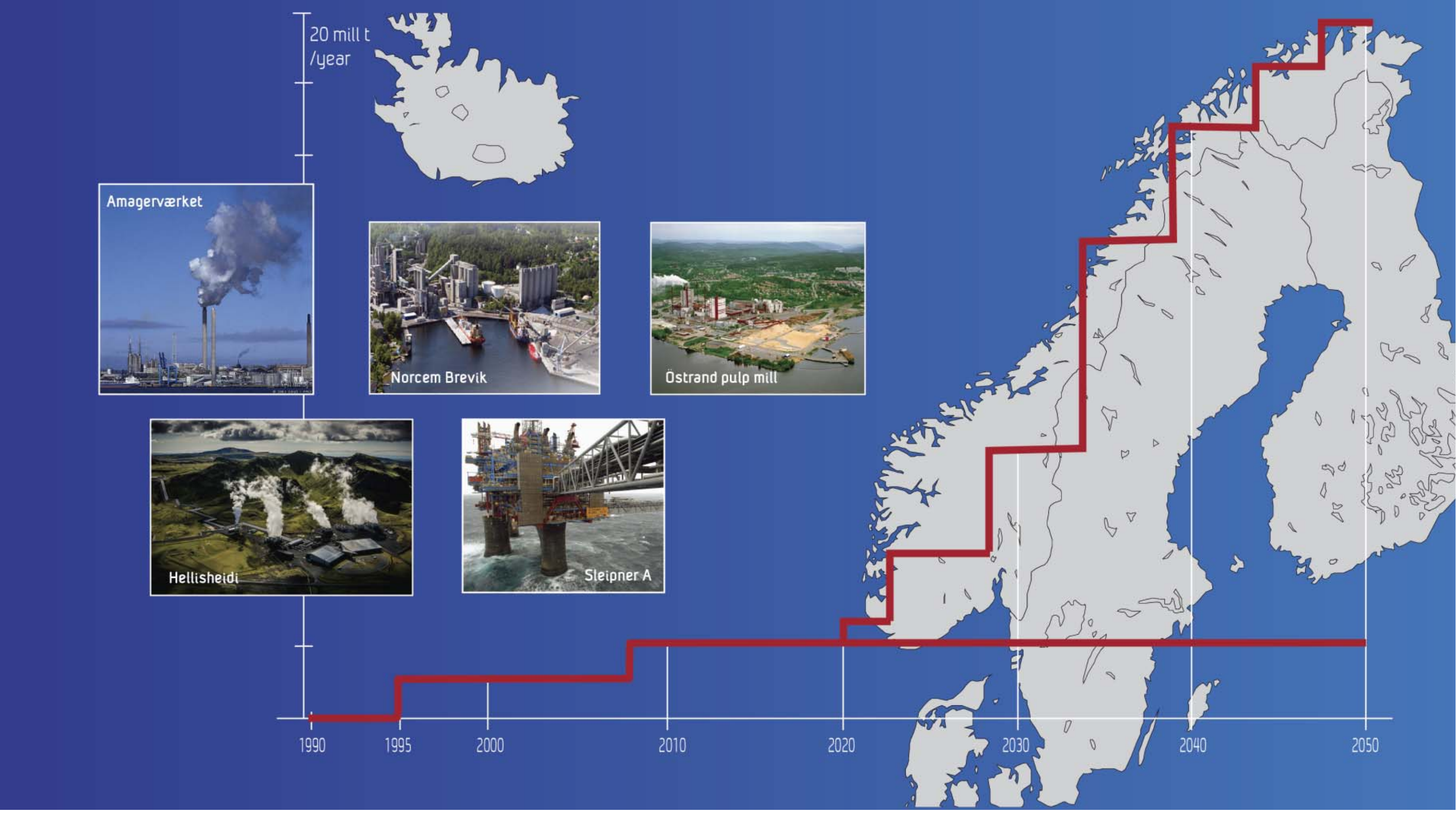


Characterisation and selection of the most prospective CO_2 storage sites in the Nordic region

K.L. Anthonsen, P. Aagaard, P. E. S. Bergmo, S. R. Gislason,
A. Lothe, G. M. Mortensen, S. Ó. Snæbjörnsdottir

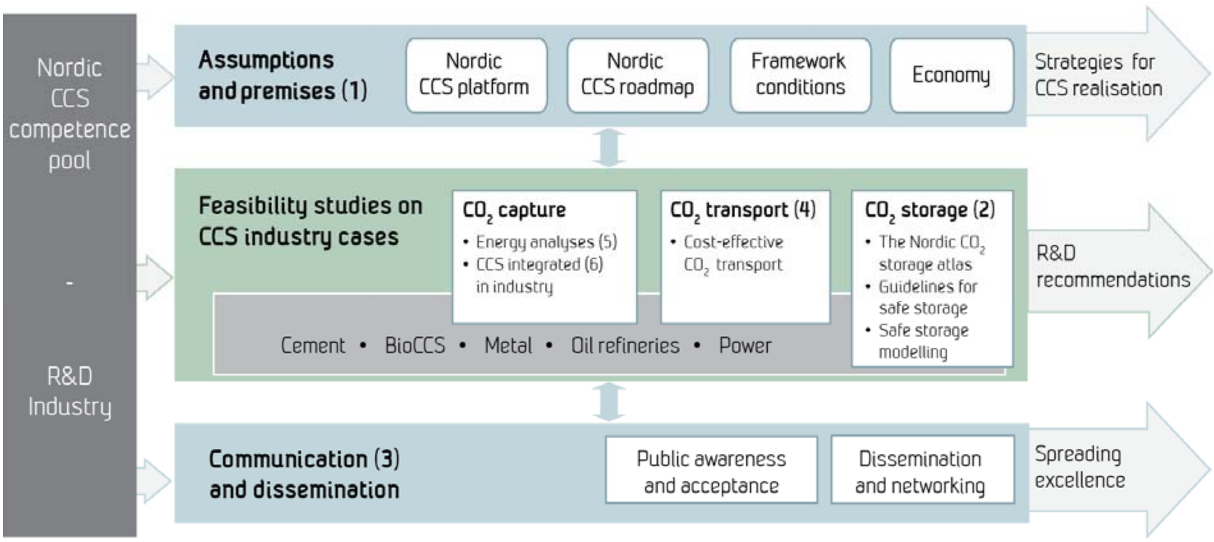
NORDICCS Conference contribution D 6.1.1407 (10)

October 2014

norden
Top-level Research Initiative

nordiccs
Nordic CCS Competence Centre

NORDICCS concept:



Partners:

VTT, CHALMERS University of Technology, IVL Swedish Environmental Research Institute, SGU Sveriges geologiska undersökning Geological Survey of Sweden, GEUS, Orkuveita Reykjavíkur, SINTEF, NTNU, UiO University of Oslo, tel-tek, University of Iceland, Statoil, GASSCO, NORCEM HeidelbergCement Group, VATTENFALL, CO2 Technology Centre Mongstad

Contact: Centre Director Nils A. Røkke • + 47 951 56 181 • Nils.A.Rokke@sintef.no
www.sintef.no/NORDICCS

Summary

An attempting to single out the most attractive storage areas among a large number of mapped CO_2 storage formations, units and traps in the Nordic region, has resulted in a characterisation and ranking procedure for saline aquifer. The ranking methodology is kept simple and divided into four main groups with the most important criteria for reservoir properties, seal properties, safety and data coverage. Based on the ranking 18 of the most prospective CO_2 storage sites have been selected. Furthermore, the critical factors determining if a basalt area is suitable for CO_2 injection is illustrated by an injection site on Iceland.

Keywords Site characterisation, ranking procedure, site selection, Nordic region.

Authors
Karen Lyng Anthonsen, GEUS – Geological Survay of Denmark and Greenland, Denmark, kla@geus.dk
Per Aagaard, University of Oslo, Norway, per.aagaard@geo.uio.no
P.E.S. Bergmo, Sintef, Norway, Per.Bergmo@sintef.no
Sigurdur Gislason, University of Iceland, Iceland, sigrg@raunvis.hi.is
A.Lothe, Sintef, Norway, Ane.Lothe@sintef.no
Gry Møl Mortensen, Geological Survey of Sweden, Sweden, Gry.Mol.Mortensen@sgu.se
Sandra Ó. Snæbjörnsdóttir, University of Iceland, Iceland, sos22@hi.is

Date October 2014

Top-level Research Initiative

About NORDICCS

Nordic CCS Competence Centre, NORDICCS, is a networking platform for increased CCS deployment in the Nordic countries. NORDICCS has 10 research partners and six industry partners, is led by SINTEF Energy Research, and is supported by Nordic Innovation through the Top-level Research Initiative.

For more information regarding NORDICCS and available reports, please visit http://www.sintef.no/NORDICCS.

Characterisation and selection of the most prospective CO_2 storage sites in the Nordic region

K. L. Anthonsen[a], P. Aagaard[b], P. E. S. Bergmo[c], S. R. Gislason[d], A. E. Lothe[c], G. M. Mortensen[e], S. Ó. Snæbjörnsdottir[d]

[a]Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark

[b]Department of Geosciences, University of Oslo, P.O. Box 1047 Blindern, NO-0316 Oslo, Norway

[c]SINTEF Petroleum Research, P.O. Box 4763 Sluppen, NO-7465 Trondheim, Norway

[d]Institute of Earth Sciences, University of Iceland, Sturlugata 7, IS-101 Reykjavík, Iceland

[e]Geological Survey of Sweden, Kiliansgatan 10, SE-223 50 Lund, Sweden

European screening and mapping projects of potential CO_2 storage areas have indicated a large potential storage capacity in the Nordic region. The large potential storage capacity arises from the existence of extensive sedimentary basins south and southeast of Sweden, on- and offshore the Danish area and along the Norwegian coast. The storage possibilities include both saline aquifers and hydrocarbon fields, whereas Iceland has a possible future storage option in porous basalts.

In 2011 the Nordic Top-level Research Initiative funded a Nordic centre of excellence for CCS, named NORDICCS, and one of the main outcomes will be a web-based Nordic CO_2 storage atlas to be released in 2015. This work builds partly on existing mapping projects, such as GESTCO, GeoCapacity and the Norwegian storage atlas, but also includes mapping of new storage sites in Sweden, in the southern parts of Denmark and in the Norwegian part of the North Sea. More than 100 not previously mapped geological traps and storage units have been identified during 2013.

To support future planning of CO_2 storage operations in the Nordic region, the NORDICCS storage group have made a selection of the most prospective CO_2 storage sites for safe and permanent storage of CO_2. This selection is based on a characterisation and ranking procedure. A ranking of storage sites can be viewed from a political, economic or geological point of view each leading to a set of ranking criteria with differentiated weighting factors for the potential storage sites e.g. distance from source, on- or offshore location, injectivity, storage capacity etc.. In NORDICCS, the storage group have primarily based the ranking on geological criteria excluding economic and political criteria, such as distance to source and on- or offshore location, because political and economic conditions are inherently variable. The ranking methodology is kept simple and reflects the most important criteria, such as storage capacity, reservoir quality, safety and data coverage, and the evaluation of the storage site characteristics are to some extent based on the Norwegian CO_2 storage atlas for the North Sea (Halland et al. 2011).

The ranking with respect to storage capacity is affected by the level of assessment, i.e. if the estimate is theoretical, effective or based on a practical evaluation (Bachu et al. 2007). For the reservoir quality, heterogeneity, porosity, permeability, injectivity, depth and volume are the important properties influencing the ranking level. The safety aspect takes into account the sealing properties of the caprock, i.e. thickness, rock composition, fault intensity and heterogeneity. Additionally the level of knowledge for a potential storage site is an important ranking criterion, reflected in the data coverage category where age and density of seismic survey, together with numbers of wells and quality of data obtained from these wells are included.

Following the ranking procedure, the 20 highest ranked potential storage sites within the Nordic region are selected and a thorough geological description of each storage sites specific characteristic will be publically available in the Nordic CO_2 Storage atlas. The ranking will be made both for each individual country and as an integrated Nordic ranking list of the most prospective storage sites.

Bachu, S., Bonijoly, D., Bradshaw, J., Burruss, R., Holloway, S., Christensen N.P., Mathiassen, O-M., 2007. CO2 storage capacity estimations: Methodology and gaps. International Journal of Greenhouse Gas Control, p 430-443.

Halland, E.K., Gjeldvik, I.T., Johansen, W.T., Magnus, C., Meling, I.M., Pedersen, S., Riis, F., Solbakk, T., Tappel, I., 2011. CO_2 Storage Atlas, Norwegian North Sea. Norwegian Petroleum directorate, 71pp.

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 63 (2014) 4884 – 4896

Energy Procedia

GHGT-12

Characterisation and selection of the most prospective CO_2 storage sites in the Nordic region

K.L. Anthonsen[a,]*, P. Aagaard[b], P. E. S. Bergmo[c], S. R. Gislason[d], A.E. Lothe[c], G. M. Mortensen[e], S. Ó. Snæbjörnsdóttir[d]

[a]*Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark*
[b]*Department of Geosciences, University of Oslo, PO Box 1047 Blindern, NO-0316 Oslo, Norway*
[c]*SINTEF Petroleum Research, P.O. Box 4763 Sluppen, NO-7465 Trondheim, Norway*
[d]*Institute of Earth Sciences, University of Iceland, Sturlugata 7, IS-101 Reykjavík, Iceland*
[e]*Geological Survey of Sweden, Kiliansgatan 10, SE-223 50 Lund, Sweden*

Abstract

An attempting to single out the most attractive storage areas among a large number of mapped CO_2 storage formations, units and traps in the Nordic region, has resulted in a characterisation and ranking procedure for saline aquifer. The ranking methodology is kept simple and divided into four main groups with the most important criteria for reservoir properties, seal properties, safety and data coverage. Based on the ranking 18 of the most prospective CO_2 storage sites have been selected. Furthermore, the critical factors determining if a basalt area is suitable for CO_2 injection is illustrated by an injection site on Iceland.

Peer-review under responsibility of the Organizing Committee of GHGT-12

Keywords: Site characterisation; Ranking procedure; Site selection; Nordic region.

1. Introduction

European screening and mapping projects of prospective CO_2 storage areas have indicated a large potential storage capacity in the Nordic region [1][2][3]. The large potential storage capacity arises from the existence of

* Corresponding author. Tel.: +45-9133-3724; fax: +45-3814-2050.
E-mail address: kla@geus.dk

Peer-review under responsibility of the Organizing Committee of GHGT-12
doi:10.1016/j.egypro.2014.11.519

extensive sedimentary basins south and southeast of Sweden, on- and offshore Denmark and along the Norwegian coast. The storage prospects include both saline aquifers and hydrocarbon fields, and a future option for CO_2 storage in porous basalts on Iceland. But which of the around 150 mapped stores sites are the best with respect to safe and permanent storage of CO_2?

In order to answer this question, a procedure for characterisation and ranking have been developed for the Nordic storage sites, attempting to single out the most attractive storage areas among a large number of mapped storage formations, units and traps mapped in the Nordic region.

2. Methodology

The selection of the best Nordic storage sites is based on a characterisation and ranking procedure developed for the Nordic region within the NORDICCS Competence Centre. The procedure is developed for aquifer storage sites, but a description of key parameters for selection of areas suitable for mineral storage in porous basaltic rocks has also been implemented.

2.1 Methodology for characterisation and ranking of aquifer storage sites

A review of previous studies on characterisation criteria made the basis for discussion of which criteria to include in the Nordic storage site ranking procedure. It was decided primarily to base the ranking on geological criteria, excluding economic and political criteria, such as distance to source and on- or offshore location, because political and economic conditions are inherently variable. The ranking methodology is kept simple and divided into four main groups with the most important criteria for reservoir properties, seal properties, safety and data coverage. The storage site characterisation criteria are to some extent based on experience from the EU GeoCapacity project and the Norwegian CO_2 storage atlas for the North Sea [2] [4].

The reservoir quality criteria included are depth, porosity, permeability, heterogeneity, pore pressure and thickness of the reservoir layers (Table 1). For the seal the criteria are, thickness, fault intensity, lateral extent, multiple sealing layers and lithology of the primary seal was considered most important (Table 2). The safety category takes into account seismicity and risk of groundwater contamination (Table 3). Additionally the level of knowledge for a potential storage site is an important criterion, reflected in the data coverage category where age and type of seismic survey, together with numbers of wells drilled into the reservoir is evaluated (table 4).

Each criterion was then divided into three categories; preferred, questionable and hazardous, depending on a value or range of values decided for ranking criteria. In the final ranking procedure the criteria values was transformed into a number from 1-3, where the highest number was given to values within the preferred category and the lowest to the hazardous category. The number of criteria is 15, implying that the most prospective sites will end up with a score of 45.

Table 1. Characterisation and ranking criteria for reservoir properties.

Reservoir properties	Preferred	Questionable	Hazardous	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.	Since heterogeneity is hard to quantify it advisable to give a remark about interpreted depositional environment and if the area has known diagenesis

			Diagenesis	
Pore pressure	Hydrostatic or lower		Overpressure	
Thickness (Net sand)	>50m	15-50m	<15m	

Table 2. Characterisation and ranking criteria for seal properties.

Seal properties	Preferred	Questionable	Hazardous	Remarks
Thickness	>50m	20-50m	<20m	
Lithology of the primary seal	Homogeneous clay, mud or evaporites	Chalk	High content of silt or sand	
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	

Table 3. Characterisation and ranking criteria for safety properties.

Safety	Preferred	Questionable	Hazardous	Remarks
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	Risk of contamination of groundwater

Table 4. Characterisation and ranking criteria for data coverage.

Data coverage	Preferred	Questionable	Hazardous	Remarks
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 older than 1970 or sparse data	

Storage capacity has not been included in the ranking procedure as a ranking criterion because size has no influence on the site properties, but since storage capacity is an important quality this has been used to rank the sites in cases where two or more sites got the same ranking score.

The ranking with respect to storage capacity is based on static capacity estimate methodology used in the EU GeoCapacity project, which is a slightly modified version of the methodology proposed by Bachu et al. [5,6], except for a few sites where capacity are based on modelling.

2.2 Methodology for characterisation of mineral storage sites in basaltic rocks

The geological setting of Iceland is very different from the other Nordic countries. Iceland is the largest landmass found above sea level at the mid oceanic ridges, mostly made of igneous basaltic rocks younger than 20 million year old. Most of the ongoing CCS-projects are injecting CO_2 into large sedimentary basins where the CO_2 is injected as a separate buoyant phase which is trapped below an impermeable cap rock. In Iceland an alternative method, the so called CarbFix method, where the CO_2 is dissolved during injection into porous basaltic rock is being tested. Because the CO_2 is dissolved it is not buoyant and no cap rock is required. The CO_2 charged water accelerates metal release and formation of solid carbonates for long term storage of CO_2 [7].

Since about 90% of Iceland is basalt, theoretically much of it could be used for injection of CO_2, fully dissolved in water. Most of the pore space in the older rocks is filled with secondary minerals, thus the young and porous basaltic formations, found within the active rift zone and covering about one third of Iceland, are the most feasible for carbon storage onshore [8].

Some key factors have to be considered for successful injection of CO_2 fully dissolved in water. One of the main requirements is availability of water, but the CarbFix method requires substantial water; only about 5% of the injected mass is CO_2 [8,6]. Another aspect that has to be taken into account is mobility of metals and the possibility of groundwater contamination. The reaction between the CO_2-charged water and the basaltic rocks not only releases divalent cations that end up in carbonates, but also other metals that can be harmful for the biota. The toxic metal release is the most dangerous at the early stage of CO_2 injection into basalt [10,11,12]. Natural analogues have shown the secondary minerals, such as carbonates, effectively scavenge the potential toxic metals that are released at early stages [10,12].

Basaltic rock injection is still in its infancy, though if it can be up scaled, it may provide a safe alternative to the injection of pure CO_2 into sedimentary basins. Studies on natural analogs for CO_2 storage in basaltic rocks have revealed a large storage potential [13,14].Onshore projects on mineral storage of CO_2 in basalt, such as the CarbFix project in SW-Iceland [7,9,15] and the Big Sky Carbon Sequestration Partnership (BSCP) in the northwest United States near Wallula, Washington [16,17] are yet the only projects where CO_2 is stored in basalt. The largest storage potential lies offshore, with long-term advantages for safe and secure CO_2 storage in the mid-ocean ridges [14,18].

3. Results of site characterisation and ranking in the Nordic region

3.1 Denmark

In total twenty traps and one storage unit have been mapped and characterised with respect to the selected criteria. Out of the 21 prospects the five best sites has been selected. The results of the Danish ranking are listed in Table 5.

Table 5. The five most prospective storage sites in Denmark.

Ranking criteria	Gassum Aquifer (unit)	Havnsø (trap)	Gassum (trap)	Thisted (trap)	Hanstholm (trap)
Ranking score (max. 45)	43	43	43	42	42
Storage Capacity (Mt)	3700*	926	630	11039	2753
Reservoir properties					
Primary reservoir fm.	Gassum	Gassum	Gassum	Skagerrak	Gassum
Depth, top (msl.)	1000	1500	1460	1166	1000
Porosity (mD)	23	22	25	15	20
Permeability (%)	210	500	300-2000	10-100	-
Heterogeneity (N/G)	0.50	0.67	0.32	0.47	0.40
Facies	Shore/delta	Shore/delta	Shore/delta	Alluvial fans	Shore/delta
Pore pressure**	hs	hs	hs	hs	hs
Net sand thickness (m)	50	100	53	449	230
Seal properties					
Primary seal fm.	Fjerritslev	Fjerritslev	Fjerritslev	Oddesund	Fjerritslev
Thickness (m)	>100	260	320	240	500
Lithology	claystone	mudstone	mudstone	claystone	claystone
Fault intensity	low	low	low	low	low

Lateral extend	continuous	continuous	continuous	continuous	continuous
Multiple seals	yes	yes	yes	yes	yes
Safety					
Seismicity	low	low	low	low	low
Groundwater contamination	no	no	no	no	no
Data coverage					
Wells	0	1	1	0	1
Seismic survey	2D	2D	2D	2D	2D

*Storage capacity based on modelling.
** Pore pressure: hs = hydrostatic pressure

Tree sites scored 43 in the ranking; Gassum Aquifer, Havnsø and Gassum structure, listed after their storage capacity. The most prospective site in Denmark based on the ranking procedure and storage capacity is the Gassum Aquifer, see Fig. 1. The Gassum Aquifer is a large open dipping aquifer with a modelled storage capacity of 3700 Mt [19], but existence of only 2D seismic surveys and no wells through the storage unit makes the data more uncertain. The Havnsø and Gassum sites are anticline structure with no major faults cutting through the structures. The Gassum structure has a higher heterogeneity and lower permeability than the Havnsø structure, but the advantage of having a well drilled on top of the structure making data more reliable. Both the Thisted and Hanstholm structures scored 42 and both sites are large anticline structures. The Hanstholm structure has a higher porosity than Thisted, but on the other hand, data from the Thisted structure is based on 4 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.

The lack of new high quality data is a general issue for all Danish sites; both wells and seismic survey are often old, due to the fact that there is no hydrocarbon exploration in these areas since the beginning of the 1970ties.

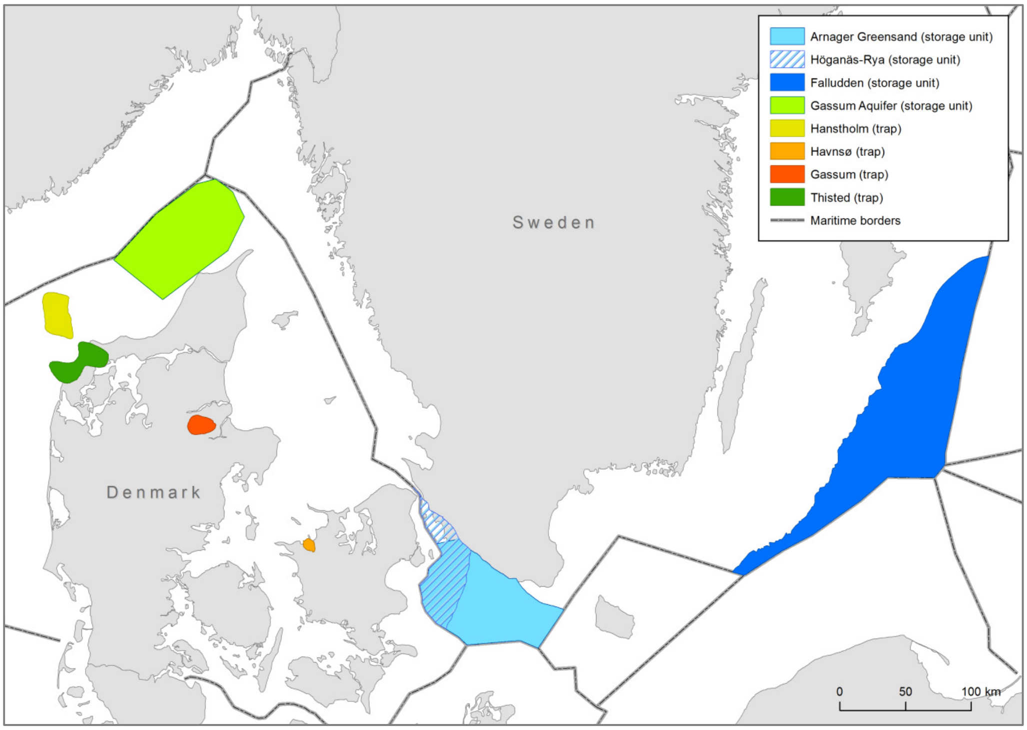


Fig. 1. Location of the ranked and selected Danish and Swedish storage sites.

3.2 Norway

For Norway a total of 27 possible storage formations have been mapped and characterized with respect to the selected criteria. Out of all the mapped storage formations, the 10 most promising formations have been selected. For the Norwegian storages formation, no upper limit as e.g. 800 meters has been used, giving a larger storage capacity for some of the formations than realistically can be utilized for CO_2 storage. The results of the Norwegian ranking procedure are listed in Table 6a and 6b.

Table 6a. The ten most prospective storage formations in Norway, part I.

Ranking criteria	Sognefjord Fm. North Sea	Krossfjord Fm. North Sea	Utsira Fm.* North Sea	Skade Fm.* North Sea [20]	Heimdal Fm.
Ranking score (max. 45)	45	45	44	44	44
Storage Capacity (Mt)	11465	3977	21300	7560	5112
Reservoir properties					
Age / primary reservoir fm.	Late Jurassic	Middle Jurassic	Late Middle Miocene to Upper Pliocene	Early Miocene	Paleocene
Depth, top (msl.)	1400-2000*	1650-2250*	450 to 1500 m. Central Viking Graben 500-750 m	850-1140	2000-2100
Porosity (%)	18-25**	25	21	35	25-30
Permeability (mD)	150-300**	400	1000	?	800-1000
Heterogeneity (N/G)	0.9	0.8	0.7	0.7	0.85
Facies	Wave dominated asymmetric deltaic coast [21]	Shallowmarine, wave- to tide dominated shoreface deposits [22]	Marine environment with reworked sheet sands [23,24]	Marine turbidite deposits with thin claystone interbeds [23,24]	Viking Graben: Submarine fans [25]
Pore pressure***	<hs	<hs	<hs	<hs	<hs
Net sand thickness (m)	55-180**	65-135**	max. 350	120	50-295
Seal properties					
Primary seal fm.	Draupne Fm. in the Horda Platform	Heather Fm.	Upper Nordland Gr.	Hordaland Gr.	Lista Fm.
Thickness (m)	Several hundred meters [26]	1000m in graben	500-1500 m [20]	100 m	50-several hundred meters [25]
Lithology	claystone	Siltstone and silty claystone	claystone	claystone	shales
Fault intensity	low	low	low	low	medium
Lateral extend	continuous	continuous	continuous	widespread	widespread
Multiple seals	yes	yes	no	yes	yes
Safety					
Seismicity	low	low	low	low	low
Groundwater contamination	no	no	no	no	no
Data coverage					
Wells	Several, type well	Several, type	Several, type	Type well 24/12-1	Type well

	31/2-1 [26]	well 31/2-1[26]	well 16/1-1		24/4-1
Seismic survey	2D and 3D	2D and 3D	2D and 3D	2D and 3D	2D and 3D

*Storage capacity estimated for the entire formations including storage above 800 meter.
**Different fault blocks
*** Pore pressure: hs = hydrostatic pressure

Table 6b. The ten most prospective storage formations in Norway, Part II.

Ranking criteria	Fensfjord Fm. North Sea	Frigg Fm. North Sea	Garn Fm. Norwegian Sea	Johansen Fm.	Statfjord Gr. North Sea
Ranking score (max. 45)	44	44	43	42	42
Storage Capacity (Mt)	4100	1164	8003	861	1850
Reservoir properties					
Age primary reservoir fm.	Middle Jurassic	Early Eocene	Middle Jurassic	Lower Jurassic	Late Triassic-Early Jurassic
Depth, top (msl.)	1550-1850	1800	1200-1750	2000-2700	1800-2750
Porosity (%)	25	30	20-25	0.1	22
Permeability (mD)	150	1000	400-500	400	200
Heterogeneity (N/G)	0.8	0.85	0.2-0.5	0.8	0.5
Facies	Shallowmarine, wave- to tide dominated shoreface deposits [22]	Submarine fans with stacked channels, lobe and interchannels sandstone interval with shales in between [27,28]	Progradation of braided river systems and delta front [29]	Wave dominated asymmetric deltaic coast [30]	Transition from continental to shallow marine [26]
Pore pressure*	Moderate	<hs	<hs	Some parts have overpressure	Parts are over pressured
Net sand thickness (m)	42-170	155, max thickness 300 in block 25/1 [20]	100-185	95-130	95-286
Seal properties					
Primary seal fm.	Heather Fm.	Hordaland Gr.	Viking Gr.	Drake Fm. above Cook Fm.	Dunlin Group
Thickness (m)	1000 m in graben [26]	Several hundred metres	Approx. 1000 m	80-100	Several hundred metres
Lithology	Siltstone and silty claystone	claystone	shales and mudstone	Claystone and shale	Shales and siltstones
Fault intensity	low	low	low	moderate	low
Lateral extend	wide	wide	wide	wide	wide
Multiple seals	yes	?	yes	yes	?
Safety					
Seismicity	low	low	low	low	low
Groundwater contamination	no	no	no	no	no
Data coverage					
Wells	Many, Type well	Many, Type	Several, type	Several, type	Several, type

	31/2-1	well 25/1-1	well 6407/1-3	well 31/2-1	well 33/12-2
Seismic survey	2D and 3D	2D and 3D	2D Trøndelag Platform, 2D and 3D in Halten Terrace area	2D and 3D	2D and 3D

* Pore pressure: hs = hydrostatic pressure

Selection of the 10 most promising storage units is not based on the score only (Fig. 2). Several storage formations had the same ranking, and only small changes in the reservoir properties could change the site from good to not. Originally, several units from the Barents Sea like e.g. Stø Formation and Tubåen Formation were on the top ten list, having a ranking score of 42 and 43 respectively. However, it is well known both from exploration and from Statoil's injection campaign at 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 quite some quartz cementation, causing reduction in porosity and permeability. The later uplift for the Snøhvit reservoir is about 1km.Therefore, we have not included them in this ranking.

This ranking has not considered parameters like economy, distance to shore, transport of CO_2 and so forth. The ranking was only based on geological criteria. Many formations offshore Norway has 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, it exist some uncertainty coming 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 Utsira Formation, Sognefjord Formation or the Skade Formation. They all have storage capacity >10 000 Mt, shallow burial < 2 km, high porosity and permeability values.

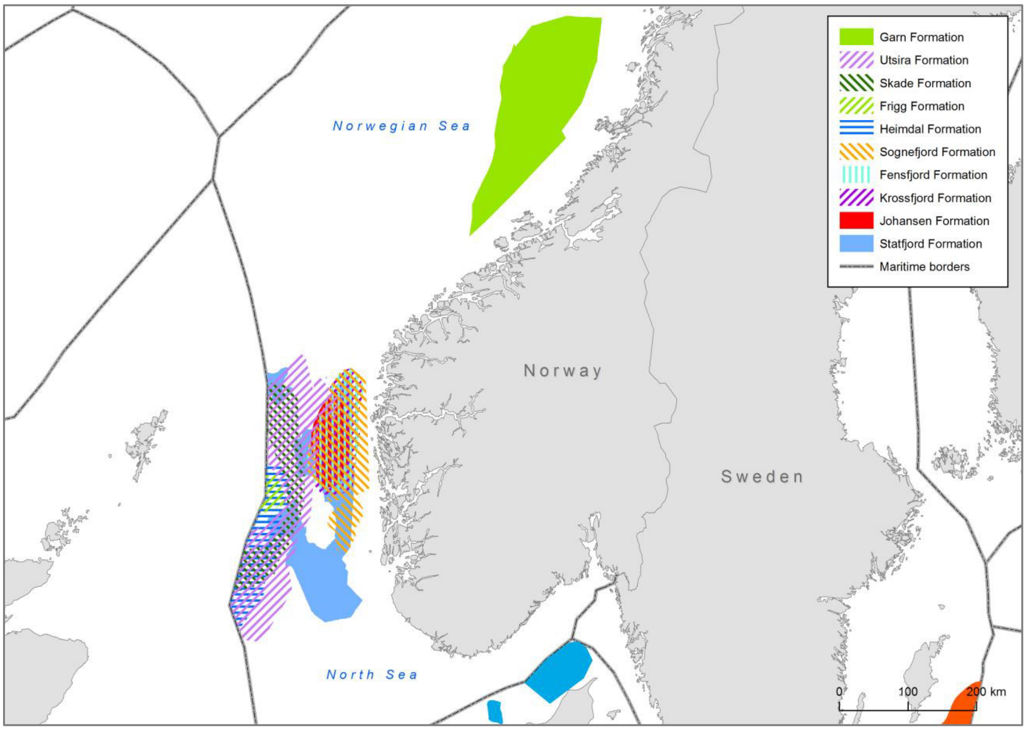


Fig. 2. Location of the Norwegian selected and ranked storage formations.

3.3 Sweden

Eight storage units and one trap have been identified in the southernmost part of Sweden. The three most prospective storage sites have been selected due to the NORDICCS ranking methodology. The Swedish ranking parameters are listed in table 7.

Table 7. The three most prospective storage sites in Sweden.

Ranking criteria	Faludden (unit)	Arnager Greensand (unit)	Höganäs-Rya (unit)
Ranking score (max. 45)	40	39	39
Storage Capacity (Mt)	745	521	543
Reservoir properties			
Primary reservoir fm.	Borgholm	Arnager Greensand	Höganäs, Rya
Depth, top (msl.)	830	946	976
Porosity (mD)	14	26	23
Permeability (%)	147	400	200
Heterogeneity (N/G)	0.90	0.80	0.51
Facies	shore/delta	marine	shore/delta
Pore pressure*	hs?	hs	hs
Net sand thickness (m)	41	31	92
Seal properties			
Primary seal fm.	Silurian marlstone	Höllviken	Höllviken
Thickness (m)	500	1000	1000
Lithology	marlstone	clayey limestone, chalk	clayey limestone, chalk
Fault intensity	low	moderate	moderate
Lateral extend	continuous	continuous	continuous
Multiple seals	yes	no	yes
Safety			
Seismicity	low	low	low
Groundwater contamination	no	unsure	unsure
Data coverage			
Wells	5	24	13
Seismic survey	2D	2D	no

* Pore pressure: hs = hydrostatic pressure

The Faludden sandstone is a member of the Borgholm Formation located in the south-east Baltic Sea (Fig. 1). The Faludden sandstone is a stratigraphic confined, open saline aquifer forming a large lens-shaped weakly east-south-east dipping aquifer composed of very homogeneous Middle Cambrian sandstone. Minor interbeds of shale and siltstone represents fluvial and deltaic influences [31]. The regional distribution of the Faludden sandstone covers an area of c. 33000 km2 in Swedish territory including the potential storage unit covering an area of c. 11000 km^2 [32]. The Faludden sandstone pinches out towards the north-west but continues as the Deimena Formation to the south-east where it outcrops in Estonia and is deeply buried towards the other Baltic countries [33]. The Faludden sandstone is capped by a regional distributed multi-layered seal of a total c. 600 m of bentonitic limestone and marlstone.

The Arnager Greensand Formation is located in south-west Scania and represents a weakly north-east dipping large open saline aquifer confined to the north-east by the Romeleåsen Fault Zone continuing to the south-west across the Swedish economic zone. The sandstone outcrops in Denmark at the island of Bornholm. The Arnager Greensand Formation is composed of Early Albian-Cenomanian unconsolidated sandstone displaying a very high porosity and permeability. The regional distribution of the Arnager Greensand in Swedish territory covers an area of c. 8800 km^2 whereas the part suitable for CO_2 storage covers an area of c. 5200 km^2 [32]. The Arnager Greensand is capped by a regional distributed seal of c. 1000 m clayey limestone and chalk.

The Höganäs-Rya sequence belongs to the Höganäs Formation and the Rya Formation respectively, a Swedish equivalent to the Gassum Formation in Denmark and Norway. The sequence is located in south-west Scania and represents a weakly north-east dipping semi-closed saline aquifer confined to the north by the Romeleåsen Fault Zone and to the east by the Svedala Fault Zone and continuing into the Danish and North German Basin. The Höganäs-Rya sequence consists of Late Rhaetian-Early Jurassic multi-layered sand- and claystone with shale and coal interbeds covering an area in Swedish territory of c. 4000 km^2 including the potential CO_2 storage area of c. 2100 km^2 [32]. Great lateral variation of individual lens-shaped sand bodies occur and some of these may act as stratigraphic closures confined by dense claystone [31]. The Höganäs-Rya sequence is capped by a regional distributed multi-layered seal composed of a thin (6 m) but dense layer of shale followed by c. 1000 m clayey limestone and chalk.

In general, there is a lack of modern high quality data for all potential Swedish storage sites. Available data consists of old (1970-80s) 2D seismic data together with a limited number of deep wells from the same period of time. No seismic data exists for the Höganäs-Rya sequence.

3.4 Iceland

CarbFix [7,14,15,34,35] is the only ongoing CCS project in Iceland (Fig. 3). CarbFix is a combined industrial/academic collaboration project between Reykjavík Energy, the Institute of Earth Science at the University of Iceland, Earth Institute-Lamont-Doherty Earth Observatory at Columbia University in New York and the Centre National de la Recherche Scientifique/Universite Paul Sabatier in Toulouse, that was developed in order to assess the feasibility of in situ CO_2 mineral storage in basaltic rocks in Iceland. The project consists of a CO_2 pilot injection, laboratory based experiments, study of natural analogues, predictive model development, numerical modelling and model validation, as well as cost analysis.

Several injection experiments have been and are being carried out at the CarbFix sites from 2008 to the present. Tracer test were conducted under natural and forced conditions at the CarbFix I site from 2008 to 2011, to define the hydrology of the system and scale reactive transport models [9,15,37,38,39]. Pure CO_2 injection was done in 2011 and 2012. A gas mixture of CO_2-H_2S-H_2, captured from the power plant, was injected in 2012. By mid-year 2014, CO_2-H_2S gas mixture, captured and separated from the gas stream of the Hellisheidi power plant, has been injected deep into the geothermal system at the CarbFix 2 site. The gas mixture was injected into the geothermal system to lower the capture and gas separation cost and conduct the injection under sterile (fee of bacteria) conditions [36].

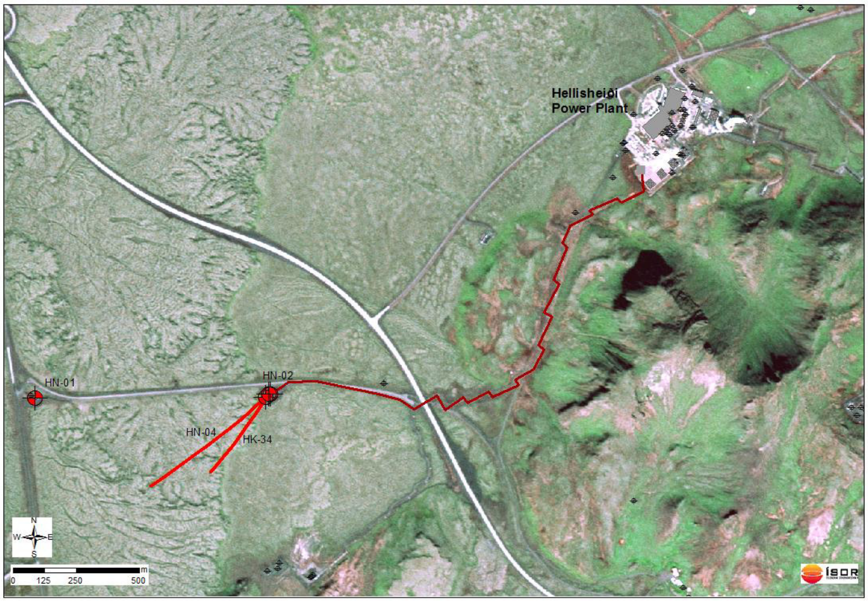


Fig. 3. Aerial photo showing Hellisheiði power plant and the CarbFix I and CarbFix II injection sites

4. Conclusions

There are many possible storage formations on the Norwegian continental shelf, each with a large number of storage units and traps. This paper, sum up the ten most promising formations for storage based on the selection criteria. From the ranking and the storage capacity it seems that three of the best units for large scale industrial storage would be the Utsira Formation, the Sognefjord Formation and the Skade Formation. They all have storage capacity >10 000 Mt, shallow burial < 2 km, high porosity and permeability values.

In Denmark 21 prospective CO_2 storage sites was ranked and the five best sites was selected. The most prospective site is the Gassum Aquifer offshore northern Denmark, followed by Havnsø, Gassum, Thisted and Hanstholm, which all four are anticline traps. None of the Danish sites has the possibility to reach a maximum ranking score, due to the lack of new high quality data as 3D seismic survey. It is a general issue for all Danish sites, that both wells and seismic survey often are older, since only very limited hydrocarbon exploration has taken place outside the Danish Central Graben since the beginning of the 1970ties.

The issue with old data also concerns Sweden, and has influence on the ranking score for the Swedish sites. Sweden has selected three prospective storage unites, the Falluden Sandstone, the Höganäs-Rya and the Arnager Greensand, all located in the Baltic region in the southern part of Sweden.

The geological setting of Iceland is very different from the other Nordic countries. In Iceland an alternative method, the so called CarbFix method, where the CO_2 is dissolved in water during injection into porous basaltic rocks, is being tested. In theory large amounts of CO_2 can be stored in porous basalts on Iceland, but access to water and a high porosity are the critical factors determining if a potential area is suitable for injection.

Acknowledgement

This publication has been produced with support from the NORDICCS Centre, performed under the Top-level Research Initiative CO_2 Capture and Storage program, and Nordic Innovation. The authors acknowledge the following partners for their contributions: Statoil, Gassco, Norcem, Reykjavik Energy, CO_2 Technology Centre Mongstad, Vattenfall and the Top-level Research Initiative (Project number 11029).

References

[1] Christensen, NP, Holloway S. *Geological Storage of CO_2 from Combustion of Fossil Fuel*. Summary report, 2nd edition. EU Project No. ENK6-CT-1999-00010, 2004.

[2] Vangklide-Pedersen T, editor. *EU GeoCapacity – Assessing European Capacity for Geological Storage of Carbon Dioxide*. GeoCapacity Final Report. EU Project no. SES6-518318, 2009.

[3] Anthonsen KL, Aagaard P, Bergmo PES, Erlström M, Faleide JI, Gislason SR, Mortensen GM, Snæbjörnsdottir SÓ. CO_2 storage potential in the Nordic region. *Energy Procedia* 2013;37:5080-5092.

[4] Halland EK, Gjeldvik IT, Johansen WT, Magnus C, Meling IM, Pedersen S, Riis F, Solbakk T, Tappel I. *CO_2 Storage Atlas Norwegian North Sea*. Norwegian Petroleum directorate; 2011.

[5] Bachu S, Bonijoly D, Bradshaw J, Burruss R, Holloway S, Christensen NP, Mathiassen O-M,. CO_2 storage capacity estimations: Methodology and gaps. *Int Greenh Gas Con* 2007;1:430-443.

[6] Vangkilde-Pedersen T, Vosgerau HJ, Willscher B, Neele F, Van der Meer B, Bossie-Codreanu D, Wojcicki A, Le Nindre Y-M, Kirk K, Anthonsen KL. *Capacity standards and site selection criteria*. EU GeoCapacity report D 26, 2009.

[7] Gislason SR, Oelkers EH. Carbon storage in Basalt. *Science* 2014;344: 373-374.

[8] Snæbjörnsdóttir SO, Wiese F, Fridriksson T, Armannsson H, Einarsson GM, Gislason SR. CO_2 storage potential of basaltic rocks in Iceland and the oceanic ridges. 2014; This issue.

[9] Gislason SR, Wolff-Boenisch D, Stefansson A, Oelkers EH, Gunnlaugsson E, Sigurdardottir H, Sigfusson B, Broecker WS, Matter JS, Stute M, Axelsson G, Fridriksson T. Mineral sequestration of carbon dioxide in basalt: a preinjection overview of the CarbFix project. *Int J Greenh Gas Con* 2010;4:537–545.

[10] Flaathen TK, Gislason, SR, Oelkers EH, Sveinbjörnsdóttir ÁE. Chemical evolution of the Mt. Hekla, Iceland, groundwaters: A natural analogue for CO2 sequestration in basaltic rocks. *Appl Geochem* 2009;24:463–474.

[11] Galeczka I, Wolff-Boenisch D, Gislason SR. Experimental Studies of Basalt-H2O-CO2 Interaction with a High Pressure Column Flow Reactor: the Mobility of Metals. *Energy Procedia* 2013;37:5823-5833.

[12] Olsson J, Stipp SLS, Makovicky E, Gislason SR. Metal scavenging by calcium carbonate at the Eyjafjallajökull volcano: A carbon capture and storage analogue. *Chem Geol* 2014;384:135-148.

[13] Wiese F, Fridriksson T, Ármannsson H. *CO_2 fixation by calcite in high-temperature geothermal systems in Iceland*. Report, ISOR 2008/003.

[14] Snæbjörnsdóttir SO, Mesfin KG, Gunnarsson I, Aradottir ES, Sigfusson B, Gunnlaugsson E, Oelkers EH, Stute M, Matter J, Gislason SR. CarbFix: Injection of CO_2 and CO_2-H_2S gas mixture at Hellisheidi SW-Iceland. First results on chemical monitoring. Abstract in Intnational Carbon Conference, Reykjavik; 2014.

[15] Aradóttir ES, Sonnenthal E, Bjornsson G, Jonsson, H. Multidimensional reactive transport modelling of CO_2 mineral sequestration in basalts at the Hellisheidi geothermal field, Iceland. *Int Greenh Gas Con* 2012;9:24–40.

[16] McGrail BP, Spane FA, Sullivan EC, Bacon DH, Hund G. The Wallula basalt sequestration pilot project. *Energy Procedia* 2011; 4: 5653−5660.

[17] McGrail BP, Freeman CJ, Brown CF, Sullivan EC, White SK, Reddy S, Garber RD, Tobin D, Gilmartin JJ, Steffensen EJ. Overcoming business model uncertainty in a carbon dioxide capture and sequestration project: Case study at the Boise White Paper Mill. *Int J Greenh Gas Con* 2012; 9:91−102.

[18] Goldberg DS, Kent DV, Olsen PE. Potential on-shore and off-shore reservoirs for CO_2 sequestration in Central Atlantic magmatic province basalts. *Proc Natl Acad Sci USA* 2010;107:1327–1332.

[19] Bergmo PES, Szczepan P, Aagaard P. Frykman P, Haugen HA, Bjørnsen D. Evaluation of CO_2 storage potential in Skagerrak. *Energy Procedia* 2013;37: 4863-4871.

[20] Bøe R, Magnus C, Osmundsen PT, Rindstad BI. *CO_2 point sources and subsurface storage capacities for CO_2 in aquifers in Norway*. NGU report 2002.010.

[21] Dreyer T, Whitaker M, Dexter J, Flesche H, Larsen E. From spit system to tide-dominated delta: integrated reservoir model of the Upper Jurassic Sognefjord Formation on the Troll West Field. *Geol Soc London, Petrol Geol Con* 2005;6:423-448.

[22] Holgate NE, Jackson CAL, Hampson GJ, Dreyer T. Sedimentology and sequence stratigraphy of the Middle-Upper Jurassic Krossfjord and Fensfjord formations, Troll Field, northern North Sea. *Petrol Geos* 2013;39:2012-2039.

[23] Eidvin T, Rundberg Y, Smelror M. Revised chronology of Neogene sands (Utsira and Skade formations) in the central North Sea. In: Hurst A, editor. *Onshore-Offshore Relationships on the Nordic Atlantic Margin*. Trondheim: NGF Abstracts and proceedings of the Norwegian Petroleum Society and Norwegian Geological Society Conference; 2002, p. 51-53

[24] Gregersen U, Johansen PN. Distribution of the Neogene Utsira Sand and Hutton Sand, and the succeeding deposits in the Viking Graben area, North Sea. *Mar Petrol Geol* 2007;24:591-608.

[25] Isaksen D, Tonstad K. *A revised Cretaceous and Tertiary lithostratigraphic nomenclature for the Norwegian North Sea*. NPD-Bulletin No. 5; 1989.

[26] Vollset J, Dore AG. *A revised Triassic and Jurassic lithostratigraphic nomenclature for the Norwegian North Sea*. NPD Bulletin No 3; 1984.

[27] Bowman MBJ. Cenozoic. In Glennie KW, editor. *Introduction to the Petroleum Geology of the North Sea*. 4th ed. Blackwell Scientific Publications; 1998, p. 350-375.

[28] Heritier FE, Lossel P, Wathne E. Frigg Field—Large Submarine-Fan Trap in Lower Eocene Rocks of the Viking Graben, North Sea1 In Illing LV, Hobson GD, editors. *Petroleum Geology of the Continental Shelf of North-West Europe*. London: Heyden; 1980, p. 380-391.

[29] Dalland A, Worsley D, Ofstad K. *A lithostratigraphic scheme for the Mesozoic and Cenozoic succession offshore mid- and northern Norway*. NPD-Bulletin No. 4; 1988.

[30] Sundal A, Nystuen JP, Rørvik KL, Dypvik H, Aagaard P. A revised depositional model for the Johansen Formation - Implications for reservoir quality. Submitted.

[31] Erlström M, Frederiksson D, Juhojuntti N, Sivhed U, Wickström L.Lagring av koldioxid i berggrunden - krav, förutsättningar och möjligheter. *Rapporter och meddelanden 131, Geological Survey of Sweden* (SGU); 2011.

[32] Mortensen GM. CO_2 Storage Atlas for Sweden - a contribution to the Nordic Competence Centre for CCS, NORDICCS. In: *31st Nordic Geological Winter Meeting*, Lund; 2014.

[33] Sliaupa S, Sliaupiene R, Nulle I, Nulle U, Shogenova A, Shogenov K, Jarmo K, Wickström L, Erlström E. *Options for geological storage of CO_2 in the Baltic Sea region*. Contribution to the ENeRG network and the CGS Europe project. 2012.

[34] Oelkers EH, Gislason SR, Matter J. Mineral carbonation of CO_2. *Elements* 2008;4: 331–335.

[35] Alfredsson HA, Oelkers EH, Hardarsson BS, Franzson H, Gunnlaugsson E, Gislason SR, 2013. The geology and water chemistry of the Hellisheidi, SW-Iceland carbon storage site. *Int J Greenh Gas Con* 2013;12: 399-418.

[36] Gislason SR, Broecker WS, Gunnlaugsson E, Snæbjörnsdóttir S, Mesfin K, Alfredsson H, Aradóttir E, Sigfusson B, Gunnarsson I, Stute M, Matter J, Ragnheidardottir E, Galeczka I, Guðbrandsson S, Stockman G, Wolff-Boenisch D, Stefansson A, Faathen T, Gysi A, Olssen J, Didriksen K, Stipp S, Menes B, Oelkers EH. Rapid solubility and mineral storage of CO_2 in basalt. *Energy Procedia* 2014; This issue.

[37] Khalilabad MR, Axelsson G, Gislason SR. Aquifer characterization with tracer test technique; permanent CO_2 sequestration into basalt, SW Iceland. *Min Mag* 2008; 72: 121–125.

[38] Matter JM, Broecker WS, Gislason SR, Gunnlaugsson E, Oelkers EH, Stute M, Sigurdardóttir H, Stefansson A, Alfredsson HA, Aradóttir ES, Axelsson G, Sigfusson B, Wolff-Boenisch D. The CarbFix pilot project − storing carbon dioxide in basalt. *Energy Procedia* 2011;4:5579–5585.

[39] Matter J, Stute M, Hall J, Mesfin K, Snæbjörnsdóttir SÓ, Gislason SR, Oelkers EH, Sigfusson B, Gunnarsson I, Aradottir ES, Alfredsson HA, Gunnlaugsson E, Broecker WS. Monitoring permanent CO_2 storage by in situ mineral carbonation using a reactive tracer technique. *Energy Procedia* 2014; this issue.

Characterisation and selection of the most prospective CO_2 storage sites in the Nordic region

norden
Top-level Research Iniative

nordiccs
Nordic CCS Competence Centre

K.L. Anthonsen[a], P. Aagaard[b], P. E. S. Bergmo[c], S. R. Gislason[d], A.E. Lothe[c], G. M. Mortensen[e], S. Ó. Snæbjörnsdóttir[d]

[a]Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark - [b]Department of Geosciences, University of Oslo, PO Box 1047 Blindern, NO-0316 Oslo, Norway
[c]SINTEF Petroleum Research, P.O. Box 4763 Sluppen, NO-7465 Trondheim, Norway - [d]Institute of Earth Sciences, University of Iceland, Sturlugata 7, IS-101 Reykjavík, Iceland
[e]Geological Survey of Sweden, Kiliansgatan 10, SE-223 50 Lund, Sweden

Introduction

An attempting to single out the most attractive storage areas among > 150 mapped CO_2 storage formations, units and traps in the Nordic region, has resulted in a characterisation and ranking procedure for saline aquifer. The ranking methodology is kept simple and divided into four main groups with the most important criteria for reservoir properties, seal properties, safety and data coverage. Based on the ranking 18 of the most prospective CO_2 storage sites have been selected. Furthermore, the critical factors determining if a basalt area is suitable for CO_2 injection is illustrated by an injection site on Iceland.

Table 1. Characterisation and ranking criteria for reservoir properties.

Reservoir properties	Preferred	Questionable	Hazardous	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 difficult 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	

Table 2. Characterisation and ranking criteria for seal properties.

Seal properties	Preferred	Questionable	Hazardous	Remarks
Thickness	>50m	20-50m	<20m	
Lithology of the primary seal	Homogeneous clay, mud or evaporites	Chalk	High content of silt or sand	
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	

Table 3. Characterisation and ranking criteria for safety properties.

Safety	Preferred	Questionable	Hazardous	Remarks
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	

Table 4. Characterisation and ranking criteria for data coverage.

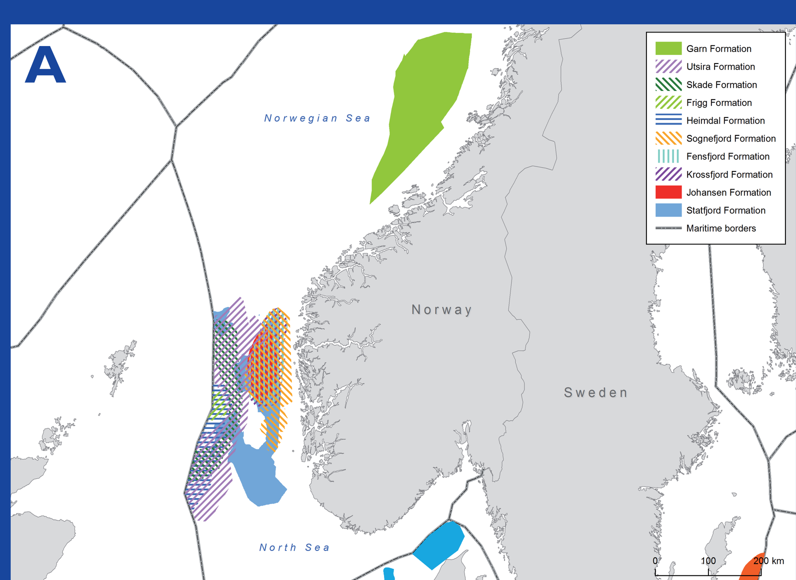
coverage	Preferred	Questionable	Hazardous	Remarks
Wells	Well though the actual trap or storage unit	Well(s) though equivalent geological formations	No well data	
Seismic survey	3D seismic	2D seismic younger than 1970	2D seismic older than 1970 or sparse data	

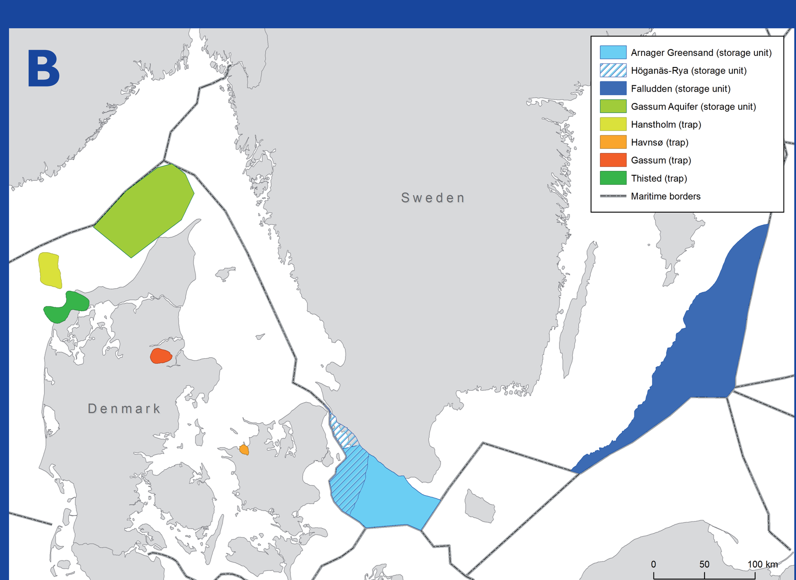
Characterisation and selection procedure for saline aquifer

The storage site characterisation criteria are to some extent based on experience from the EU GeoCapacity project and the Norwegian CO_2 storage atlas for the North Sea [1] [2].

The reservoir quality criteria are shown in table 1, the seal the criteria in table 2, the safety category in table 3 and the data coverage category in table 4. Each criterion is divided into three categories; *preferred*, *questionable* and *hazardous*, depending on a value or range of values. In the final ranking procedure the criteria values was transformed into a number from 1-3, where the highest number was given to values within the preferred category and the lowest to the hazardous category. The number of criteria are 15, implying that the most prospective sites will end up with a score of 45.

In Iceland an alternative method is being tested, the so called CarbFix method, where the CO_2 is dissolved during injection into porous basaltic rocks. Because the CO_2 is dissolved it is not buoyant and no caprock is required. The CO_2 charged water accelerates metal release and formation of solid carbonates for long term storage of CO_2 [7]. The main requirements are high porosity and availability of water, the CarbFix method requires substantial water supply; only about 5% of the injected mass is CO_2 [3,4,5].





Conclusions

There are many possible storage formations on the Norwegian continental shelf, each with a large number of storage units and traps. From the ranking and the storage capacity it seems that three of the best units for large scale industrial storage would be the Utsira Formation, the Sognefjord Formation and the Skade Formation. They all have storage capacity >10 000 Mt, shallow burial < 2 km, high porosity and permeability values, see figure A.

In Denmark 21 prospective CO_2 storage sites was ranked and the five best sites was selected. The most prospective site is the Gassum Aquifer, a storage unit offshore northern Denmark, followed by Havnsø, Gassum, Thisted and Hanstholm, which all four are anticline traps, see figure B.

Sweden has selected three prospective storage unites, the Falluden Sandstone, the Höganäs-Rya and the Arnager Greensand, all located in the Baltic region in the southern part of Sweden, see figure B.

Intensive hydrocarbon exploration in Norway has resulted in a large amount of high quality data as e.g. 3D seismic surveys. None of the Danish and Swedish sites has the possibility to reach a maximum ranking score, due to the fact that existing well data and seismic survey often are old and sparse, because only very limited hydrocarbon exploration has been taken place in Sweden and in Denmark outside the Danish Central Graben, since the 1970ties.

In Iceland an alternative method is being tested, the so called CarbFix method, where the CO_2 is dissolved in water during injection into porous basaltic rocks. In theory large amounts of CO_2 can be stored in porous basalts on Iceland, but access to water and a high porosity are the critical factors determining if a potential area is suitable for injection.

Acknowledgement

This publication has been produced with support from the NORDICCS Centre, performed under the Top-level Research Initiative CO_2 Capture and Storage program, and Nordic Innovation. The authors acknowledge the following partners for their contributions: Statoil, Gassco, Norcem, Reykjavik Energy, CO_2 Technology Centre Mongstad, Vattenfall and the Top-level Research Initiative (Project number 11029).

Denmark

Ranking criteria	Gassum Aquifer (unit)	Havnsø (trap)	Gassum (trap)	Thisted (trap)	Hanstholm (trap)
Ranking score (max. 45)	43	43	43	42	42
Storage Capacity (Mt)	3700*	926	630	11039	2753
Reservoir properties					
Primary reservoir fm.	Gassum	Gassum	Gassum	Skagerrak	Gassum
Depth, top (msl.)	1000	1500	1460	1166	1000
Porosity (mD)	23	22	25	15	20
Permeability (%)	210	500	300-2000	10-100	-
Heterogeneity (N/G)	0.50	0.67	0.32	0.47	0.40
Facies	Shore/delta	Shore/delta	Shore/delta	Alluvial fans	Shore/delta
Pore pressure**	hs	hs	hs	hs	hs
Net sand thickness (m)	50	100	53	449	230
Seal properties					
Primary seal fm.	Fjerritslev	Fjerritslev	Fjerritslev	Oddesund	Fjerritslev
Thickness (m)	>100	260	320	240	500
Lithology	claystone	mudstone	mudstone	claystone	claystone
Fault intensity	low	low	low	low	low
Lateral extend	continuous	continuous	continuous	continuous	continuous
Multiple seals	yes	yes	yes	yes	yes
Safety					
Seismicity	low	low	low	low	low
Groundwater contamination	no	no	no	no	no
Data coverage					
Wells	0	1	1	0	1
Seismic survey	2D	2D	2D	2D	2D

*Storage capacity based on modelling.
** Pore pressure: hs = hydrostatic pressure

Sweden

Ranking criteria	Faludden (unit)	Arnager Greensand (unit)	HöganäsRya (unit)
Ranking score (max. 45)	40	39	39
Storage Capacity (Mt)	745	521	543
Reservoir properties			
Primary reservoir fm.	Borgholm	Arnager Greensand	Höganäs, Rya
Depth, top (msl.)	830	946	976
Porosity (mD)	14	26	23
Permeability (%)	147	400	200
Heterogeneity (N/G)	0.90	0.80	0.51
Facies	shore/delta	marine	shore/delta
Pore pressure*	hs?	hs	hs
Net sand thickness (m)	41	31	92
Seal properties			
Primary seal fm.	Silurian marlstone	Höllviken	Höllviken
Thickness (m)	500	1000	1000
Lithology	marlstone	clayey limestone, chalk	clayey limestone, chalk
Fault intensity	low	moderate	moderate
Lateral extend	continuous	continuous	continuous
Multiple seals	yes	no	yes
Safety			
Seismicity	low	low	low
Groundwater contamination	no	unsure	unsure
Data coverage			
Wells	5	24	13
Seismic survey	2D	2D	no

* Pore pressure: hs = hydrostatic pressure

Norway, part I

Ranking criteria	Sognefjord Fm. North Sea	Krossfjord Fm. North Sea	Utsira Fm*. North Sea	Skade Fm.* North Sea [20]	Heimdal Fm.
Ranking score (max. 45)	45	45	44	44	44
Storage Capacity (Mt)	11465	3977	21300	7560	5112
Reservoir properties					
Age / primary reservoir fm.	Late Jurassic	Middle Jurassic	Late Middle Miocene to Upper Pliocene	Early Miocene	Paleocene
Depth, top (msl.)	1400-2000*	1650-2250*	450 to 1500 m. Central Viking Graben 500-750 m	850-1140	2000-2100
Porosity (%)	18-25**	25	21	35	25-30
Permeability (mD)	150-300**	400	1000	?	800-1000
Heterogeneity (N/G)	0.9	0.8	0.7	0.7	0.85
Facies	Wave dominated asymmetric deltaic coast	Shallowmarine, wave-to tide dominated shoreface deposits	Marine environment with reworked sheetsands	Marine turbidite deposits with thin claystone interbeds	Viking Graben: Submarine fans
Pore pressure***	<hs	<hs	<hs	<hs	<hs
Net sand thickness (m)	55-180**	65-135**	max. 350	120	50-295
Seal properties					
Primary seal fm.	Draupne Fm. in the Horda Platform	Heather Fm	Upper Nordland Gr.	Hordaland Gr.	Lista Fm.
Thickness (m)	Several hundred meters	1000m in graben	500-1500 m	100 m	50-several hundred meters
Lithology	claystone	Siltstone and silty claystone	claystone	claystone	shales
Fault intensity	low	low	low	low	medium
Lateral extend	continuous	continuous	continuous	widespread	widespread
Multiple seals	yes	yes	no	yes	yes
Safety					
Seismicity	low	low	low	low	low
Groundwater contamination	no	no	no	no	no
Data coverage					
Wells	Several, type well 31/2-1	Several, type well 31/2-1	Several, type well 16/1-1	Type well 24/12-1	Type well 24/4-1
Seismic survey	2D and 3D	2D and 3D	2D and 3D	2D and 3D	2D and 3D

* Storage capacity estimated for the entire formations including storage above 800 meter.
** Different fault blocks
*** Pore pressure: hs = hydrostatic pressure

Norway, part II

Ranking criteria	Fensfjord Fm. North Sea	Frigg Fm. North Sea	Garn Fm. Norwegian Sea	Johansen Fm.	Statfjord North Sea
Ranking score (max. 45)	44	44	43	42	42
Storage Capacity (Mt)	4100	1164	8003	861	1850
Reservoir properties					
Age primary reservoir fm.	Middle Jurassic	Early Eocene	Middle Jurassic	Lower Jurassic	Late Triassic-Early Jurassic
Depth, top (msl.)	1550-1850	1800	1200-1750	2000-2700	1800-2750
Porosity (%)	25	30	20-25	0.1	22
Permeability (mD)	150	1000	400-500	400	200
Heterogeneity (N/G)	0.8	0.85	0.2-0.5	0.8	0.5
Facies	Shallowmarine, wave- to tide dominated shoreface deposits	Submarine fans with stacked channels, lobe and interchannels sandstone interval with shales in between	Progradation of braided river systems and delta front	Wave dominated asymmetric deltaic coast	Transition from continental to shallow marine
Pore pressure*	Moderate	<hs	<hs	Some parts have overpressure	Parts are over pressured
Net sandthickness (m)	42-170	155, max thickness 300 in block 25/1	100-185	95-130	95-286
Seal properties					
Primary seal fm.	Heather Fm.	Hordaland Gr.	Viking Gr.	Drake Fmabove Cook Fm.	Dunlin Group
Thickness (m)	1000 m in graben	Several hundred metres	Approx.1000 m	80-100	Several hundred metres
Lithology	Siltstone and silty claystone	claystone	shales and mudstone	Claystone and shale	Shales and siltstones
Fault intensity	low	low	low	moderate	low
Lateral extend	wide	wide	wide	wide	wide
Multiple seals	yes	?	yes	yes	?
Safety					
Seismicity	low	low	low	low	low
Groundwater contamination	no	no	no	no	no
Data coverage					
Wells	Many, Type well 31/2-1	Many, Type well 25/1-1	Several, type well 6407/1-3	Several, type well 31/2-1	Several, type well 33/12-2
Seismic survey	2D and 3D	2D and 3D	2D Trøndelag Platform, 2D and 3D in Halten Terrace area	2D and 3D	2D and 3D

* Pore pressure: hs = hydrostatic pressure

References

[1] Vangklide-Pedersen T, editor. EU GeoCapacity – Assessing European Capacity for Geological Storage of Carbon Dioxide. GeoCapacity Final Report. EU Project no. SES6-518318, 2009.
[2] Halland EK, Gjeldvik IT, Johansen WT, Magnus C, Meling IM, Pedersen S, Riis F, Solbakk T, Tappel I. CO_2 Storage Atlas Norwegian North Sea. Norwegian Petroleum directorate; 2011.
[3] Gislason SR, Oelkers EH. Carbon storage in Basalt. Science 2014;344: 373-374.
[4] Snæbjörnsdóttir SO, Wiese F, Fridriksson T, Armannsson H, Einarsson GM, Gislason SR. CO_2 storage potential of basaltic rocks in Iceland and the oceanic ridges. 2014; GHGT-12.
[5] Gislason SR, Wolff-Boenisch D, Stefansson A, Oelkers EH, Gunnlaugsson E, Sigurdardottir H, Sigfusson B, Broecker WS, Matter JS, Stute M, Axelsson G, Fridriksson T. Mineral sequestration of carbon dioxide in basalt: a preinjection overview of the CarbFix project. Int J Greenh Gas Con 2010;4:537–545.