

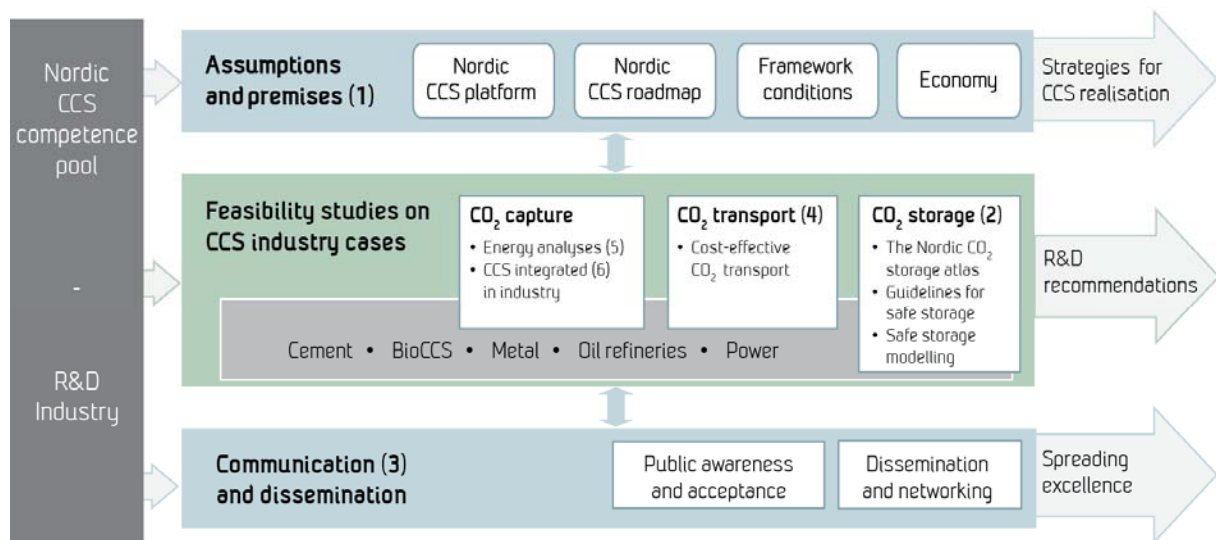
## CO<sub>2</sub> storage potential in the Nordic region

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**NORDICCS concept:**



**Partners:**



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# Summary

European research projects mapping and assessing geological storage capacity have indicated a large potential in the Nordic region accounting for 59% of the total mapped European storage capacity of 358 Gt. These studies, however did only include storage capacities from Denmark and Norway and thus failed to review the capacities from Finland, Iceland and Sweden. A new Nordic expertise centre for CCS named NORDICCS will in the coming years attempt to improve the mapping of CO<sub>2</sub> storage sites and storage capacity estimations within the Nordic region.

Preliminary results indicate that large sedimentary basins in the Baltic Sea, the Skagerrak area, the North Sea and the area offshore mid-Norway will be able to store large amounts of CO<sub>2</sub> in deep saline aquifers and depleted oil and gas fields. In addition early research results from Iceland indicate a large potential for in-situ mineralisation of CO<sub>2</sub> in porous basalts, and a minor potential for mineral trapping in ultramafic rocks in Finland. Data from all five Nordic countries underlines results of the previous European projects; the total updated assessed geological storage potential in selected areas is 76 Gt for in saline aquifers, 29 Gt for hydrocarbon fields and between 62-333 Gt for areas with potential for mineral trapping.

**Keywords** CCS, storage capacity, Nordic region, saline aquifers, hydrocarbon fields, mineral trapping

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## 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.*

*The views presented in this report solely represent those of the authors and do not necessarily reflect those of other members in the NORDICCS consortia, NORDEN, The Top Level Research Initiative or Nordic Innovation.*

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## CO<sub>2</sub> storage potential in the Nordic region

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European mapping of geological CO<sub>2</sub> storage sites and estimations of CO<sub>2</sub> storage capacities have indicated a large potential in the Nordic region. Extensive sedimentary basins in the Baltic Sea, the Skagerrak area, the North Sea and the area offshore mid-Norway have been assessed to be able to store large amounts of CO<sub>2</sub> in deep saline aquifers and depleted oil and gas fields.

According to the most recent European capacity estimations from the EU GeoCapacity project (2009), the total European storage capacity is calculated to be 358 Giga tonnes (Gt), with 114 Gt onshore and 244 Gt offshore, comprising capacity estimations for hydrocarbon reservoirs and aquifers. The Nordic region total capacity is estimated 212 Gt, with 209 Gt related to offshore and 3 Gt to onshore storage sites. Storage in depleted hydrocarbon reservoirs accounts for 13.5 Gt of the total offshore capacity in the Nordic region. These capacity estimations only include data from Denmark and Norway since remaining Nordic countries, Finland, Iceland and Sweden, did not participate in the EU GeoCapacity project. The fact that the Nordic region has 59% of the currently mapped total storage capacity in Europe, and 86% of all offshore capacity, renders it the most prospective region in Europe for geological storage of CO<sub>2</sub>.

Inventories and analysis of European stationary CO<sub>2</sub> emission sources with an emission level above 100,000 tonnes CO<sub>2</sub>/year prove an annual emission of 1.9 Gt; 1.3 Gt of this CO<sub>2</sub> is emitted in the northern part of Europe, which thus constitutes the main catchment area for CO<sub>2</sub> storage in the Baltic Sea, the North Sea, and offshore mid-Norway.

Apart from large storage potential in deep saline aquifers and hydrocarbon fields, research projects regarding mineral trapping of CO<sub>2</sub> in basalts are taking place in Iceland. This research area is in an initial stage, however early results indicate a large potential for *in-situ* mineralisation of CO<sub>2</sub> in porous basalts.

To enhance awareness of the unique opportunities for geological CO<sub>2</sub> storage in the Nordic region, a new expertise centre for CCS was established in 2011. During the next 4 years, this centre, called NORDICCS, will work towards the realisation of CCS within the Nordic countries. One of the tasks is to create an updated inventory of potential geological storage sites including all of the Nordic countries, and to improve the accuracy of the capacity estimations. Further characterisation and screening of the storage sites will be performed in order to identify the most prospective storage sites and create a joint atlas for CO<sub>2</sub> storage in the Nordic region.

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## CO<sub>2</sub> storage potential in the Nordic region

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### Abstract

European research projects mapping and assessing geological storage capacity have indicated a large potential in the Nordic region accounting for 59% of the total mapped European storage capacity of 358 Gt. These studies, however did only include storage capacities from Denmark and Norway and thus failed to review the capacities from Finland, Iceland and Sweden. A new Nordic expertise centre for CCS named NORDICCS will in the coming years attempt to improve the mapping of CO<sub>2</sub> storage sites and storage capacity estimations within the Nordic region. Preliminary results indicate that large sedimentary basins in the Baltic Sea, the Skagerrak area, the North Sea and the area offshore mid-Norway will be able to store large amounts of CO<sub>2</sub> in deep saline aquifers and depleted oil and gas fields. In addition early research results from Iceland indicate a large potential for in-situ mineralisation of CO<sub>2</sub> in porous basalts, and a minor potential for mineral trapping in ultramafic rocks in Finland. Data from all five Nordic countries underlines results of the previous European projects; the total updated assessed geological storage potential in selected areas is 76 Gt for in saline aquifers, 29 Gt for hydrocarbon fields and between 62–333 Gt for areas with potential for mineral trapping.

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*Keywords:* CO<sub>2</sub> storage; Nordic region; storage capacity; NORDICCS.

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## Introduction

Previous mapping projects of geological CO<sub>2</sub> storage sites and estimations of CO<sub>2</sub> storage capacities in Europe have indicated a large potential in the Nordic region. The variable geological environment in the Nordic region from old basement rocks beneath Finland and most of Sweden, across the Caledonian mountains on-shore Norway, the large sedimentary basins in the sub-surface of Denmark and off-shore Norway and Sweden to the active mid Atlantic rift zone in Iceland is reflected in each countries very different CO<sub>2</sub> storage potential. The largest storage potential is found in extensive sedimentary basins in the Baltic Sea, the Skagerrak area, the North Sea and the area offshore mid-Norway (Fig. 1).



Fig. 1. The Nordic countries and sedimentary basins in the Nordic region.

According to the most recent European capacity estimations from the EU GeoCapacity project (2009), the total European storage capacity is calculated to be 358 Giga tons (Gt), with 114 Gt onshore and 244 Gt offshore, comprising capacity estimations for hydrocarbon reservoirs and aquifers (Vangkilde-Pedersen [1]). The Nordic region total capacity is estimated 212 Gt, with 209 Gt related to offshore and 3 Gt to onshore storage sites. Storage in depleted hydrocarbon reservoirs accounts for 13.5 Gt of the total offshore capacity in the Nordic region. These capacity estimations only include data from Denmark and Norway since remaining Nordic countries, Finland, Iceland and Sweden, did not participate in the EU GeoCapacity project. The results of EU GeoCapacity indicates that the Nordic region has 59% of the currently mapped total storage capacity in Europe, and 86% of all offshore capacity, renders it the most prospective region in Europe for geological storage of CO<sub>2</sub>.

Inventories and analysis of European stationary CO<sub>2</sub> emission sources with an emission level above 100,000 tonnes CO<sub>2</sub>/year prove an annual emission of 1.9 Gt; 1.3 Gt of this CO<sub>2</sub> is emitted in the northern

part of Europe, forming a potential catchment area for CO<sub>2</sub> storage in the Baltic Sea, the North Sea, and offshore mid-Norway (Fig. 2).

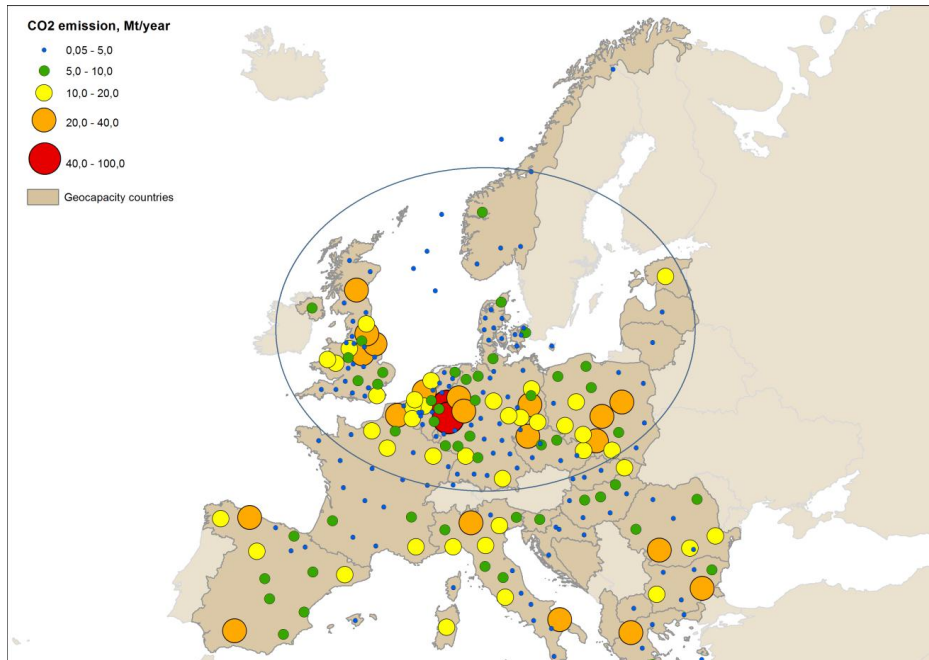


Fig. 2. The yearly CO<sub>2</sub> emission from regionally clustered large stationary emission sources mapped in the EU GeoCapacity project. The total yearly CO<sub>2</sub> emission within the circle is ca. 1.3 Gt.

The succeeding overview of the up to date knowledge on geological storage in the Nordic region will include assessment of storage capacities from all five Nordic countries improving previous European research projects conclusions.

## 2. Nordic CO<sub>2</sub> storage potential

A summary of the research methodology and preliminary storage capacities in the Nordic countries are given below.

### 2.1 Denmark

Research in Denmark has focused on sandstone formations within a depth range of 800 – 3000 m, i.e. between the depth required for CO<sub>2</sub> to become a dense fluid and the depth below which reservoir quality typically deteriorates. To be considered a potential candidate the sediment layer must consist of mainly sandstone with porosity between 15 and 35%. The coarser-grained sandstones are preferable since they have higher injectivity. The formations with the most promising potential for CO<sub>2</sub> storage in Denmark are the Bunter Sandstone Formation, the Skagerrak Formation, the Gassum Formation and the Haldager Sand Formation (Fig. 3).

The Triassic Bunter Sandstone and Skagerrak Formations are present throughout the Danish area, but thin and locally absent across the Ringkøbing–Fyn High. The large net sand thicknesses of the Bunter Sandstone/Skagerrak Formations, provides huge storage volumes although with variable injectivity. The Upper Triassic–Lower Jurassic Gassum Formation is present in the Norwegian-Danish Basin, on the Ringkøbing–Fyn High and in the south eastern part of Denmark. It demonstrates a remarkable thickness of more than 300 m in the Sorgenfrei-Tornquist Zone. The burial depth versus reservoir properties makes the Gassum Formation the most attractive storage option for CO<sub>2</sub> storage (Larsen et al. [2]). The Middle Jurassic Haldager Sand Formation is present in the central and north eastern part of the Norwegian-Danish Basin, in the Sorgenfrei-Tornquist Zone and on the Skagerrak-Kattegat Platform (Fig. 3). The thickness of the formation shows large variations between a few metres and up to 200 m. A marked thinning is seen southwest and northeast of the Sorgenfrei-Tornquist Zone related to the Middle Jurassic uplift event (Nielsen [3]). Geological formations in Denmark with sealing properties are lacustrine and marine mudrocks with a large clay content, evaporites and carbonates. The most important sealing rock type in the Danish area is marine mudstones, which is present at several stratigraphic levels.

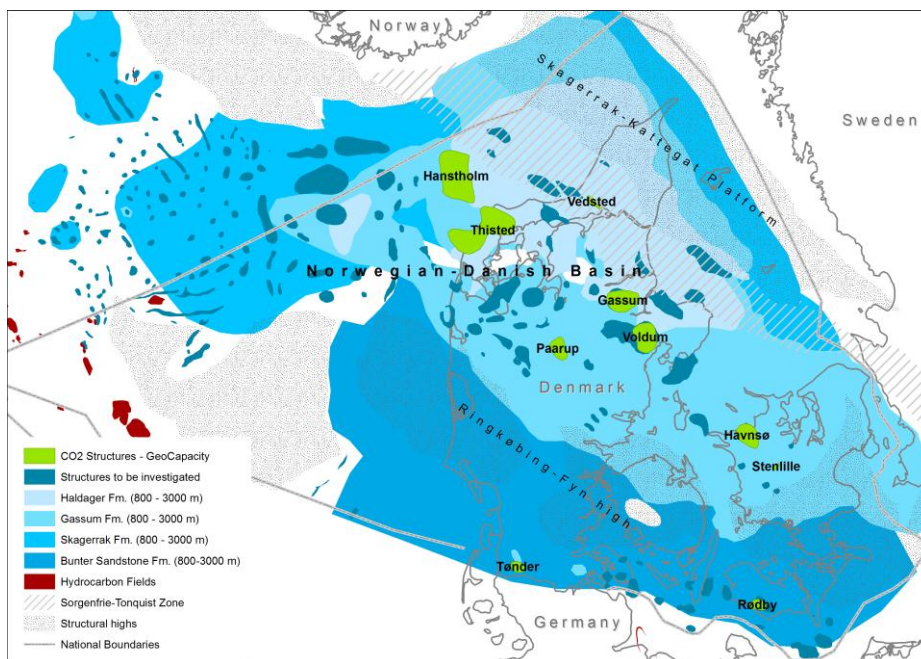


Fig. 3. The distribution of Danish geological formations in the depth interval 800 – 3000 meters which is considered the most optimal for CO<sub>2</sub> injection. Geological structures related to salt movement form domes and diapirs.

In order to gain public and political acceptance, structural traps are considered essential, when considering storage in Denmark. Storing CO<sub>2</sub> in defined geological structures in the subsurface allows continuous monitoring of the injected CO<sub>2</sub> and eventually meets the demand for future recovery of all or parts of the injected gas (Larsen et al. [2]). The majority of the individual structures with potential for CO<sub>2</sub> storage are related to movement of the Zechstein salt (Fig. 3). The salt movement has caused formation of a wide range of structures from gentle domes to diapirs. The dome structures most often



form anticlines with 4-way closures and lack of significant faulting. The diapir structures on the contrary breaks through the overlaying deposits and faults accompany the salt structures.

In the EU GeoCapacity project a number of geological structures were selected and evaluated with regards to the possibility for CO<sub>2</sub> storage (Fig. 3) (Vangkilde-Pedersen [1]). The selected structures are mainly identified on the basis of old seismic data, and in case of future utilization, the structures will need further investigations and qualification based on new seismic data and wells. The data suggest that the structural traps alone may provide storage for at least 16 Gt CO<sub>2</sub> assuming that the effective storage capacity is 40% of the total pore volume within the structure, see Table 1. Unfaulted, thick units of claystones or evaporites seal the traps (Larsen et al. [2]).

Table 1. Total estimated CO<sub>2</sub> storage capacity for Danish geological structures

Name of structures	Estimated CO <sub>2</sub> storage capacity (Gt)
Hanstholm	2.8
Gassum	0.6
Havnsø	0.9
Paarup	0.09
Rødby	0.2
Stenlille	0.05
Thisted	11
Tønder	0.09
Vedsted	0.2
Voldum	0.3
Total storage capacity in Mt	16.2

Apart from the ten structures described in the EU GeoCapacity project many other geological structures within the Danish territory may prove suitable for CO<sub>2</sub> storage especially in the eastern part of the Norwegian-Danish Basin and close to the Sorgenfrei-Tornquist Zone where the sedimentary succession is extensive, the potential for CO<sub>2</sub> storage seems to be promising. The Danish CO<sub>2</sub> storage potential in hydrocarbon fields is calculated to 2,2 Gt (Vangkilde-Pedersen [1]).

## 2.2 Finland

Finland has a potential for mineral carbonation in ultramafic rocks at about 2-3 Gt (Aatos et al. [4]) and a recent work concerning the potential for applying CCS in the Nordic countries, “Potential for carbon, capture and storage (CCS) in the Nordic region” (Teir et al. [5]), concluded that Finland has no storage capacity in sedimentary formations (saline aquifers).

## 2.3 Iceland

Carbonate minerals provide a long-lasting, thermodynamically stable, and environmentally benign carbon storage host. The main disadvantage of this method is that it can take a long time, years to thousands of years (IPCC [6]). Mineral carbonation of CO<sub>2</sub> could be enhanced by injecting CO<sub>2</sub> fully

dissolved in water and/or by injection into silicate rocks rich in divalent metal cations such as basalts (mafic rock) and ultramafic rocks (Oelkers et al. [7], Matter and Kelemen [8], Gislason et al. [9]). Basaltic rocks are one of the most reactive rock types of the Earth's crust and contain reactive minerals and glasses with high potential for CO<sub>2</sub> storage. About 10% of the terrestrial part of the Earth is composed of basalt and much of the ocean floor, covering about 70% of the Earth's surface, is made of basalt (Fig. 4). Important volumes of mafic and ultramafic rocks are present on the continents. For example, the Columbia River basalts in the USA have a volume of 174,000 km<sup>3</sup> and the Siberian basalts have a volume greater than 1,000,000 km<sup>3</sup>.



Fig. 4. The distribution of major basaltic terrain on the terrestrial part of the Earth (Oelkers et al., 2008).

Iceland is 103,000 km<sup>2</sup>, mostly made of young, 0-20 M yr, igneous rocks and sediment thereof. Over 500 wells, deeper than 1000 m, have been drilled all over Iceland, showing variable alteration stage and porosity. The youngest formations have the highest porosity but most of the primary pore space in the oldest Tertiary rock is filled with secondary minerals (Neuhoff et al. [10]). The initial porosity of the lava flows range from 5 to 40 % (Franzson et al. [11], Franzson et al. [12]), mostly present in the glassy tops and bottoms of these flows. Some porosity is also contained in cooling cracks and columnar jointing. Alteration of the basaltic lava flows commonly leads to smectite, zeolite and sometimes calcite precipitation in the top 1000 m and a decrease in porosity to 1 - 10% (Sigurdsson and Stefánsson [13], Neuhoff et al. [9]). Younger cracks and faults, due to tectonic activity can increase the porosity.

Theoretically much of Iceland could be used for injecting CO<sub>2</sub>, fully dissolved in water, into basaltic rocks. This method requires a lot of water, about 10 to 30 tonnes of water per tonne of injected CO<sub>2</sub> (Gislason et al. [9]). The water availability and transmissivity of wells will limit the injection on land, but in coastal areas there is endless supply of seawater and sometimes high porosity reactive basaltic sediments are within “reach” from the coast. Therefore, injecting CO<sub>2</sub> charged seawater into basalt is an interesting opportunity that needs to be explored (Goldberg et al. [14], Wolff-Boenisch et al. [15]).

The large volumes of mafic and ultramafic rocks on the Earth's surface have correspondingly large CO<sub>2</sub> storage capacities. McGrail et al. [16] estimated that the Columbia River basalts alone have the capacity to store over 100 Gt of CO<sub>2</sub>, assuming an interflow thickness of 10 m with an average porosity of 15% and 10 available interflow zones at an average hydrostatic pressure of 100 atm. Using the same assumptions as McGrail et al. [16] the capacity to store CO<sub>2</sub> in the bedrock of Iceland is over 60 Gt CO<sub>2</sub>.

Furthermore, Goldberg et al. [14] and Goldberg et al. [17] demonstrated the large storage capacity of sub-oceanic basalt formations at the Juan De Fuca Plate east of Oregon, USA. The area specified to meet the depth and geological condition feasible for CO<sub>2</sub> storage is calculated to be about 78.000 km<sup>2</sup>. Assuming that a channel system dominates the permeability over one-sixth of the upper 600 m of the area, it is estimated to contain 7,800 km<sup>3</sup> of highly permeable basalt. Given an average channel porosity of 10%, 780 km<sup>3</sup> of potential pore volume will be available for CO<sub>2</sub> storage. If all of the CO<sub>2</sub> becomes fixed as carbonate, this reservoir could hold about 250 Gt of carbon. Applying these calculations on the bedrock of Iceland, over 330 Gt of carbon could be stored in the basaltic rock formations.

Thus, CO<sub>2</sub> storage in basalts is now considered to be a promising option for CO<sub>2</sub> storage and the feasibility of CO<sub>2</sub> storage in basaltic rocks is currently investigated in few field-scale pilot injection studies such as into dolerite sills present within the Newark basin, eastern USA (Matter et al. [18]), the Columbia River basalt, western USA (the Big Sky project) (McGrail et al. [16]), and the basalt hosted aquifer system in SW- Iceland (the CarbFix project) (Gislason et al. [9], Aradóttir et al. [19]).

#### 2.4 Norway

Several former screening studies (Bøe et al. [20]) have concluded that there is considerable CO<sub>2</sub> storage capacity in offshore aquifers and depleted oil and gas reservoirs; in fact that a major part of European storage capacity is to be found in sedimentary basins on the Norwegian shelf. Bøe et al. [20] estimated the storage capacity in the depth interval 0.8-4 km below sea level on the Norwegian shelf, to be ca. 13 Gt CO<sub>2</sub> in geological traps (outside hydrocarbon fields), while the storage capacity in aquifers not confined to traps to be at least 280 Gt CO<sub>2</sub>. Norwegian mainland has no aquifers suitable for carbon storage, but there is an unmapped potential for mineral carbonation (ultramafic/mafic rocks, anorthosite, nephelinesyenite, a.o.).

A large part of the North Sea has been well mapped geologically as a result of petroleum exploration since the nineteen sixties, while other areas are less known due not being licenced for exploration or considered to have limited probability of petroleum finds, on this basis extensive knowledge about potential reservoirs/aquifers for carbon storage exists. These clastic reservoirs are specially found in Triassic, Jurassic, Palaeogene and Neogene formations.

Norwegian petroleum directorate (NPD) recently evaluated the North Sea carbon storage potential in areas that has been open for petroleum exploration (south of 62° north latitude) more closely (Halland et al. [21]). In addition to estimation of storage capacity following the EU GeoCapacity approach with efficiency factors, the various aquifers and structures were ranked based on reservoir quality, sealing quality, well leakage risks, and data coverage (wells and seismic surveys). NPD has used the burial depth range of 800 - 2500 m below sea level in their initial selection criteria. Several aquifers have also been excluded from the list due to conflict with petroleum exploration and or production.

The CO<sub>2</sub> storage atlas also consider maturity of the prospects, from initial volume calculations based on thickness and porosity, to exclusion based on cut off criteria, and to more detailed characterization that can lead to storage permits. Relevant reservoir simulations are needed for being considered a mature prospect.

Table 2 taken from the NPD storage capacity summary sheet (Halland et al. [21]), gives an overview of CO<sub>2</sub> storage estimates in the Norwegian sector of the North Sea and Skagerrak area. NPD's evaluation gives a total capacity in saline aquifers of 43 Gt CO<sub>2</sub> with an additional 27 Gt in petroleum related fields (abandoned fields and fields open for EOR or closure up to 2050).

Table 2. Overview of estimated CO<sub>2</sub> storage capacity in the Norwegian North Sea and Skaggeiak, based on Halland et al. 2011.

The storage prospects have been grouped into 1) saline aquifers, and 2) petroleum related fields.

Aquifers Basin/reservoir	Estimated CO <sub>2</sub> storage capacity (Gt)
Utsira and Skade	15.8
Bryne/Sandnes southern parts	13.6
Sognefjord Delta east	4.1
Stratfjord Fm. East	3.6
Gassum	2.9
Bryne/Sandnes Farsund Basin	2.3
Johansen and Cook	1.8
Fiskerbanke	1
Hugin East	0.1
Stord Basin, Jura	0.1
Stord Basin, mounds	0.05
Hydrocarbon fields	Estimated CO <sub>2</sub> storage capacity (Gt)
Abandoned fields	3
Fields in production 2030	4
Fields in production 2050	6
Sognefjord delta including Troll	14

The main saline aquifers are the Neogene Utsira and Skade Formations in the central North Sea and the Middle to Upper Jurassic sands of the Vestland Group (Bryne and Sandnes Formations) in the Central Graben and the Norwegian-Danish Basin. There is also a large saline aquifer in the Sognefjord delta complex belonging to the Troll petroleum field that will not be available for carbon store until production ends or will be connected with EOR. In the evaluation of NPD, this aquifer has been grouped with the field related storage prospects. The reservoir simulations performed for two mature cases in Table 2, are done without water production, which together with injection strategy, partly explain the large reduction in capacity. The petroleum related fields encompass both abandoned fields like the large depleted Frigg gas field complex (transboundary between Norway and the UK), and those fields that are near the end of production and where enhanced recovery with CO<sub>2</sub> is an option.

### 2.5 Sweden

In 2011 the Geological Survey of Sweden presented a report reviewing the Swedish bedrock regarding its suitability for geological storage of CO<sub>2</sub> (Erlström and Sivhed [22], Erlström et al. [23]). This screening recognized three areas of interest regarding CO<sub>2</sub> storage. All three areas are situated off-shore in the southernmost part of Sweden and all constitute deep sandstone aquifers (Deep Saline Aquifers) of various thickness and extension. According to Swedish legislation regarding implementation of the EU-

directive (2009) on-shore CO<sub>2</sub> storage in full scale on Swedish territory is not permitted. Furthermore, Swedish contribution to CO<sub>2</sub> storage in hydrocarbon fields or by mineral trapping is negligible due to lack of reservoir rocks and required physical properties or association to valuable mineral resources, e.g. ores.

The largest and most promising area is situated in the southeast area of the Baltic Sea (A, Fig. 5) where a thick Cambrian sequence of alternating sandstone and shale occur. The Lower Cambrian sandstones (När- and Viklau sandstone) comprise a net sand thickness of 30–70 m with a regional distribution. In the Swedish sector alone, the Upper Cambrian sandstone (Faludden sandstone) comprises a total thickness of up to 50 m with a regional distribution of app 13500 km<sup>2</sup> at depths below 800 m. Preliminary interpretations indicate permeability <50 mD and porosity <10% in the När- and Viklau sandstones and permeability of app 220 mD and porosities averaging 16% in the Faludden sandstone. In addition, the Faludden sandstone is distributed even further ESE as the Deimena Formation into Baltic territories where also numerous Cambrian hydrocarbon traps occur. Only smaller structural traps are identified in the Swedish sequence. On top of the Cambrian sequence is 4–6 m Alum shale succeeded by 65–125 m Ordovician benthonic limestone and shale followed by an extensive (600–850 m) Silurian sequence of marlstone. The Ordovician and Silurian sequences are poorly investigated according to physical properties but both comprise promising properties as suitable cap rocks.

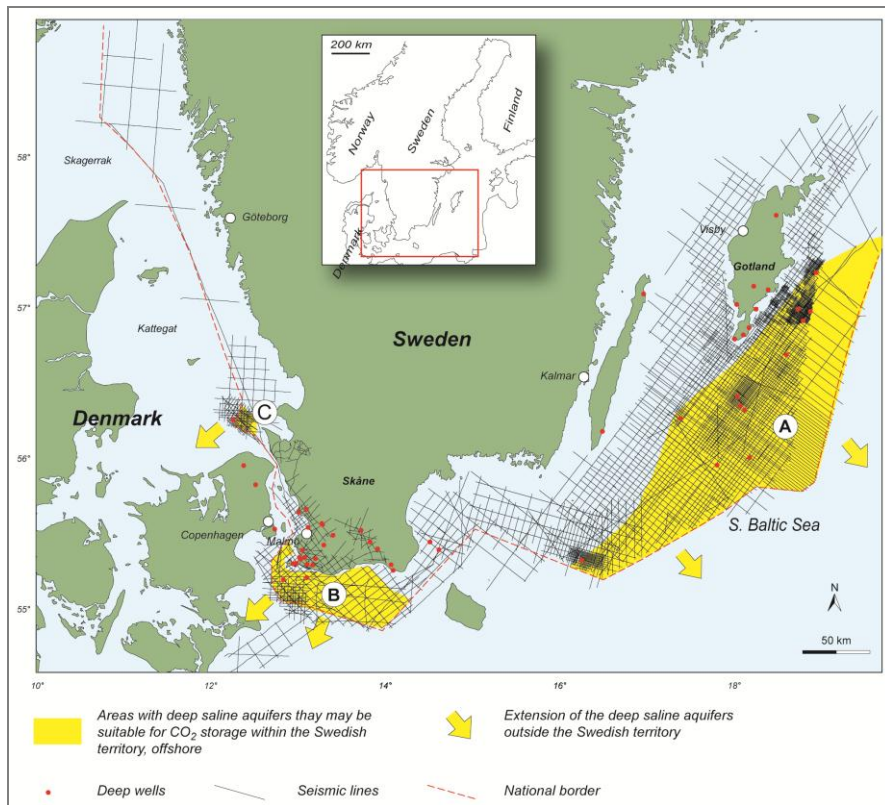


Fig. 5. Areas with deep saline aquifers suitable for CO<sub>2</sub> storage offshore Sweden.



Very preliminary estimations of the total CO<sub>2</sub> storage capacity in the Cambrian sandstone aquifers in the southeast Baltic Sea on Swedish territory suggest between 450 Mt and 4.5 Gt due to high uncertainty in physical factors such as porosity and permeability.

In addition to the primary area of the southeast Baltic Sea two smaller and much more uncertain areas are recognized as possibly candidates for CO<sub>2</sub> storage. The off-shore area of the Southwest Skåne (B, Fig. 1) constitutes a marginal part to the Danish Basin and the sub-surface geology displays a succession of strata which include both suitable aquifer intervals and cap rock. The area is situated in a tectonically more complex area and constitutes a 2–4 km thick sequence of sedimentary rock containing several aquifers at required depth. No structural traps have been identified. Three potential aquifer units have been recognized: the Lower Triassic Bunt- and Ljunghusen sandstones (40–100 m, distribution of app 850 km<sup>2</sup>, homogeneous), the Uppermost Triassic to Hettangian Höganäs Formation (100 m, distribution of app 2900 km<sup>2</sup>, heterogeneous) and the Lower Cretaceous Arnager Greensand (20–60 m, distribution of app 9500 km<sup>2</sup>, homogeneous). All three aquifers have shown permeability >100 mD and average porosities at 20–30%. Elaborating investigations regarding physical properties of cap rocks are required. Although, all three aquifers are overlaid by an extensive sequence of clayey limestone, siltstone, claystone and chalk, and even local inter-layering of clayey rocks may pose secondary cap rocks. Furthermore, the aquifers in Southwest Skåne are potential geothermal aquifers. The EU funded MUSTANG-CO<sub>2</sub> project have used SW Skåne as one of the test sites for modelling scenarios as it exemplifies a multi-layered aquifer system.

Estimated CO<sub>2</sub> storage capacity in the Triassic sandstone aquifer in the southwest Skåne is 750 Mt, the Jurassic sandstone aquifer in the southwest Skåne is 4.5 Gt and the Cretaceous sandstone aquifer in the southwest Skåne is 5 Gt. It must be noted though, that these figures are connected to great uncertainty and requires thorough further research as to get a better assessment of the storage capacity.

Finally, the last area of possible interest is in the southeast part of the Kattegat Sea (C, Fig. 5) and comprises a smaller area in Swedish territory of 25–50 km<sup>2</sup>. Potential storage aquifer consists of a more than 1000 m thick inter-bedded sandstone belonging to the Upper Triassic Skagerrak Formation with a total thickness of sand layers of app 50 m. The deposit is found on depth between 1000 and 2000 m and data from geophysical logs indicate porosity at app 25%. Occurrence of anticline structure suggests suitable trap for storage although further studies are required for confirmation of applicability. Even physical properties of cap rocks require further investigations. Although, alternating layers of claystone and the top layer of 20–50 m clay and claystone on top of the Skagerrak Formation indicate good sealing properties. Preliminary estimations of CO<sub>2</sub> storage capacity in the Skagerrak Formation on Swedish territory in the southernmost part of Kattegat suggest 80-150 Mt.

All three areas described were subject to regional seismic surveys during the 1970s and 1980s performed by the Swedish Oil Prospecting Company (OPAB) and the Swedish Exploration Consortium (SECAB). Furthermore, both SGU and OPAB drilled numerous deep prospecting wells during the 1940-1960s in Skåne and in the Baltic Sea. All data are stored at SGU but most of it needs to be scrutinized and interpreted regarding CO<sub>2</sub> storage related information. In general, physical properties for especially the cap rock units require supplementary investigations and analyses to confirm their suitability. The extended propagation of the highly promising Faludden-Deimena sandstone in the southeast Baltic Sea into Baltic territory suggests the needs for a joint collaboration to assess its suitability as candidate for CO<sub>2</sub> storage in the Baltic region.

### 3. Nordic CCS cooperation

To enhance awareness of the unique opportunities for geological CO<sub>2</sub> storage in the Nordic region, a new expertise centre for CCS was established in 2011 funded by the Nordic countries research program -

the Nordic Top-level Research Initiative and partners from industry. During the next 4 years, this centre, called NORDICCS, will work towards the realisation of CCS within the Nordic countries. One of the tasks is to create an updated inventory of potential geological storage sites including all of the Nordic countries, and to improve the accuracy of the capacity estimations. Characterisation and screening of storage areas will be performed in order to identify the most prospective storage sites and create a joint atlas for CO<sub>2</sub> storage in the Nordic region.

#### 4. Conclusions

The most prospective area for CO<sub>2</sub> storage in the Nordic region is the Norwegian North Sea due to existence of extensive saline aquifers and hydrocarbon fields and the fact that the area is relative well exploited as the result of intensive oil and gas exploration through more than forty years. The most recent storage capacity estimates released by the Norwegian Petroleum Directorate indicate a total storage capacity of approximately 72 Gt in the Norwegian North Sea including both saline aquifers and hydrocarbon fields, see table 3.

Only a minor part of the Danish subsurface is included in the storage estimates and only takes storage in geological traps into account, the total estimated storage capacity for these 10 traps is close to 16 Gt. Future survey of potential storage formation and traps can reveal large storage capacities in several stratigraphic intervals of Triassic and Jurassic age in the Danish subsurface. Additional 2 Gt can be stored in Danish Hydrocarbon fields.

Mapping of Swedish storage sites has identified three areas of interest. The most promising area is a thick Cambrian sequence with several sandstone intervals situated east of Sweden in the Baltic Sea, in addition a smaller area southwest of Skåne and a minor area at the Swedish west coast have been recognised. Assessments of the three Swedish potential storage areas indicate a total storage capacity of more than 15 Gt.

Both Finland and Iceland lack opportunities for CO<sub>2</sub> storage in sedimentary bedrocks but have a storage potential for mineral trapping in ultramafic and basaltic rocks. In Finland mapped storage capacity estimated to a maximum of 3 Gt CO<sub>2</sub> in ultramafic rocks.

Research projects regarding mineral trapping of CO<sub>2</sub> in basalts are taking place in Iceland. This research area is in an initial stage, however early results indicate a large potential for in-situ mineralisation of CO<sub>2</sub> in porous basalts and have on the basis of north American calculation methods estimated that Iceland potentially has storage capacity between 60 and 330 Gt CO<sub>2</sub> in porous basalts.

Table 3. Estimated CO<sub>2</sub> storage capacity in the Nordic region

Country	Saline aquifers Gt	Hydrocarbon fields Gt	Mineral trapping Gt
Denmark	16,2*	2,2	-
Finland	-	-	2-3
Iceland	-	-	60-330**
Norway	45,4***	27	-
Sweden	14,9	-	-

\* Only estimations from traps are included

\*\* Preliminary estimates

\*\*\* Only estimations from the Norwegian North sea area are included

It must be noted though, that these figures are connected to great uncertainty and requires thorough further research as to get a better assessment of the storage capacity. The NORDICCS Centre will in the coming years attempt to improve the mapping of CO<sub>2</sub> storage sites and storage capacity estimations within the region. However, this compilation of CO<sub>2</sub> storage capacity assessments for the Nordic region only underlines the results of the EU GeoCapacity project demonstrating the regions large potential storage capacity.

## Acknowledgements

This publication has been produced with support from the NORDICCS Centre, performed under the Top-level Research Initiative CO<sub>2</sub> Capture and Storage program, and Nordic Innovation. The authors acknowledge the following partners for their contributions: Statoil, Gassco, Norcem, Reykjavik Energy, and the Top-level Research Initiative (Project number 11029).

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# CO<sub>2</sub> storage potential in the Nordic region

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## Nordic CCS cooperation

To enhance awareness of the unique opportunities for geological CO<sub>2</sub> storage in the Nordic region, a new expertise centre for CCS was established in 2011 funded by the Nordic countries research program - the Nordic Top-level Research Initiative and partners from industry. During the next 4 years, this centre, called NORDICCS, will work towards the realisation of CCS within the Nordic countries. One of the tasks is to create an updated potential geological storage sites including data from all Nordic countries, and to improve the accuracy of the capacity estimations. Characterisation and screening of storage areas will be performed in order to identify the most prospective storage sites and create a joint atlas for CO<sub>2</sub> storage in the Nordic region.

Country	Saline aquifers Gt	Hydrocarbon fields Gt	Mineral trapping Gt
Denmark	16.2*	2.2	-
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\* Only estimations from 10 traps are included  
 \*\* Preliminary estimates  
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It must be noted though, that these figures are connected to great uncertainty and requires thorough further research as to get a better assessment of the storage capacity. The NORDICCS Centre will in the coming years attempt to improve the mapping of CO<sub>2</sub> storage sites and storage capacity estimations within the region. However, this compilation of CO<sub>2</sub> storage capacity assessments for the Nordic region only underlines the results of the EU GeoCapacity project demonstrating the regions large potential storage capacity.

## Iceland

Iceland is 103.000 km<sup>2</sup>, mostly made of young, 0-20 M yr, igneous rocks and sediment thereof, showing variable alteration stage and porosity. The youngest formations have the highest porosity but most of the primary pore space in the oldest Tertiary rock is filled with secondary minerals [5]. The initial porosity of the lava flows range from 5 to 40 % [6] mostly present in the glassy tops and bottoms of the flows.

Theoretically large areas in Iceland could be used for injecting CO<sub>2</sub> dissolved in water into basaltic rocks. This method requires a lot of water, about 10 to 30 tonnes of water per tonne of injected CO<sub>2</sub> [7]. The water availability and transmissivity of the injection wells will limit the CO<sub>2</sub> injection on land, but in coastal areas with access to endless supply of seawater and where high porosity reactive basaltic sediments are within "reach" from the coast, this method may have a large potential.

Initial estimations of CO<sub>2</sub> storage capacities for mafic and ultramafic rocks based on methodology of [8] indicate the capacity to store CO<sub>2</sub> in the bedrock of Iceland is over 60 Gt CO<sub>2</sub>. Furthermore, [9] demonstrated large storage capacity in sub-oceanic basalt formations and applying these calculations on the bedrock of Iceland, over 330 Gt CO<sub>2</sub> could be stored in the basaltic rock formations.

CO<sub>2</sub> storage in basalts is considered to be a promising option for CO<sub>2</sub> storage and the feasibility of CO<sub>2</sub> storage in basaltic rocks is currently investigated in field-scale pilot injection studies such the basalt hosted aquifer system in SVV- Iceland - the CarbFix project [7].

## Norway

Several former screening studies [10] have concluded a considerable CO<sub>2</sub> storage capacity in offshore Norwegian aquifers and depleted oil and gas reservoirs; in fact the majority of the European storage capacity is to be found in sedimentary basins on the Norwegian shelf.

A large part of the North Sea has been well mapped geologically as a result of petroleum exploration since the nineteen sixties, on this basis extensive knowledge about potential reservoirs/aquifers for carbon storage exists. These clastic reservoirs are specially found in Triassic, Jurassic, Palaeogene and Neogene formations.

The Norwegian petroleum directorate (NPD) recently evaluated the North Sea carbon storage potential in areas that has been open for petroleum exploration (south of 62° north latitude) more closely [11]. NPD has used the burial depth range of 800 - 2500 m below sea level in their initial selection criteria and several aquifers have been excluded from the list due to conflict with petroleum exploration and/or production.

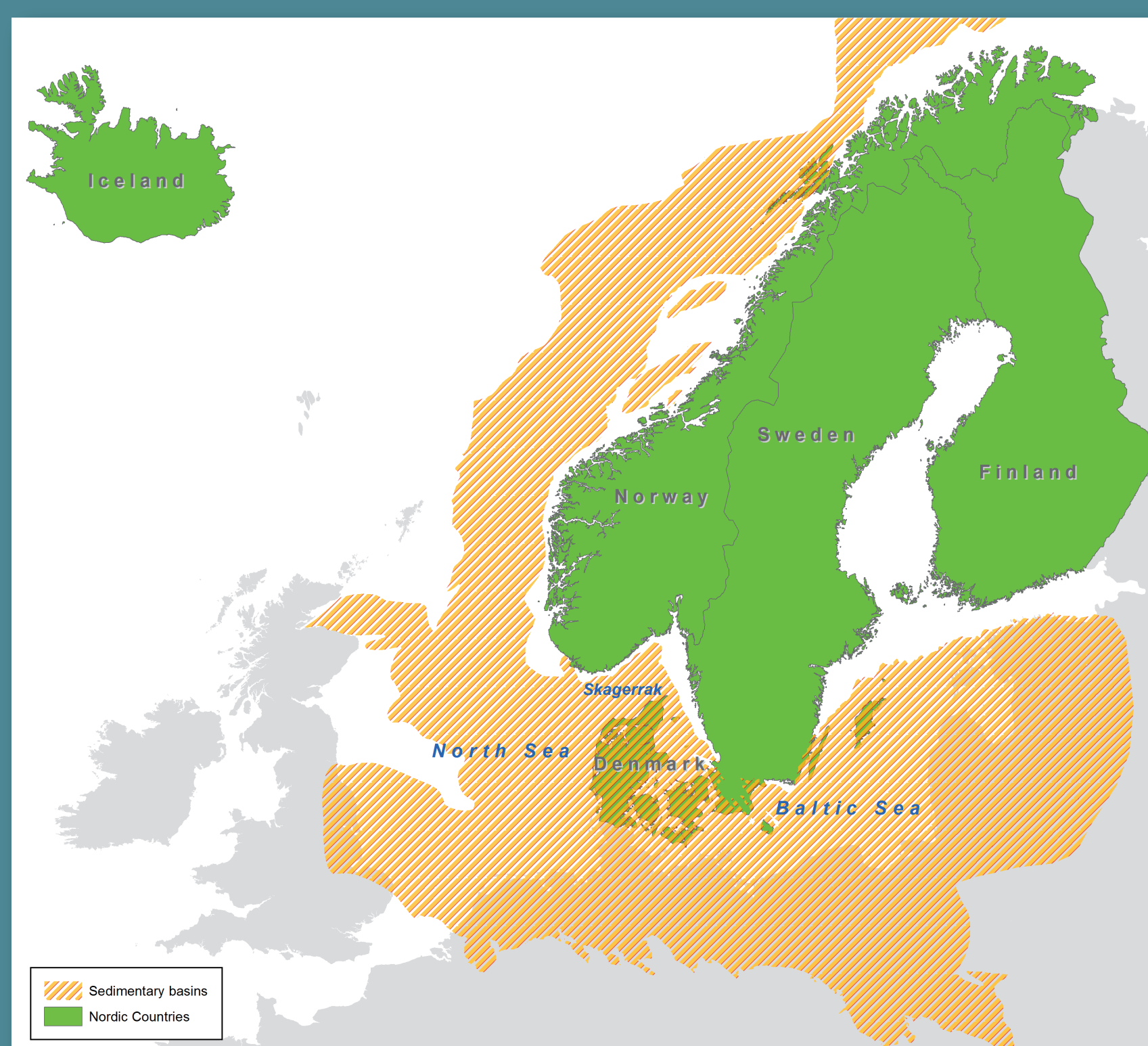
The Norwegian petroleum directorate storage capacity summary sheet [16], gives an overview of CO<sub>2</sub> storage estimates in the Norwegian sector of the North Sea and Skagerrak area. NPD estimate a total capacity in saline aquifers of 43 Gt CO<sub>2</sub> with an additional 27 Gt in petroleum related fields (abandoned fields and fields open for EOR or closure up to 2050).

Overview of estimated CO<sub>2</sub> storage capacity in the Norwegian North Sea and Skagerrak, based on Halland et al. 2011.

Aquifers	Estimated CO <sub>2</sub> storage capacity (Gt)
Basin/reservoir	
Utsira and Skade	15.8
Bryne/Sandnes southern parts	13.6
Sognefjord Delta east	4.1
Stratford Fm. East	3.6
Gassum	2.9
Bryne/Sandnes Farsund Basin	2.3
Johansen and Cook	1.8
Fiskerbanke	1
Hugin East	0.1
Stord Basin, Jura	0.1
Stord Basin, mounds	0.05
Hydrocarbon fields	Estimated CO <sub>2</sub> storage capacity (Gt)
Abandoned fields	3
Fields in production 2030	4
Fields in production 2050	6
Sognefjord delta including Troll	14

## Acknowledgement

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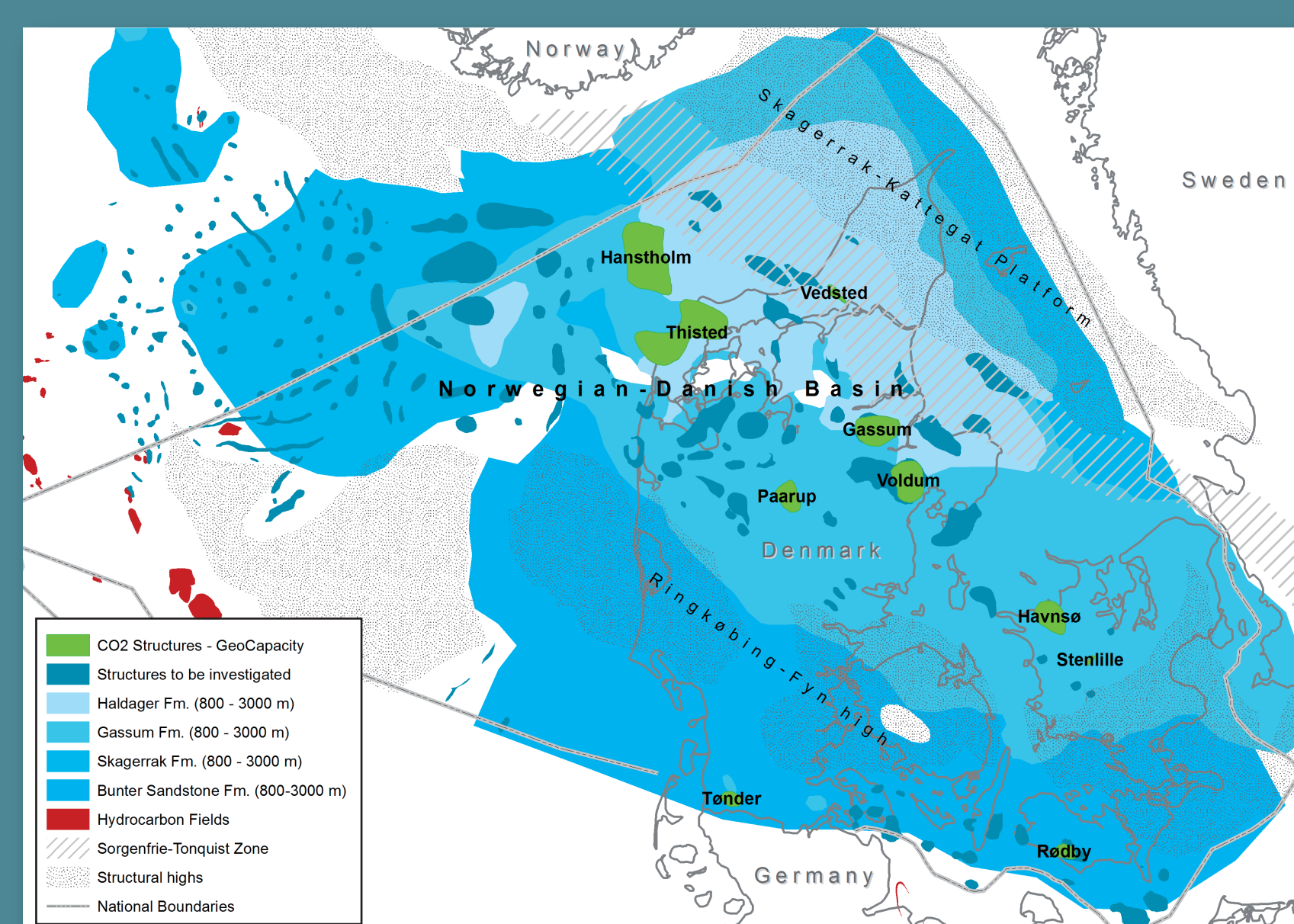
The Nordic countries and sedimentary basins in the Nordic region.

## Denmark

The most promising formations in Denmark with CO<sub>2</sub> storage potential are the Triassic Bunter Sandstone Formation, the Skagerrak Formation and the Gassum Formation, together with the Jurassic Haldager Sand Formation.

Within the potential storage formations 10 geological structures have been selected and evaluated with respect to the possibility for CO<sub>2</sub> storage [1]. The majority of the individual structures are related to movement of the Zechstein salt causing formation of a wide range of structures from gentle domes to diapirs. The dome structures most often form anticlines with 4-way closures and lack of significant faulting. The selected structures are mainly identified on the basis of old seismic data and will in case of future utilization need thorough investigations. The data suggest that the structural traps alone may provide storage for at least 16 Gt CO<sub>2</sub> assuming that the effective storage capacity is 40% of the total pore volume within the structure. Unfaulted, thick units of claystones or evaporites seal the traps [2].

Apart from the 10 selected structures many other geological structures within the Danish territory may prove suitable for CO<sub>2</sub> storage especially in the eastern part of the Norwegian-Danish Basin and close to the Sorgenfrei-Tornquist Zone where the sedimentary succession is extensive, the potential for CO<sub>2</sub> storage seems to be promising. The Danish CO<sub>2</sub> storage potential in hydrocarbon fields is calculated to 2,2 Gt [1].



The distribution of Danish geological formations in the depth interval 800 - 3000 meters which is considered the most optimal for CO<sub>2</sub> injection. Geological structures related to salt movement form domes and diapirs.

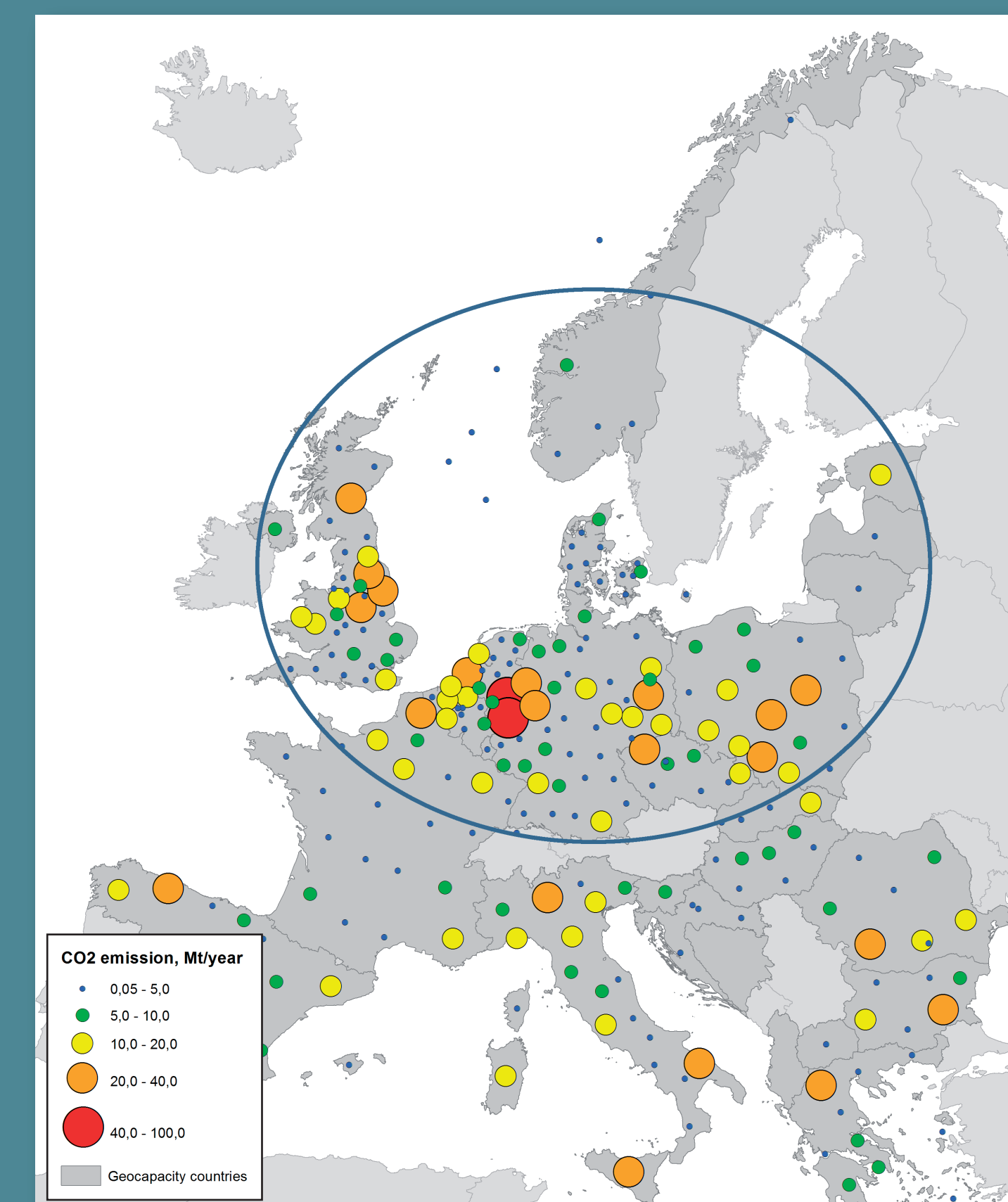
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## Introduction

According to the most recent European capacity estimations from the EU GeoCapacity project (2009), the total European storage capacity is calculated to be 358 Giga tons (Gt), with 114 Gt onshore and 244 Gt offshore, comprising capacity estimations for hydrocarbon reservoirs and saline aquifers [1]. The results of EU GeoCapacity indicates that the Nordic region has 59% of the currently mapped total storage capacity in Europe, and 86% of all offshore capacity, renders it the most prospective region in Europe for geological storage of CO<sub>2</sub>.

Inventories and analysis of European stationary CO<sub>2</sub> emission sources with an emission level above 100,000 tons CO<sub>2</sub>/year prove an annual emission of 1.9 Gt; 1.3 Gt of this CO<sub>2</sub> is emitted in the northern part of Europe, forming a potential catchment area for CO<sub>2</sub> storage in the Baltic Sea, the North Sea, and offshore mid-Norway.



Yearly CO<sub>2</sub> emission from regionally clustered large stationary emission sources mapped in the EU GeoCapacity project. The total yearly CO<sub>2</sub> emission within the circle is 1.3 Gt.

## Finland

Finland has a potential for mineral carbonation in ultramafic rocks at about 2-3 Gt [3] and a recent work concerning the potential for applying CCS in the Nordic countries, "Potential for carbon, capture and storage (CCS) in the Nordic region" [4], concluded that Finland has no storage capacity in sedimentary formations (saline aquifers).

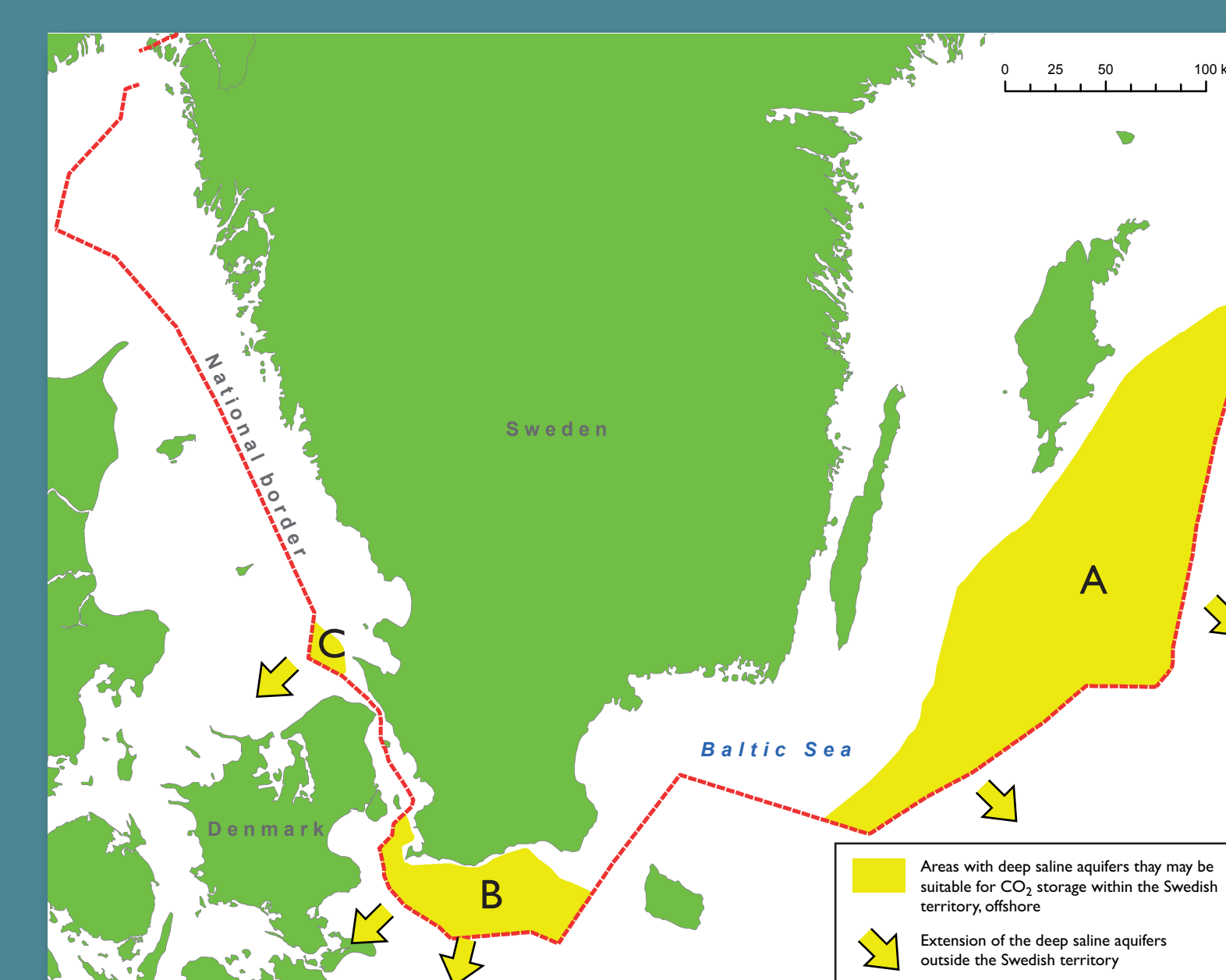
## Sweden

In 2011 the Geological Survey of Sweden presented a report reviewing the Swedish bedrock regarding its suitability for geological storage of CO<sub>2</sub> [17], [18]. This screening recognized three areas of interest regarding CO<sub>2</sub> storage. All three areas are situated off-shore in the southernmost part of Sweden and all constitute deep sandstone aquifers of various thickness and extension.

The largest and most promising area is situated in the southeast area of the Baltic Sea (A) where a thick Cambrian sequence of alternating sandstone and shale occur. Very preliminary estimations of the total CO<sub>2</sub> storage capacity in the Cambrian sandstone aquifers on Swedish territory suggest between 450 Mt and 4.5 Gt due to high uncertainty in physical factors such as porosity and permeability.

Two smaller and much more uncertain areas off-shore of the Southwest Skåne are recognized as possibly candidates for CO<sub>2</sub> storage (B). They constitute a marginal part to the Danish Basin and the sub-surface geology displays a succession of strata which include both suitable aquifer intervals and cap rock. Very preliminary estimated CO<sub>2</sub> storage capacity in area B is app. 750 Mt in the Triassic sandstone aquifer; 4.5 Gt in the Jurassic sandstone aquifer and 5 Gt in the Cretaceous sandstone aquifer.

The last area of possible interest is in the southeast part of the Kattegat Sea (C) and comprises a smaller area in Swedish territory of 25-50 km<sup>2</sup>. Potential storage aquifer consists of a more than 1000 m thick inter-bedded sandstone belonging to the Upper Triassic Skagerrak Formation with a total thickness of sand layers of app 50 m. Preliminary estimations of CO<sub>2</sub> storage capacity in the Skagerrak Formation on Swedish territory suggest 80-150 Mt.



Areas with deep saline aquifers suitable for CO<sub>2</sub> storage offshore Sweden.