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Quality ranking of the best CO_2 storage aquifers in the Nordic countries

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Abstract

Ranking of CO_2 storage sites in the Nordic countries has previously been reported from the NORDICCS project. The ranking was based on geological characteristics of reservoir and seal, data coverage and safety evaluation of the storage complex. Estimated storage capacity were included but not taken into account in the ranking except if two storage sites were equally ranked. This paper presents a method for evaluating knowledge gaps for a storage site based on characterisation and assessment criteria presented in the EU CCS Directive, and a new updated ranking is presented where knowledge gaps are taken into account.

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Keywords: CO_2 storage; Nordic countries; North Sea; Baltic Sea; knowledge gaps; storage site ranking

1. Introduction

Mapping and characterisation of deep saline aquifers for CO_2 storage in (Northern) Europe has been subject to several research programs from 1993 to present. The most comprehensive are the JOULE-II project (1993-1995) [1], the GESTCO project (1999-2003) [2], the EU GeoCapacity project (2006-2009) [3] and the Norwegian Petroleum Directorate's (NPD) CO_2 storage atlas for the Norwegian Continental Shelf published in 2014 [4]. Besides characterising the geology of the storage formation and seal, estimates of storage capacity for the mapped storage units or structural traps are given.

In the Nordic countries (Denmark, Sweden, Finland, Iceland and Norway), screening for CO_2 storage possibilities has primarily been performed off-shore in the Norwegian and the Danish parts of the North Sea, in the Norwegian Sea and in the Barents Sea. In addition, several on-shore structures have been mapped in Denmark and the Swedish Geological Survey (SGU) has mapped potential CO_2 storage aquifers on- and off-shore south-west Scania together with the Swedish part of the southeast Baltic Sea (see Figure 1). Finland and Iceland have no sedimentary rocks suitable for large-scale CO_2 storage, although in

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Iceland the possibility for mineral trapping of CO_2 in basalt formations has been studied [5, 6] and first order estimates of storage capacity have been made [7].

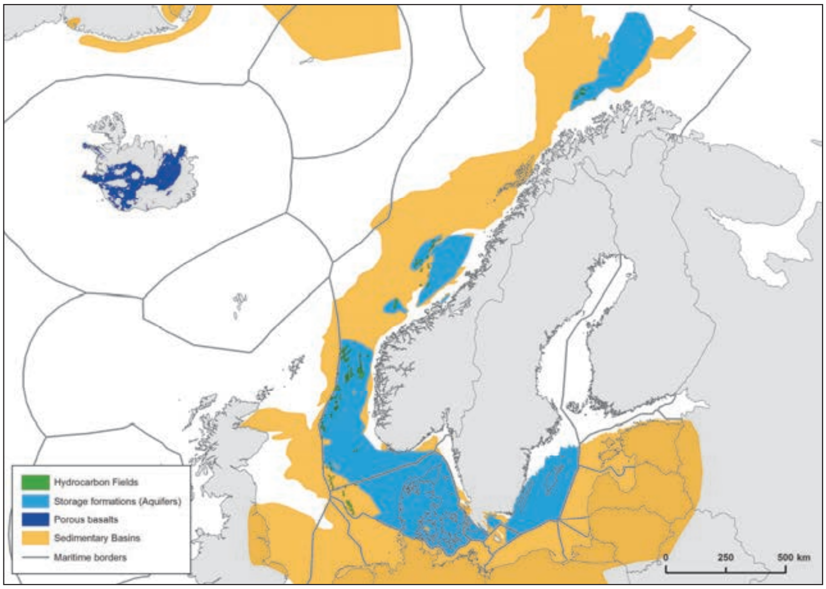

Figure 1 Overview of sedimentary basins, hydrocarbon fields and storage formations and aquifers in the Nordic countries.

The Norwegian-Danish basin has up to 9 kilometers thick Late Paleozoic to Cenozoic age sedimentary successions. Several sedimentary formations and groups are considered suitable for CO_2 storage. These are; the Bunter Sandstone and Skagerrak Formations (Triassic), the Gassum Formation (Upper Triassic–Lower Jurassic), the Haldager Sand Formation (Middle Jurassic) and the Frederikshavn Formation (Upper Jurassic–Lower Cretaceous). In the onshore or nearshore Danish areas, the burial depth and reservoir properties makes Gassum Formation the most attractive storage option [8]. In the southern and western regions the Bunter Sandstone Formation and the Skagerrak Formation are considered the best target for CO_2 storage. Due to post depositional flow of Permian salt which formed large domal structures and diapirs, more than 100 onshore and offshore geological structures have been mapped. Further detailed studies are necessary to determine the potential of these structures for CO_2 storage in Denmark. An additional screening for CO_2 storage sites in the southern part of Denmark has been performed, identifying 13 structures potentially suitable for CO_2 storage, 3 in the Southern North Sea and 9 in the West Baltic Sea within the Danish sector and one within the German sector [9].

Eight potential storage units in deep saline aquifers have been identified in southern Sweden [10, 11]. In the southeast Baltic Sea, two stratigraphic intervals with three potential storage units were identified. These are the Viklau and När aquifers in the Early Cambrian File Haidar Formation and the Faludden aquifer in the Middle Cambrian Borgholm Formation. In south-west Scania, five stratigraphic intervals with five potential storage units have been identified. These are; the Bunter Sandstone aquifer in the Early Triassic Ljunghusen Sandstone and Hammar Formation, the Höganäs-Rya aquifer in the Late Triassic-Early Jurassic Höganäs Formation and Rya Formation, two Lower Cretaceous sand units (Unit A and B) in an undefined stratigraphic interval and finally, the Arnager Greensand aquifer in the Early Albian–Cenomanian Arnager Greensand Formation. Based on the current knowledge of reservoir properties, the Faludden, Arnager Greensand and Höganäs-Rya aquifers represent the most promising storage units [12]. A more detailed description of these formations can be found in [13].

Off-shore Norway, all the way from the Barents Sea to the southern Norwegian North Sea large aquifers suitable for CO_2 storage can be found in Late-Triassic and Jurassic deposits, in early Paleogene deposits and in Neogene deposits. In the southern Barents Sea the main storage options can be found in the Hammerfest Basin and the Bjarmeland Platform (for details see the NPD Storage Atlas [4] or the GESTCO report [2]). Potential storage aquifers in the Norwegian Sea are within the Late Jurassic Rogn Formation, the Late Cretaceous Lysing Formation, the Middle and Early Jurassic Garn and Ile formations and the Early Jurassic - Late Triassic Tilje and Åre formations. In the Norwegian North Sea, the aquifers with the largest theoretical capacities are in the Tertiary Utsira, Skade, Frigg, Heimdal and Ty formations, the Cretaceous Tor Formation, and the Jurassic Brent Group and Statfjord Formation. Triassic rocks have very large volumes, but are possibly not well suited for the storage of CO_2, due to low permeabilities. Along the coast, the most promising aquifers are in the Fiskebank, Sandnes- Bryne- Gassum- and Sognefjord-Fensfjord-Krossfjord- formations.

For the Nordic countries, more than 80 potential CO_2 storage sites in aquifer units and structures have been mapped and characterised based on data with variable quality and level of detail. A ranking of these storage sites with emphasis on geological features has been performed in the NORDICCS project [12] and is described below.

1.1. Storage site ranking in the NORDICCS project

Within the NORDICCS project a method for screening and ranking the CO_2 storage sites has been proposed based on data availability, the geological properties of the storage complexes and potential risks associated with a CO_2 storage operation. The ranking follows a similar approach as in the Norwegian Storage Atlas from NPD with check lists for reservoir and seal properties, data coverage and potential risks. Storage capacity has not been used in the ranking except where two storage sites have the same ranking score. The final ranking criteria consisted of six reservoir properties, five seal properties, two safety criteria, and two criteria related to data coverage. In the ranking procedure, the criteria evaluations were transformed into a number (1, 2 or 3), where the highest value corresponded to the preferred property characteristics. Maximum overall score for the ranking is 45. Details on the ranking methodology and results from the ranking are described in [12]. From the ranking 3 Swedish, 5 Danish and 10 Norwegian CO_2 storage sites were selected as best options from each nation. Table 1 lists estimated storage capacity, results of the ranking of reservoir properties, seal properties, safety and data coverage and the total ranking score.

Table 1 Main results from the ranking of CO_2 storage sites in the Nordic region with estimated storage capacity from [12].

Storage sites	Theoretical capacity	Reservoir properties	Seal properties	Safety	Data coverage	Total ranking
Formations/units and structures (s)	Mt	Score (max 18)	Score (max 15)	Score (max 6)	Score (max 6)	Score (max 45)
Sognefjord Fm.	11465	18	15	6	6	45
Krossfjord Fm.	3977	18	15	6	6	45
Utsira Fm.	21300	18	14	6	6	44
Skade Fm.	7560	18	14	6	6	44
Heimdal Fm.	5112	18	14	6	6	44
Fensfjord Fm.	4100	17	15	6	6	44
Frigg Fm.	1164	18	14	6	6	44
Havnsø (s)	926	17	15	6	4	42
Gassum (s)	630	17	15	6	4	42
Hanstholm (s)	2753	17	15	6	4	42
Johansen Fm.	861	15	15	6	6	42
Statfjord Gp.	1850	15	15	6	6	42
Gassum Aquifer	3700	16	15	6	4	41
Garn Fm.	8003	17	15	6	3	41
Thisted (s)	11039	14	15	6	5	40
Faludden	745	15	14	6	5	40
Arnager Greensand	521	17	12	5	5	39
Höganäs-Rya	543	17	13	5	4	39

The ranking resulted in a top score for several of the evaluated storage sites and good scores for the rest. However, there are still large uncertainties in many of the evaluated parameters and more data and knowledge is required before any of the sites are ready for CO_2 injection. In order to give an evaluation of the parameters on which the ranking is based on and the readiness level of the high ranked storage sites a method for estimating knowledge gaps for a CO_2 storage site is proposed in this paper.

2. Methodology

Before a CO_2 storage site can obtain permission and start to operate, a full characterisation and assessment of the storage complex will be required. Annex I in the EU CCS Directive (EU Guidance Document 2 for implementing the EU Directive [14]) proposes a number of criteria required for characterisation and assessment of potential storage complexes. Based on the suggestions in the EU Guidance Document, a simplified and practical scoring/ranking scheme is constructed to map the knowledge gaps in a potential CO_2 storage site. The EU Guidance Document sets up three main characterisation and assessment steps. This includes; collection of data sufficient enough to construct a 3D static geological model of the site and the surrounding storage complex, the construction of such a model, modelling to assess dynamic behaviour of the site and complex due to CO_2 injection, a sensitivity analysis of the models and a risk assessment with regard to integrity and safety of the storage site and complex. Based on this a simplified and practical scoring/ranking scheme has been constructed following five required characterisation/assessment steps:

- Collection of geological data.
- Construction of a 3D static geological model of site and complex.
- Perform dynamic modelling.
- Perform parameter sensitivity analysis.
- Perform risk assessment.

In order to compare different storage complexes and identify missing data or assessment, the scoring/ranking scheme shown in Table 2 is proposed. Each type of data, input to models, simulations and assessments should be given a score corresponding to data availability/quality and quality of modelling and assessment. Top score is assigned the value 0, while missing or poor quality data, characterisation or assessment, are given negative values (-1, -2, -3). A storage complex ready for CO_2 storage gets a total score of 0. The lowest score possible is -87 and a low score represents a poorly characterised storage site based on little or low quality data.

Table 2 Knowledge gap score card for characterisation and assessment of potential storage complex and surrounding area based on Annex I of EU CCS-Directive. Each parameter in green cells should be given a score between 0 (high) and -3 (low).

Data Collection	3D Static Geological Model	Dynamic Modelling	Sensitivity Characterisation	Risk Assessment
Sufficient to construct 3D static geological model for site and complex	Characterisation of Storage Site and Complex	Assess Dynamic behaviour of site and Complex due to CO_2 injection	Assess sensitivity of the assessment to changes in assumptions	Assessment of safety and integrity of Site and Complex
Geology and geophysics	Geological structure mapping	Injection rates & CO_2 stream properties	Alter parameter models to determine sensitivity	Hazards characterisation
Hydrogeology	Geomechanical, geochemical, and flow properties of overburden and surrounding formations	Coupled process modelling		Exposure Assessment
Reservoir Parameters	Fracture system characterisation	Reactive processes		Effects assessment
Geochemistry	Areal and vertical extent of complex	Reservoir simulations		Risk characterisation
Geomechanics	Pore space volume	Short & long term simulations		
Seismicity	Baseline fluid distribution			
Natural and man-made leakage pathways	Fault and seal integrity			
Field studies				
Population Distribution				
Natural Resources				
Interactions with other activities				
Proximity to potential sources, supply volume, and transport network				

The EU CCS Directive does not state the required quality of data or level of detail for each step of the characterisation and assessment except that it should be according to best practice at the time of assessment. This leaves some room for interpretation and the result of the knowledge gap evaluation could change based on what is assumed sufficient concerning data and modelling. However, summarising the score for each of the five main required steps will give a good indication of the status in the process of qualifying each storage site, identify gaps in knowledge and illustrate differences between storage sites.

3. Results

SGU has evaluated knowledge gaps in the selected Swedish storage sites, Geological Survey of Denmark and Greenland has evaluated the Danish storage sites, while the Norwegian sites were evaluated by University of Oslo and SINTEF. The top ranked Swedish and Danish aquifers and a selection of five of the top ranked Norwegian aquifers were evaluated. Figure 2 show the location and outline of the evaluated aquifers. To identify critical knowledge gaps and compare the potential storage candidates, the scores from the five main steps in Table 2 are summarised for each country in the next sub-sections and Table 3 to Table 5.

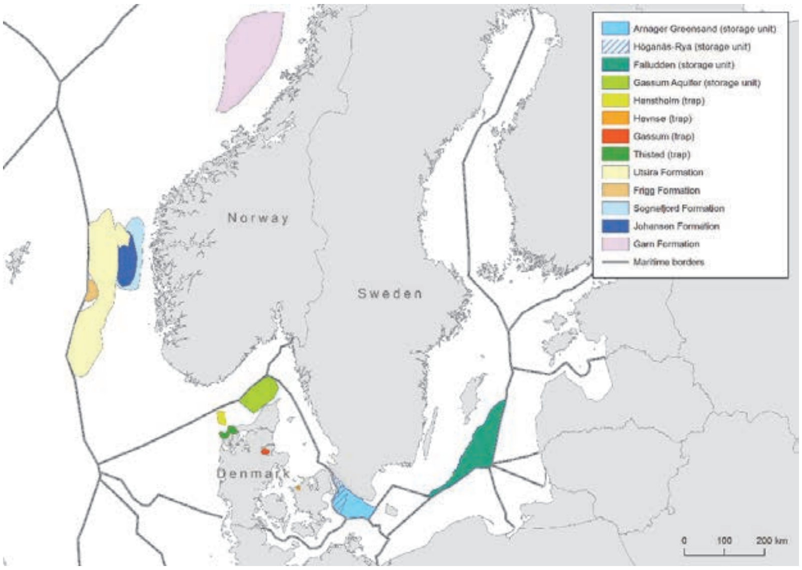

Figure 2 Location and outline of the aquifers subject to knowledge gap evaluation.

3.1. Sweden

The Swedish storage candidate with least knowledge gaps identified is Faludden. No sensitivity or risk assessment has been performed for any of the Swedish storage sites. The main reason for the many knowledge gaps of Faludden is, however, lack of good quality geological data. These data are needed both for constructing the static 3D geological model and to refine the dynamic simulations in [13] further. The Arnager Greensand has more or less the same knowledge gaps as Faludden but has less data. Only very limited seismic data exist for the third candidate, the Höganäs-Rya sequence, and thus this site need more exploration activities before any adequate characterisation and assessment can be done. In general, modern data for the three storage sites are very sparse as the exploration activities in these areas took place during the 1970–80s. Hence, seismic data are in 2D format and mostly from the Faludden and Arnager Greensand areas. Only a few deep wells were drilled and mostly onshore.

Table 3 Knowledge gaps for selected potential Swedish CO_2 storage complexes

Sweden	*Data collection*	*3D static model*	*Dynamic modelling*	*Sensitivity char*	*Risk assessment*	*Total score*
Faludden	-20	-15	-10	-3	-12	-60
Arnager Greensand	-24	-15	-10	-3	-12	-64
Höganäs-Rya	-29	-17	-15	-3	-12	-76

3.2. Denmark

The three best Danish storage sites, with respect to knowledge gaps, are the Hanstholm structure, the Gassum aquifer, and the Gassum structure. Although they are missing sensitivity and risk assessment (as for all Danish sites), they have a reasonable amount of geological data, 3D geological models and dynamic simulations of CO_2 injection and storage have been performed

[15]. However, the geological input is from old exploration wells, traditional 2D seismic surveys, and older log practice. Therefore, retrieving more high quality geological data for input to the models should be prioritised. Especially the Havnsø and the Thisted structures have most knowledge gaps to be filled.

Table 4 Knowledge gaps for selected potential Danish CO_2 storage complexes

Denmark	*Data collection*	*3D static model*	*Dynamic modelling*	*Sensitivity char*	*Risk assessment*	*Total score*
Hanstholm structure	-16	-7	-9	-3	-12	-47
Gassum aquifer	-16	-10	-7	-3	-12	-48
Gassum structure	-17	-8	-9	-3	-12	-49
Havnsø structure	-20	-13	-9	-3	-12	-57
Thisted structure	-16	-16	-15	-3	-12	-62

3.3. Norway

The three best Norwegian storage sites, when it comes to knowledge gaps, are the Frigg Formation including the Frigg depleted gas field, the Utsira aquifer, and the Johansen aquifer. Having produced gas for a number of years, the Frigg area has just a few minor knowledge gaps including expected geo-mechanical and structural response during injection. The risk assessment can also be improved. The Utsira aquifer and its surroundings is presently the storage complex for the Sleipner CO_2 injection, so it has been well monitored and studied [16, 17]. However, if the Utsira aquifer were to be targeted for larger scale storage of CO_2, future studies should focus on reservoir management in order to increase the storage efficiency factor and for parts of Utsira more data should be collected. The Johansen aquifer will primarily need a representative drilling to verify the geological model and the dynamic simulations, but it is otherwise well covered by 3D seismic data and the structural setting is assessed during production from overlying hydrocarbon reservoirs (Troll Field) [18, 19]. The Sognefjord Delta complex is also a good storage candidate, but it needs more dynamic modelling and more extensive risk assessment. The Garn aquifer offshore Mid-Norway is a promising sloping aquifer, but it needs more work (improved geological data, an updated static 3D geological model, dynamic modelling and risk assessment) before it can be qualified for CO_2 storage.

Table 5 Knowledge gaps for a selection of the highest ranked Norwegian CO_2 storage complexes

Norway	*Data collection*	*3D static model*	*Dynamic modelling*	*Sensitivity char*	*Risk assessment*	*Total score*
Frigg structure	-6	-3	-2	-1	-5	-17
Utsira aquifer	-9	-5	-2	-1	-5	-22
Johansen aquifer	-10	-6	-3	-1	-6	-26
Sognefjord Delta Complex	-7	-4	-7	-2	-8	-28
Garn aquifer	-17	-8	-7	-1	-10	-43

4. Discussion

The selected Norwegian CO_2 storage complexes have less knowledge gaps to be filled compared to Danish and Swedish candidates due to extensive petroleum exploration and production. The Norwegian continental shelf generally has good regional data coverage and several site-specific studies have been performed, which constitute a firm base for planning offshore carbon storage. Among the Norwegian sites, Garn Formation has the lowest score due to less petroleum activity in the region where it is located. The top Danish storage sites will improve their score considerably if more and better geological data can be collected or made available and subsequently implemented in models and simulations. Additional geological data can be acquired either from reinterpretation of existing geological data or from new seismic surveys and drilling of new exploration wells. All the top Danish sites are promising candidates for CO_2 storage. The Swedish sites need to collect considerably more new data. However, studies on old cores stored at SGU could increase the knowledge of physical parameters for the seal and reservoir rocks, so that further analyses can be performed. New processing of old 2D seismic data may also provide better insight into the southeast Baltic Sea and southwest Scania.

The results from the ranking and knowledge gap evaluation can be combined to see which of the aquifers or structures are presently most suitable and best characterised for CO_2 storage. Normalising the total ranking score for each site against maximum possible score show a ranking between 86 and 98 %. These high-ranking scores reflect that the evaluated sites have been chosen because of their good characteristics. Normalising the total knowledge gap score against maximum (negative) knowledge gap show a much larger spread, with knowledge gap values between 19 and 88 %. These values reflects the variation in data, characterisation and assessment of the sites. In order to combine the ranking and knowledge gap evaluation, a readiness level is defined as the complement to knowledge gap (i.e. the knowledge or 100% - knowledge gap %). Using the readiness level to adjust the ranking score a new ranking can be presented that takes into account the knowledge of the storage sites. That is, if for example the readiness level is 80%, the new ranking value will be reduced to 80 % of the old ranking value. Table 6 lists normalised ranking (calculated from Table 1), normalised knowledge gap, readiness level and what we have denoted quality ranking, which take the knowledge into account. Observe that the new ranking values now have a larger spread and that the ranking order has changed compared to the previous ranking. The new ranking also makes it easier to discriminate between the ranked storage sites.

Table 6 Qualified ranking of selected CO_2 storage sites based on previous ranking and knowledge gap evaluation.

Storage sites	Theoretical capacity	Ranking score	Knowledge gap	Readiness level	Quality ranking
Formations/units and structures (s)	Mt	Score %	Score %	%	%
Frigg Fm.	1164	97.8	19.5	80.5	78.7
Utsira Fm.	21300	97.8	25.3	74.7	73.1
Sognefjord Fm.	11465	100.0	32.2	67.8	67.8
Johansen Fm.	861	93.3	29.9	70.1	65.4
Garn Fm.	8003	91.1	49.4	50.6	46.1
Hanstholm (s)	2753	93.3	54.0	46.0	42.9
Gassum Aquifer	3700	91.1	55.2	44.8	40.8
Gassum (s)	630	93.3	56.3	43.7	40.8
Havnsø (s)	926	93.3	65.5	34.5	32.2
Faludden	745	88.9	69.0	31.0	27.6
Thisted (s)	11039	88.9	71.3	28.7	25.5
Arnager Greensand	521	86.7	73.6	26.4	22.9
Höganäs-Rya	543	86.7	87.4	12.6	11.0

5. Conclusions

Ranking of the mapped aquifers in [12] was performed using checklists for reservoir and seal properties, data coverage and potential risks. The ranking resulted in a list of 18 storage sites characterised as the best potential CO_2 storage options in deep saline aquifers. The total estimated theoretical storage capacity for the top ranked sites is around 86 Gt, which is sufficient to store the current annual CO_2 emissions from Nordic industry sources for more than 500 years.

A method for evaluating knowledge gaps for the storage sites has been presented based on characterisation and assessment criteria presented in the EU CCS Directive. In addition a new ranking is presented where knowledge gaps are taken into account. The evaluation of knowledge gaps and the new ranking show that:

- Storage sites in or close to active petroleum regions have more high quality data available and hence less knowledge gaps.
- The Norwegian storage sites are all ranked higher than the Danish storage sites, which again is ranked higher than the Swedish storage sites.
- For Danish and Swedish storage sites, more and better quality data is required for closing some of the knowledge gaps.
- The new ranking discriminates better between the evaluated storage sites

The new ranking and knowledge gap evaluations can be used for guidance in selection of aquifers for CO_2 storage and in defining the next steps to be taken for a site to qualify for carbon storage. Many promising Nordic CO2 storage sites have been identified, and the knowledge gaps should not impede their realization but rather guide to the required steps in the characterisation and assessment process. In addition, it should be noted that the ranking presented here does not take into account location or cost, which will be of importance when selecting a storage site for CO_2.

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