Mapping and estimating the potential for geological storage of CO$_2$ in the Nordic countries – a new project in NORDICCS

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November 2012
NORDICCS concept:

**Assumptions and premises (1)**
- Nordic CCS platform
- Nordic CCS roadmap
- Framework conditions
- Economy

**Strategies for CCS realisation**

**Feasibility studies on CCS industry cases**
- CO₂ capture
  - Energy analyses (%)
  - CCS integrated (6) in industry
- CO₂ transport (4)
  - Cost-effective CO₂ transport
- CO₂ storage (2)
  - The Nordic CO₂ storage atlas
  - Guidelines for safe storage
  - Site storage modelling

**R&D recommendations**

**Communication (3) and dissemination**
- Cement
- BioCCS
- Metal
- Oil refineries
- Power
- Public awareness and acceptance
- Dissemination and networking

**Spreading excellence**

**Partners:**

- Chalmers University of Technology
- IVL Swedish Environmental Research Institute
- SGU Swedish geotechnical conditioning service of Sweden
- GUS
- NTNU Norwegian University of Science and Technology
- University of Oslo
- University of Iceland
- Statoil
- SINTEF
- University of Copenhagen
- Vattenfall
- Norcem
- Technology Centre Mongstad

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www.sintef.no/NORDICCS
Summary

Previous European projects mapped and estimated the potential storage for hydrocarbon fields, not-mineable coal beds and saline aquifers. The European projects only included two Nordic countries (Norway and Denmark) and a unified database covering all of the Nordic countries does not exist. In November 2011, the Nordic countries research program - the Nordic Top-level Research Initiative (Nordic Innovation Center), launched NORDICCS – Nordic Competence Centre for CCS. One of the Centers major tasks is the creation of a Nordic CO2 storage atlas. NORDICCS will build a database of geological information on potential storage sites, improve methods to quantify storage capacity and defining criteria to characterise a safe storage site. Further the option to store CO2 in basalts will be considered and potential areas mapped.

**Keywords**  
CCS, Nordic, storage potential, saline aquifers, basalts

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**Date**  
November 2012

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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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Abstract: To reduce human impact on climate changes in the near future it is considered necessary to reduce CO$_2$ emissions from fossil fuel combustion. This fact has intensified research in methods capable of reducing emissions substantially and one of the methods being looked into is carbon capture and storage (CCS). CCS could relatively fast help to reduce CO$_2$ emissions form large point sources e.g. power stations, because the technology builds on already existing knowledge from oil and gas production. To be prepared for a possible future implementation of CCS it is, however, important to know where and how much CO$_2$ can be stored in the sub-surface.

Several EU co-funded projects has mapped the potential for geological storage of CO$_2$ in Europe, beginning with the Joule II project in 1993, estimating a total storage capacity of 800 giga tonne (Gt), to GeoCapacity estimating a total storage capacity of 360 Gt in 2009. The results from these projects concluded that EU has sufficient storage capacity to store the yearly emission of CO$_2$ of 1.9 Gt from large stationary point sources. The European projects mapped and estimated the potential storage for hydrocarbon fields, not-mineable coal beds and saline aquifers. The GeoCapacity project concluded that the aquifers have by far the largest storage capacities with a total capacity of 325 Gt. The European projects only included two Nordic countries (Norway and Denmark) and a unified database covering all of the Nordic countries does not exist.

It is clear, that the very different geology of the Nordic countries reflects the variation in CO$_2$ storage capacity, from the 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 to the active rift zone in Iceland. This was recently illustrated in a research study comprising an overview of the potential for applying CCS in the Nordic countries, where Finland and Sweden only had limited storage capacity; Denmark and especially Norway large CO$_2$ storage potential, and on Iceland the basaltic rocks offers the possibility to store CO$_2$ by mineral trapping, a method where the CO$_2$ is chemically attached to minerals in the basalts.

In November 2011, the Nordic countries research program - the Nordic Top-level Research Initiative (Nordic Innovation Center), launched NORDICCS – Nordic Competence Centre for CCS. One of the Centers major tasks is the creation of a Nordic CO$_2$ storage atlas. NORDICCS will build a database of geological information on potential storage sites, improve methods to quantify storage capacity and defining criteria to characterise a safe storage site. Further the option to store CO$_2$ in basalts will be considered and potential areas mapped.
Mapping and Estimating the Potential for Geological Storage of CO\textsubscript{2} in the Nordic countries – a new project in NORDICCS

Karen Lyng Anthonsen

Geological Survey of Denmark and Greenland
Danish Ministry of Climate, Energy and Building

Nordic Geological Winter Meeting, Januar 9th 2012, Reykjavik
• What is CCS?
• Key geological indicators for CO$_2$ storage sustainability
• Mapping of potential CO$_2$ storage options in Europe
• Results of European CO$_2$ storage capacity projects
• Calculation of CO$_2$ storage capacity - aquifers
• Nordic geological CO$_2$ storage projects - NORDICCS
Carbon, Capture and Storage - CCS

Emission source with CO$_2$ capture facilities

Transport
- Pipeline
- Ship

Storage
- Hydrocarbon fields
- Aquifers (saline)
- Coal fields (unmineable)
CO₂ storage options

- **Oil- and gas fields**
  Limited storage capacity, but well-known geology and proven capability to retain hydrocarbons
  Possibility to use CO₂ for enhanced oil/gas recovery (EOR/EGR)

- **Aquifers (saline)**
  Large storage volumes, but relatively unknown geology and therefore uncertainties about reservoir integrity and properties

- **Coal fields**
  Very limited storage capacity and injection rates, but possible to use CO₂ for production of methane

- **Mineral trapping**
  Research area with large perspectives
Stratigraphical trapping
Porous layer bounded by tight seal

Structural trapping
Porous layer topped by tight seal

Structural trapping
Porous layer in fault contact with seal
### Key geological indicators for storage site suitability

<table>
<thead>
<tr>
<th>Reservoir Properties</th>
<th>Positive Indicators</th>
<th>Cautionary Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>&gt;800 m, &lt;2500 m</td>
<td>&lt;800 m, &gt;2500 m</td>
</tr>
<tr>
<td>Reservoir thickness</td>
<td>&gt;50 m</td>
<td>&lt;20 m</td>
</tr>
<tr>
<td>Porosity</td>
<td>&gt;20%</td>
<td>&lt;10%</td>
</tr>
<tr>
<td>Permeability</td>
<td>&gt;500 mD</td>
<td>&lt;200 mD</td>
</tr>
<tr>
<td>Salinity</td>
<td>&gt;100 gl⁻¹</td>
<td>&lt;30 gl⁻¹</td>
</tr>
<tr>
<td>Stratigraphy</td>
<td>Uniform</td>
<td>Complex lateral variation and complex connectivity of reservoir facies</td>
</tr>
<tr>
<td>Capacity</td>
<td>Estimated effective capacity much larger than total amount of CO₂ to be injected</td>
<td>Estimated effective capacity similar to total amount of CO₂ to be injected</td>
</tr>
</tbody>
</table>

**Caprock Properties**

<table>
<thead>
<tr>
<th>Lateral continuity</th>
<th>Stratigraphically uniform, small or no faults</th>
<th>Lateral variations, medium to large faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>&gt;100 m</td>
<td>&lt;20 m</td>
</tr>
</tbody>
</table>

Chadwick et al., 2008
CO\textsubscript{2} density changes with increasing depth
Porosity decreases with depth

Permeability decreases with decreasing porosity

The optimal depth window for CO$_2$ storage is 800 – 2500 meter
CO2 storage capacity projects

- **Joule II** finalised 1993
  The joule II project: The underground disposal of carbon dioxide
  All Europe

- **GESTCO** finalised 2003
  Geological Storage of CO2 from Combustion of Fossil Fuel
  Belgium, Denmark, France, Germany, Greece, Netherlands, Norway, UK

- **Castor (WP 1.2)** finalised 2006
  Bulgaria, Croatia, Czech Rep., Hungary, Poland, Romania, Slovakia, Slovenia

- **GeoCapacity** finalised 2008
  Assessing European Capacity for Geological Storage of Carbon Dioxide
  Bulgaria, Croatia, Czech Rep., Denmark, Estonia, France, Germany, Greece, Hungary, Italy, Latvia, Lithuania, Netherlands, Poland, Romania, Slovakia, Slovenia, Spain, UK (Albania, FYROM, Bosnia-Herzegovina, Luxembourg)
Mapping of CO$_2$ storage capacity in Europe

Geological storage mapping projects
- GESTCO countries (2003)
- CASTOR WP1.2 countries (2006)
- GeoCapacity countries (2008)
Mapping of emission sources and infrastructure

Stationary CO$_2$ emission sources exceeding 100 kt CO$_2$ / year

Data sources:
- annual reports for the EU ETS
- national allocation plans
- qualified estimations where data not available

Infrastructure mapping
- pipelines
CO₂ emission sources

- 0,00 - 1,00
- 1,01 - 3,00
- 3,01 - 5,00
- 5,01 - 10,00
- 10,01 - 31,35

GeoCapacity countries
Joule II estimated a total storage capacity for Europe of 800 Gt.

GeoCapacity
Emissions from large point sources in the GeoCapacity database is 1.9 Gt CO₂/year (1,900,000,000 tones).

Total European storage capacity in GeoCapacity database is 360 Gt CO₂:
- 326 Gt in aquifers
- 32 Gt in hydrocarbon fields
- 2 Gt in unmineable coal beds

Offshore storage capacity is 244 Gt, onshore capacity is 116 Gt CO₂.

Almost 200 Gt is located offshore Norway.

Total conservative European storage capacity is 117 Gt CO₂:
- 96 Gt in aquifers
- 20 Gt in hydrocarbon fields
- 1 Gt in unmineable coal beds

www.geocapacity.eu
Calculation of CO$_2$ storage capacity for aquifers
Theoretical vs. effective capacity

Theoretical capacity: \[ M_{\text{CO}_2t} = A \times h \times \phi \times \rho_{\text{CO}_2r} \]

Effective capacity: \[ M_{\text{CO}_2e} = A \times h \times \phi \times \rho_{\text{CO}_2r} \times S_{\text{eff}} \]

- \( M_{\text{CO}_2} \): Storage capacity
- \( A \): Area of aquifer
- \( h \): Height \( \times \) net to gross ratio
- \( \phi \): Average reservoir porosity
- \( \rho_{\text{CO}_2r} \): \( \text{CO}_2 \) density at reservoir conditions
- \( S_{\text{eff}} \): Storage efficiency factor - depends on connectivity to surrounding aquifer

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>Volume ((10^9 \text{ m}^3))</th>
<th>Net/gross ratio</th>
<th>Porosity</th>
<th>( \text{CO}_2 ) density ((\text{t/ m}^3))</th>
<th>Theoretical regional ( \text{CO}_2 ) storage capacity ((\text{Gt}))</th>
<th>Storage efficiency factor</th>
<th>Effective regional ( \text{CO}_2 ) storage capacity ((\text{Gt}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunter and Sk.</td>
<td>25729</td>
<td>0.25</td>
<td>0.20</td>
<td>0.625</td>
<td>804</td>
<td>0.02</td>
<td>16.1</td>
</tr>
<tr>
<td>Gassum</td>
<td>8557</td>
<td>0.25</td>
<td>0.20</td>
<td>0.625</td>
<td>267</td>
<td>0.02</td>
<td>5.3</td>
</tr>
<tr>
<td>Haldager</td>
<td>1311</td>
<td>0.25</td>
<td>0.20</td>
<td>0.625</td>
<td>41</td>
<td>0.02</td>
<td>0.8</td>
</tr>
<tr>
<td>Frederikshavn</td>
<td>5207</td>
<td>0.25</td>
<td>0.20</td>
<td>0.625</td>
<td>163</td>
<td>0.02</td>
<td>3.3</td>
</tr>
<tr>
<td><strong>Total estimated regional ( \text{CO}_2 ) storage capacity ((\text{Gt}))</strong></td>
<td><strong>1275</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>25.5</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Based US DOE methodology \( S_{\text{eff}} \) for regional aquifers is 2%
Open and semi-closed structures

**Storage coefficient (by the rule-of-thumb) \( S_{\text{cf}} \)**

*Volume of bulk reservoir shall be 5-10 times the volume of the reservoir*

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**Fault**

<table>
<thead>
<tr>
<th>Structure</th>
<th>Volume ((10^8 , \text{m}^3))</th>
<th>Net/gross ratio</th>
<th>Porosity</th>
<th>( \text{CO}_2 ) density ((U , \text{m}^3))</th>
<th>Theoretical ( \text{CO}_2 ) storage capacity (Gt)</th>
<th>Storage efficiency factor</th>
<th>Effective ( \text{CO}_2 ) storage capacity (Gt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hansholm</td>
<td>138.8</td>
<td>0.40</td>
<td>0.20</td>
<td>0.620</td>
<td>6.9</td>
<td>0.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Gassum</td>
<td>31.4</td>
<td>0.32</td>
<td>0.25</td>
<td>0.627</td>
<td>1.6</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Hanvsoe</td>
<td>25.0</td>
<td>0.67</td>
<td>0.22</td>
<td>0.629</td>
<td>2.3</td>
<td>0.4</td>
<td>0.9</td>
</tr>
<tr>
<td>Horsens</td>
<td>29.9</td>
<td>0.26</td>
<td>0.25</td>
<td>0.630</td>
<td>1.2</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Paastrup</td>
<td>15.8</td>
<td>0.23</td>
<td>0.10</td>
<td>0.625</td>
<td>0.2</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Roedby</td>
<td>14.2</td>
<td>0.18</td>
<td>0.24</td>
<td>0.620</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Stenlille</td>
<td>1.1</td>
<td>0.76</td>
<td>0.25</td>
<td>0.631</td>
<td>0.1</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Thisted</td>
<td>490.6</td>
<td>0.60</td>
<td>0.15</td>
<td>0.625</td>
<td>27.6</td>
<td>0.4</td>
<td>11.0</td>
</tr>
<tr>
<td>Toender</td>
<td>10.7</td>
<td>0.17</td>
<td>0.20</td>
<td>0.626</td>
<td>0.2</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Vedsted</td>
<td>4.3</td>
<td>0.74</td>
<td>0.20</td>
<td>0.633</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Voldum</td>
<td>30.1</td>
<td>0.38</td>
<td>0.10</td>
<td>0.630</td>
<td>0.7</td>
<td>0.4</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Total estimated regional \( \text{CO}_2 \) storage capacity (Gt) | 41.7 | 16.7
General considerations for saline aquifers

Distinguish between estimates for bulk volume of regional aquifers and estimates for individual stratigraphic/structural traps

For estimates based on the bulk volume of regional aquifers a storage efficiency factor of 2% based on work by US DOE is suggested

For trap estimates the choice of storage efficiency factor depends on whether the aquifer system is open, semi-closed or closed

For traps in open or semi-closed aquifer systems we suggest a rule-of-thumb approach with values for the storage efficiency factor in the range between 3 - 40%

Storage capacity estimates should always be accompanied with information on assumptions and approach for storage efficiency factor
Practical capacity with economic and regulatory barriers applied to effective capacity and with matching of sources and sinks: Site specific efficiency factor from reservoir simulations

Effective capacity with technical/geological cut off limits applied to theoretical capacity: Detailed estimates with evaluated efficiency factor

Theoretical capacity including large uneconomic/unrealistic volumes: Estimates without efficiency factor
Techno-Economic Resource-Reserve pyramid

- Joule II (1993) 800 Gt
- Practical capacity
- Effective capacity
- Theoretical capacity
Sedimentary basins - offshore
Why a Nordic CO2 Storage Atlas?
2010
Oljedirektoratet (Norwegian Petroleum Directorate)
CO$_2$ storage atlas for Norway – published December 2011

2011
The Nordic Top-level Research Initiative announces a call for proposals to support the establishment of a Nordic User Driven Competence Centre for realisation of Carbon Capture and Storage.

2011
NORDICCS is granted 35 mill. NOK for a 4 year period
- One of the major tasks is the creation of a Nordic CO$_2$ Storage Atlas.
NORDICCS is the Nordic CCS research and innovation platform involving the major CCS stakeholders in the five Nordic countries.

Activities

Integrating activities

- Building the Centre
- Defining a common basis

Joint R&D

- Collaborative research and development activities
- Sharing expertise and research infrastructure

Spreading excellence

- Communication to the general public
- Structured information dissemination among partners
NORDICCCS

Assumptions and premises (1)  Nordic CCS platform  Nordic CCS roadmap  Framework conditions  Economy

Strategies for CCS realisation

Feasibility studies on CCS industry cases

CO₂ capture
- Energy analyses (5)
- CCS Integrated (6)

In industry

CO₂ transport (4)
- Cost-effective CO₂ transport

Cement • BioCCS • Metal • Oil refineries • Power

CO₂ storage (2)
- The Nordic CO₂ storage atlas
- Guidelines for safe storage

R&D recommendations

Communication (3) and dissemination

Public awareness and acceptance  Dissemination and networking

Spreading excellence
Partners working with the Nordic storage atlas:
GEUS, SINTEF-PR, University of Oslo, SGU,
University of Iceland, Reykjavik Energy

The Nordic CO2 Storage Atlas
Review and update existing data bases and generate
“The Nordic CO2 Storage Atlas”

Guidelines for Safe Storage in the Nordic area
Define criteria, methods and timeframe for CO2 storage in the Nordic area

Safe Storage Modelling
Investigate the filling capacity for selected storage site cases and narrow
the uncertainty in storage capacity assessment
Expected result in 2015 – a GIS based Nordic CO₂ storage atlas
Thank you!