14th International Conference on Greenhouse Gas Control Technologies, GHGT-14

21st -25th October 2018, Melbourne, Australia

Characterization and Classification of CO_2 storage sites on the Norwegian Continental Shelf

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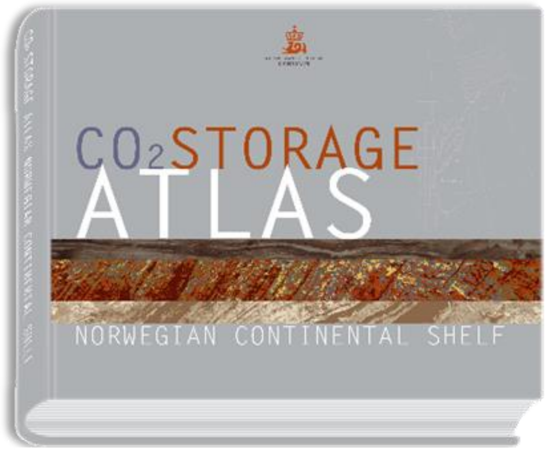
Abstract

Depending on their specific geological properties, several types of geological formations can be used to store CO_2. In the North Sea Basin, the greatest potential capacity for CO_2 storage will be in deep saline-water saturated formations or in depleted oil and gas fields.
The results presented in the CO_2 Storage Atlas are based on studies of all relevant geological formations and hydrocarbon fields on the Norwegian Continental Shelf (NCS). Norwegian Petroleum Directorate (NPD) has access to all data collected from the petroleum industry and has a national management responsibility for these data. This is vested in the Norwegian Petroleum Law. More than 50 years of petroleum activity has generated a large quantity of data. These data and analyses together with many years of dedicated work to establish geological play models, have given us a good basis for the characterization and classification of potential CO_2 storage sites.
The first step in site selection is the screening of potentially suitable formations and structures using specific criteria. In the site selection process, it should be demonstrated that the potential sites have sufficient capacity to store the expected CO_2 volume and sufficient injectivity for the expected rate of CO_2 capture and supply. The integrity of the site must be assessed for the period required by the regulatory authority to avoid any unacceptable risks to the environment, human health or other uses of the subsurface.
The aquifers were evaluated regarding reservoir quality and presence of relevant sealing formations. Those aquifers that may have a relevant storage potential in terms of depth, capacity and injectivity have been considered. The most attractive aquifers and structures were investigated by geomodelling and reservoir simulation.
In all models, it is assumed that there will be no water production. The volumes of injected CO_2 are constrained by the fracturing pressure. Our estimates of fracturing pressures are based on a large data base of leak-off tests and pore pressures in exploration wells. The regional fracture pressure trends are quite similar in North Sea and Norwegian Sea shelf, and somewhat lower in deeply eroded areas in the Barents Sea.
The scores for capacity, injectivity and seal quality are based on evaluation of each aquifer/structure. The checklist for reservoir properties gives a more detailed overview of the important parameters regarding the quality of the reservoir. These parameters are set into different checklists for detailed grading.

Keywords: CO_2 Storage sites; Characterization; Classification

1. Introduction

The CO_2 Storage Atlas of the Norwegian Continental Shelf (fig.1) [1] has been prepared by the Norwegian Petroleum Directorate, at the request of the Ministry of Petroleum and Energy.
The main objective with this study has been to identify safe and effective areas for long-term storage of CO_2. This evaluation of the geological formations, aquifers and structures for potential CO_2 storage will form the basis for any terms and conditions set for a development of a storage site offshore Norway.
The studied areas are in parts of the Norwegian Continental Shelf (NCS) which have been opened for petroleum activity (fig.2) and covers The Norwegian North Sea, The Norwegian Sea and The Barents Sea. Regulations for CO_2transport and storage on NCS were published in 2014 [2]. The regulation has adopted the EU CCS Directive and the regulatory system from our offshore petroleum regulation.



Fig*ure*.1 The Norwegian CO_2 Storage Atlas.

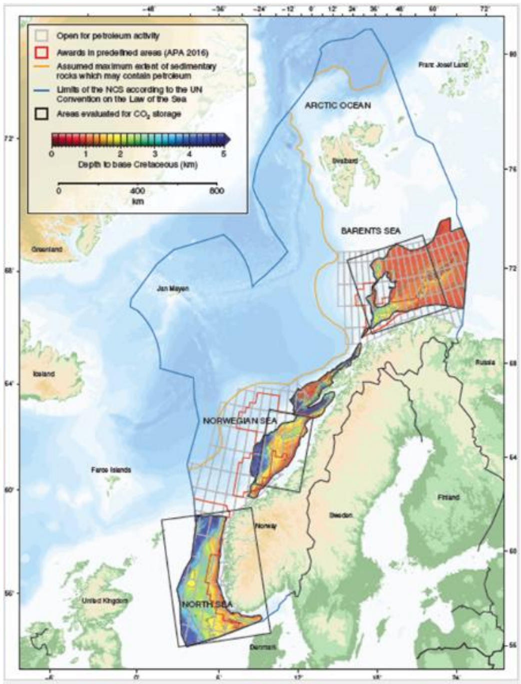


Figure2 Areas offshore Norway evaluated for potential CO_2 storage.

The NPD's data, overviews and analysis make up an important and large fact basis from more than 50 years of oil and gas activities on the Norwegian Continental Shelf (NCS). The Norwegian Petroleum Directorate (NPD) has access to all data collected on the NCS related to the petroleum activity and has a national responsibility for the data. The data available for the CO_2 storage studies covers 2D and 3D seismic data (fig.3), data from exploration and production wells such as logs, cuttings and cores as well as tests, production data and reservoir simulation models. These data, together with many years of dedicated work to establish geological play models for the NCS, have given us a good basis for characterization and capacity estimation of the evaluated CO_2 storage sites presented by this study. Two carbon capture and storage (CCS) gas projects are in operation on NCS today. The projects were established to meet the requirement of maximum allowed CO2 content in the exported gas. CO_2 is captured from the produced gas in the Sleipner area gas fields and injected at the same facility into the Utsira geological formation in the North Sea. In the Snøhvit subsea field in the Barents Sea, CO_2 is captured from the separated gas at the onshore process plant (LNG) and then piped offshore for injection through a subsea well [3].

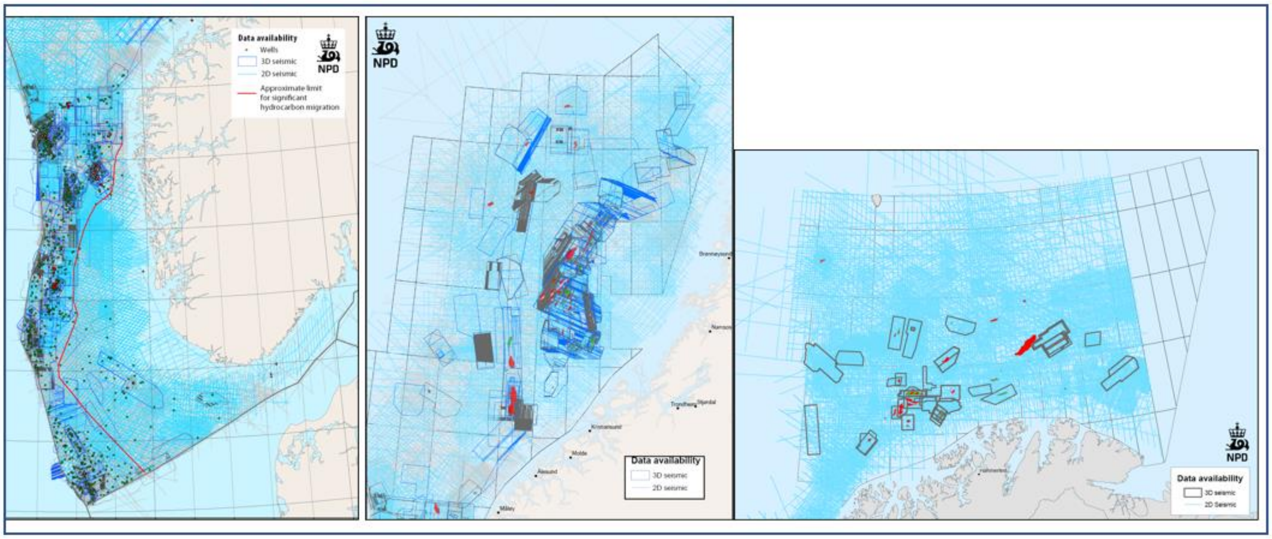


Figure 3 Seismic data coverage in the North Sea, Norwegian Sea, and The Barents Sea

2. A suitable CO_2 Storage Site

Storage of carbon dioxide is about keeping the CO_2 secured underground in a geological reservoir. To be suitable for CO_2 storage, reservoir formations need to have sufficient porosity and permeability to allow the defined volumes of CO_2 to be injected and stored, preferably in a supercritical state and to have a caprock with good quality and integrity (Fig.4) [4]. The quality and integrity of caprock preventing leakage from the reservoir is no less important than having good reservoir properties. The availability to design and develop a good monitoring system is also of paramount importance.

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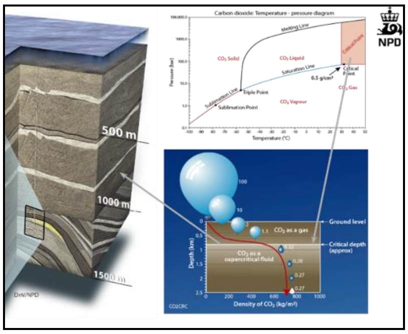

Figure 4. Supercritical conditions for CO_2 occur at 31.1°C and 7.38 megapascals (MPa), which occur approximately 800 meters below surface level. This is where the CO_2 has both gas and liquid properties and is 500 to 600 times denser (up to a density of about 700 kg/m3) than at surface conditions.

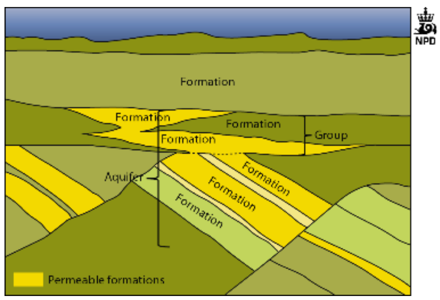

Figure.5 Relation between geological formations and aquifers.

The reservoir where CO_2 will be stored may consist of several connected geological formations (Fig.5). In the NCS CO_2 Storage Atlas such connected formations are referred to as aquifers. An aquifer can be described as a volume of connected permeable and porous formations which are sealed from other aquifers above, below and laterally by tight rocks, faults or other barriers. In an aquifer, the virgin pore pressure gradients will plot on one line or be displaced by a few bars only. When the aquifer is defined and characterized, the migration pathways and the plume development of the injected CO_2 can be modelled in the selected storage area. The CO_2 storage site selection process should demonstrate that the site has sufficient capacity to store the expected CO_2 volumes and sufficient injectivity for the expected rate of CO_2 captured and supplied. The integrity of the site must be assessed for the period required in the regulations, to avoid any unacceptable risks to the environment

In the NCS different types of aquifers and structures can be distinguished according to their geometry and storage efficiency, listed below.

- Structured aquifers.
- Monoclinal dipping aquifers
- Structural closure, abandoned gas fields.
- Structural closures, drilled and water-bearing
- CO2 storage with EOR in structures with oil or residual oil

In all models the volumes of injected CO2 are constrained by the fracturing pressure. Our estimates of fracturing pressures (Fig. 7) are based on a large data base of leak-off tests and pore pressures in exploration wells.
In exploration wells on NCS, pressure differences across faults and between reservoir formations and reservoir segments are commonly observed. Such pressure differences give indications of the sealing properties of cap rocks and faults. Based on the observations in the hydrocarbon provinces, combined with a general geological understanding, one can use the sealing properties in explored areas to predict the properties in less explored or undrilled areas.

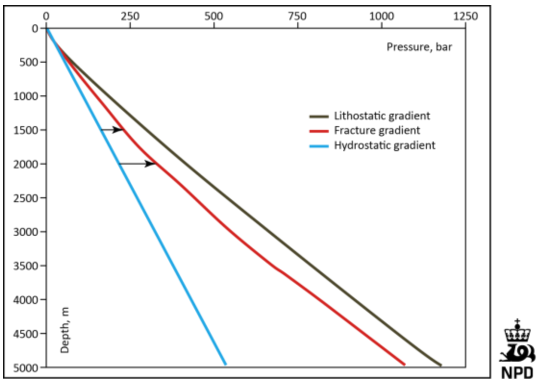

Figure 6. Pressure gradients obtained from pore pressure data and leak-off tests in wells from the Norwegian Sea and North Sea at water depths between 250 and 400 m. The fracturing gradient marks the lower boundary of measured leak-off pressures and the upper boundary of measured pore pressures. The lithostatic gradient was calculated from general compaction curves for shale and sand with a 300m water column. The hydrostatic gradient assumes sea water salinity. The arrows show how much pressure can be increased from hydrostatic pressure before it reaches the fracture gradient. In deeply eroded areas in the Barents Sea the fracturing pressures seem to be somewhat lower.

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3. Characterization of a Geological CO_2 Storage site

The characterization of potential CO_2 storage sites is an important step for ensuring the safety and integrity of a CO_2 storage project and is essential in selecting possible locations for a CCS chain. [5]. The methods used for characterization of reservoir properties are similar to well-established methods used in petroleum exploration. Characterization of cap rocks and injectivity is typically conducted in studies of field development and to some extent in basin modelling.

In subsequent steps in the workflow, pairs of potential aquifers and seals were identified, evaluated and characterized for their CO_2 storage prospectivity. Aquifers and structures within aquifers were characterized in terms of capacity, injectivity and safe storage of CO_2. Each parameter was rated with a score described in the detailed checklists and summarized to the characterization score chart for reservoir and seal, where 3 is the highest score (fig.7). The checklist for reservoir properties (fig.8 a, b) gives a more detailed overview of the important parameters regarding the quality of the reservoir. Some of the parameters were weighted, as shown in the tables. Important elements when evaluating reservoir properties are aquifer structuring, traps, thickness porosity and permeability of the reservoir.

CHARACTERIZATION OF AQUIFERS AND STRUCTURES

	Criteria	Definitions, comments	
Reservoir quality	Capacity, communicating volumes	3	Large calculated volume, dominant high scores in checklist
		2	Medium - low estimated volume, or low score in some factors
		1	Dominant low values, or at least one score close to unacceptable
	Injectivity	3	High value for permeability * thickness (k*h)
		2	Medium k*h
		1	Low k*h
Sealing quality	Seal	3	Good sealing shale, dominant high scores in checklist
		2	At least one sealing layer with acceptable properties
		1	Sealing layer with uncertain properties, low scores in checklist
	Fracture of seal	3	Dominant high scores in checklist
		2	Insignificant fractures (natural / wells)
		1	Low scores in checklist
Other leak risk	Wells	3	No previous drilling in the reservoir / safe plugging of wells
		2	Wells penetrating seal, no leakage documented
		1	Possible leaking wells / needs evaluation
Data coverage	Good data coverage	Limited data coverage	Poor data coverage

Other factors:
How easy / difficult to prepare for monitoring and intervention. The need for pressure relief. Possible support for EOR projects. Potential for conflicts with future petroleum activity.

Data coverage
Good : 3D seismic, wells through the actual aquifer/structure
Limited : 2D seismic, 3D seismic in some areas, wells through equivalent geological formations
Poor : 2D seismic or sparse data

NPD

Figure 7 From the NCS CO_2 Storage Atlas: Summary characterization score chart for reservoir and seal

CHECKLIST FOR RESERVOIR PROPERTIES

NPD

Typical high and low scores		
Reservoir Properties	High	Low
Aquifer Structuring	Mapped or possible closures	Tilted, few /uncertain closures
Traps	Defined sealed structures	Poor definition of traps
Pore pressure	Hydrostatic or lower	Overpressure
Depth	800- 2500 m	< 800 m or > 2500 m
Reservoir	Homogeneous	Heterogeneous
Net thickness	> 50 m	< 15 m
Average porosity in net reservoir	> 25 %	< 15 %
Permeability	> 500 mD	< 10 mD

Reservoir Parameters	Capacity weight	Injectivity weight	Comment
Rock volume	3		Net rock volume is appropriate in case of low net reservoir
Structuring	1		Potential for the top surface to form closures
Traps	1		Mapped structures interpreted to be 4-way closures
Pore pressure	1	1	Depleted, hydrostatic, overpressured
Depth	1	1	Depth of burial relative to optimal window 1000-2500 m
Reservoir		3	Homogeneous - heterogeneous
Thickness		1	Net thickness of reservoir sand
Porosity	3		Average porosity in net reservoir
Permeability		3	Average horizontal permeability

NPD

Figure 8 a Checklist for reservoir properties. b, Weighted reservoir parameters

CHECKLIST FOR SEALING PROPERTIES			
Typical high and low scores			
Sealing Properties	High	Low	Unacceptable values
Sealing layer	More than one seal	One seal	No known sealing layer over parts of the reservoir
Properties of seal	Proven pressure barrier/ > 100 m thickness	< 50 m thickness	
Composition of seal	High clay content, homogeneous	Silty, or silt layers	
Faults	No faulting of the seal	Big throw through seal	Tectonically active faults
Other breaks through seal	No fracture	sand injections, slumps	Active chimneys with gas leakage
Wells (exploration/ production)	No drilling through seal	High number of wells	

Cap rock Parameters	Seal weight	Well weight	Comment
Number of seals	1		Overlying sealed aquifer(s) with storage capacity
Thickness/barriers	1		Thickness of seal/ seal capacity proved in analogous cases
Composition	1		Shale, silty layers, mineralogy of shale
Faults	1		Geometry and modelled property of fault zone
Other indications	1		Seismic indications of gas leakage
Well penetrations		1	Number and status of wells penetrating seal

Figure 9a Checklist for sealing properties. b, Weighted sealing parameters evaluated storage sites

A supplementary checklist was developed for the sealing properties (fig.9 a, b).
For the sealing properties, the thickness of the seal, number of seals, composition, faults zones, geometry, activity and if there are mappable faults crossing the seal needs a thorough evaluation. Evaluation of faults and fractures through the seal, in addition to the integrity of existing wells penetrating the seal, provides important information on the sealing quality. For evaluation of regional aquifers in CO2 storage studies, the mineralogical composition and the petrophysical properties of the cap rocks are rarely well known and will then be based on knowledge of the regional geology.
Based on this evaluation and characterization, selected potential storage sites were mapped and the storage capacity was calculated for structures and aquifers. The most attractive aquifers and structures were further evaluated by geomodelling and reservoir simulation. The evaluation presented in The NCS CO2 Storage Atlas does not provide an economic assessment of the.
To complete the characterization, the aquifers were also evaluated according to the extent of data coverage. The data coverage is color-coded to illustrate the amount of data available for each aquifer and structure. Even though an extensive database has been available for our evaluation, evaluation of some areas is more uncertain due to limited seismic coverage and lack of wells. Natural seepage of gas is commonly observed in the hydrocarbon provinces in the Norwegian continental shelf. Such seepage is expected from structures and hydrocarbon source rocks where the pore pressure is close to or exceeds the fracture gradient. Seepage at the sea floor can be recognized by biological activity and by free gas bubbles. Seismically, seepage is indicated by gas chimneys or pipe structures. The seepage rates at the surface indicate that the volumes of escaped gas through a shale or clay dominated overburden are small in a time scale of a few thousand years. Rapid leakage can only take place if open permeable conduits are established to the sea floor. Such conduits could be created along wellbores or by reactivation of faults or fractures. However, established natural seepage systems are also regarded as a risk factor for CO_2 injection.

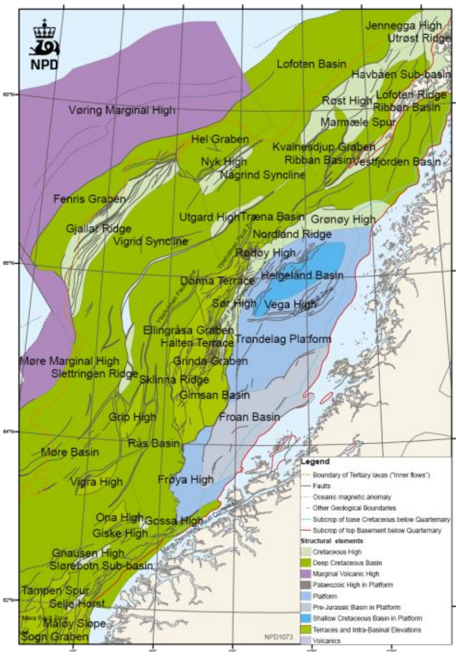
4. Capacity estimation

Several methods have been proposed to calculate the theoretical CO_2 storage capacity for saline formations [6,7]. The uncertainty in the estimates of capacity appears to depend strongly on three factors. 1) The accessibility of good

data, 2) the maturity of the selected area and 3) the assumptions used for estimating storage efficiency. In our calculations, it is assumed that volumes of injected CO_2 are constrained by the fracturing pressure, and storage efficiency is based on simple assumptions of whether the aquifer is open, closed or half-open.
In this work, it is not attempted to estimate uncertainty ranges for the capacities presented in the CO_2 atlas. The reason for this is that the main purpose of the atlas was to document and compare aquifers with significant storage potential as a first stage in the selection process. For further qualification of a storage site, a detailed uncertainty study must be provided.

As an example of a capacity estimate at aquifer level, the Froan Basin in the Norwegian Sea is shown here (fig.10a). This aquifer represents long distance migration in dipping geological formations. The main objective of this study was to estimate the amount of CO_2 that can be safely stored, mainly based on reservoir simulation. Of interest here, is the understanding of the timing and extent of long distance CO_2 migration in dipping reservoirs.
In the case of permeable beds occurring along the dip slope there is a risk that CO_2 injected down dip can migrate up to where the aquifer is truncated by the Pleistocene glacial sediments (fig.10b). This setting is like several other aquifers on the Norwegian Continental Shelf. The aquifers evaluated for CO2 storage in this area are located at a depth between 600 and 3500 m and well data shows that they have a sufficiently high permeability, porosity and connectivity to be suitable for injection and storage of CO_2.
The Froan Basin was formed by Permian-Early Triassic block faulting. The pre-Jurassic rocks of the Trøndelag Platform were deposited in the NE-SW trending echelon basins. In the early and middle Jurassic, the platform area subsided as one large basin, and the rate of sedimentation was in equilibrium with the rate of subsidence. Consequently, there is a relatively uniform thickness of Jurassic sediments overlying the Triassic and locally the Paleozoic graben infill [8]. Reservoirs which could possibly be used for CO2 injection are the Triassic and Jurassic sandstones. The main seal rocks are the middle to upper Jurassic Melke Fm and Spekk Fm shales as well as the overlying fine grained Cretaceous section. The main risk of leakage is the migration of CO_2 towards the Pleistocene layer and seepage to the sea floor (fig.10b). Well data show that all Jurassic formations are in hydrostatically pressures. It is supposed that sandstones in the Garn and Ile Formations form one aquifer, although the shales between and within the formations will constitute local seals (Fig.11).
A reservoir simulation sector model of the Garn, Not and Ile Formations was built covering about 10% of the total expected communicating aquifer volume. The top structure (Garn Fm) depth is about 1800 m in the western area and becomes shallower towards the East, with model cut-off at about 500 m depth. The main storage reservoirs are the Garn and Ile Formations with an average permeability of about 400 mD, separated by tight shales within the Not Formation. The Garn Formation consists of three reservoir zones, separated by low permeable shales.
The porosity and permeability have been stochastically modelled with both areal and vertical variation. The model layers are fine (<1m) at the top reservoir and underneath the shales to capture the vertical CO_2 saturation distribution. The CO_2 injection well is located down dip, but alternative locations and injection zones have been simulated with different injection rates.
The injection period is 50 years, and the simulation continues for 10,000 years to study the long-term CO_2 migration effects. CO_2 will continue to migrate upwards as long as it is in a free movable state.

Migration stops when CO_2 is permanently bound or trapped, by going into solution with formation water or by being residually or structurally trapped (mineralogical trapping has not been considered). Achieving trapping of sufficient volumes depends on a good sweep of the injected CO_2. Vertical spreading can to some extent be controlled by injecting into lower reservoir zones, but it is sensitive to vertical permeability and also zonal permeability distribution in the area near the well. Areal sweep can mainly be achieved through use of several injectors. Different injection rates and volumes have been simulated and upscaled to the estimated aquifer volume.



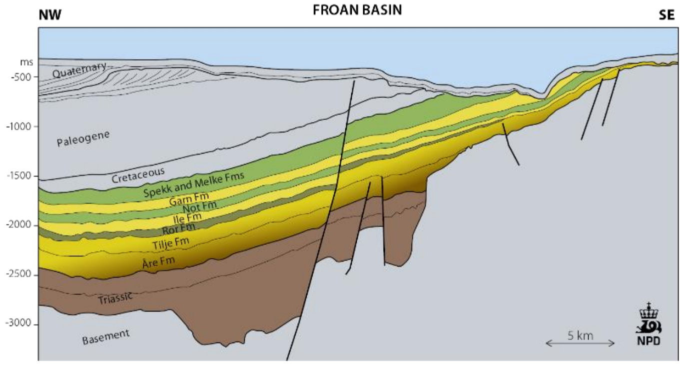


Figure 10a. Structural element map. The green area represents basins with thick Cretaceous infill, where Jurassic sediments are generally deeply buried..b). NW-SE profile showing the geometry of aquifers (yellow) and sealing formations (green) through the Froan Basin.

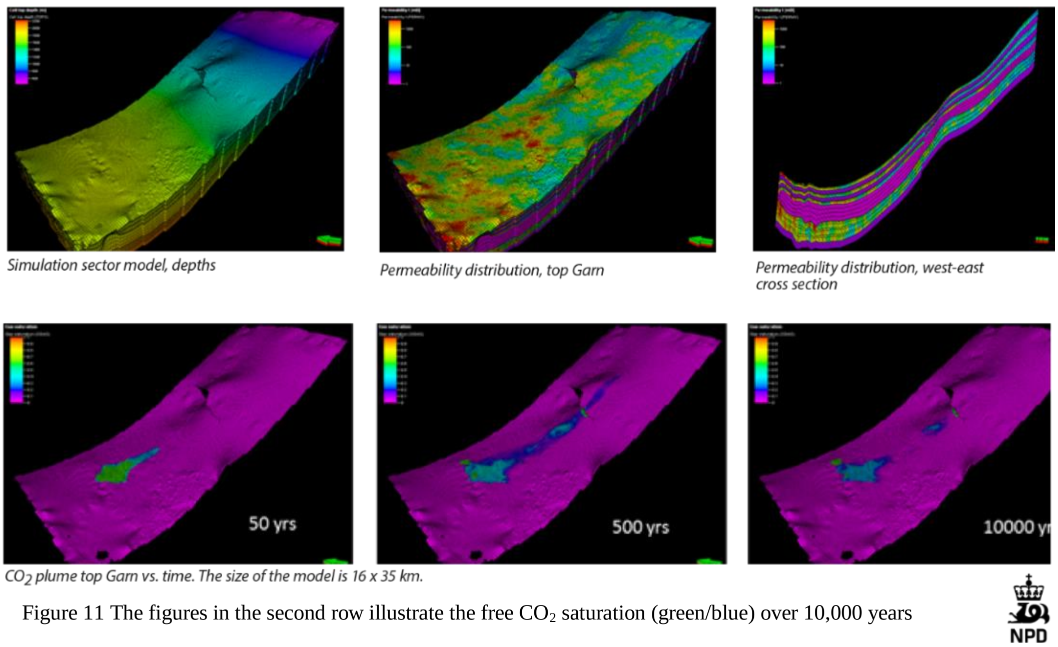


Figure 11 The figures in the second row illustrate the free CO_2 saturation (green/blue) over 10,000 years

The main upscaled scenario injects 8 MSm3 CO_2/day for 50 years. After 10.000 years the model indicates that most of the CO_2 will have gone into solution with the formation water or is residually trapped. In the table (fig.12), the results for the Garn – Ile aquifer, with a half-open case and a closed case for the aquifer, are presented to illustrate how important this assumption is for the estimates of storage volumes. Large volumes can theoretically be stored if the aquifer is in pressure communication with additional large water volumes. In the Garn-Ile case, such pressure communication could take place with sea water through the Pleistocene sediments above the truncated aquifer. In a closed aquifer case, an alternative might be to inject CO_2 and produce water. The most optimistic case would be to assume that closed structures with a large storage capacity exist and could be filled with CO_2, without any migration to the half-open eastern boundary.

The Garn/Ile aquifer		**Summary**	**Summary**
Storage system		half open	closed
Rock volume, m^3		4400 Gm^3	4400 Gm^3
Net volume, m^3		1100 Gm^3	1100 Gm^3
Pore volume, m^3		300 Gm^3	300 Gm^3
Average depth Garn Fm		1675 m	1675 m
Average depth Ile Fm		1825 m	1825 m
Average net/gross		0.25	0.25
Average porosity		0.27	0.27
Average permeability		580 mD	580 mD
Storage effieciency		4 %	0.2 %
Storage capacity aquifer		8 Gt	0.4 Gt
Reservoir quality			
	capacity	2	2
	injectivity	3	3
Seal quality			
	seal	3	3
	fractured seal	3	3
	wells	3	3
Data quality			
Maturation			

Figure12 Summary of the Froan Basin storage evaluation with half open and a closed storage system.

5. Classification of CO_2 Geological Storage

The evaluation of geological volumes suitable for injecting and storing CO_2 can be viewed as a stepwise approximation from purely hypothetical volumes up to ready for development. Our database supports us in the process of defining storage volumes in our defined maturation pyramid (modified after Bachu et al 2009[9]). This pyramid classifies the technical maturity and the knowledge of how suitable the evaluated geological area is for storage of CO_2. The different steps in the maturation, illustrated by the pyramid, are color coded. We have used the same process as in development of hydrocarbons, by connecting different steps in maturation of an area with corresponding levels in the pyramid. The evaluation carried out in the Norwegian CO_2 storage Atlas does not provide an economic assessment of the storage sites, and the storage capacities presented are deterministic. The uncertainty is illustrated by color coding in data availability and maturity. All based on the characterization system developed for this study.

The lowermost segment, blue color, represents volumes calculated from average porosity and thickness. This is done in a screening phase that identifies potential aquifers that can be suitable for storage of CO_2. The theoretical volume is based on depositional environment, diagenesis, bulk volume from area and thickness, average porosity, permeability and net/gross values.

The green color represents aquifers with more data available. The storage volumes are calculated and areas with possible conflicts of interest have been excluded. Only aquifers and prospects of reasonable size and quality are evaluated. Evaluation is based on all relevant available data.
The yellow color refers to storage volumes where trap, reservoir and seal have been mapped and evaluated in terms of regulatory and technical criteria to ensure safe and effective storage.
Red color represents the phase where injection of CO_2 into a storage site is ongoing. Throughout the injection period, the injection history is closely evaluated, and the experience gained provides further guidance on the reservoirs ability and capacity to store CO_2.

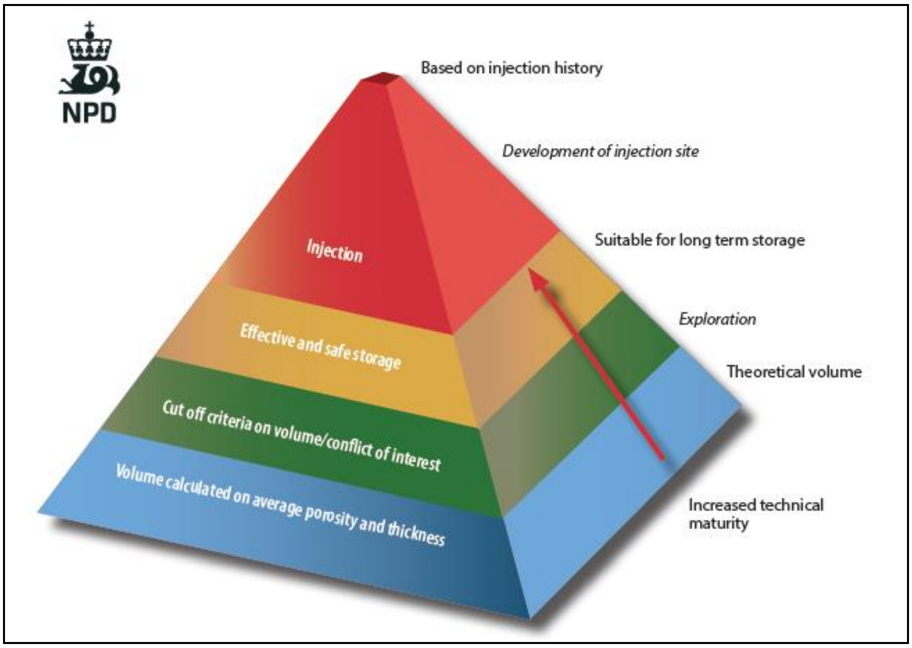


Figure 13 CO_2 Pyramid illustrating increased technical maturity

UNFC (UNECE), presented a classification system for CO_2 Injection projects in 2016 [10] and SPE has worked with a classification system, SRMS, [11]. A big effort has been done by the two groups to develop these classifications. The basis for both these classification systems are the established classification systems for oil and gas projects. Both systems are built on geological knowledge, data availability and project maturity.
An attempt has been made here to correlate the NPD classification, defined by the maturation pyramid, with these two classification systems (Fig.14).
Comparing classification for CO_2 storage capacity with classification for hydrocarbon resources and reserves and draw comparisons between extraction and injection projects can cause some challenges.

Hydrocarbons are usually trapped in structures or stratigraphic traps, while CO_2 storage sites are classified by the presence of porous and permeable geological formations. These can be represented by defined structures or large aquifers. For oil and gas discoveries categorization of economic reserves are defined by the licensee developing the field. With a continuous effort through the production phase to mature as much as possible of the hydrocarbons from resources to reserves.

UNECE	UNECE Sub-Class	SRMS	SRMS Sub-Class	NPD
Commercial Injection Projects	Development/ Active Injection	**Discovered Storage Resources/ Commercial**	Capacity	Development of Injection site
Potential Commercial Injection Projects	Development Unclarified	**Discovered Storage Resources/Sub-Commercial**	**Contingent Storage** Resources	Suitable for Long term storage
Undiscovered Reservoir/Screening projects	Geological Storage Indicated/ Identified	**Undiscovered Storage Resources (Prospect)**	Prospective Storage Resources	Exploration Phase
Screening projects	Geological Storage Inferred	**Undiscovered Storage Resources (Lead, Play)**	Prospective Storage Resources	Theoretical storage volume

Figure 14 A comparison between the UNECE, SPE and NPD s classification system.

The two classification systems define an economically viable CO_2 storage volume (capacity or reserves). How much CO_2 to be injected will be defined by the volume of CO_2 needed to be stored from an economic CCS project. For an economic evaluation, the resource estimation can be defined with a probability (P10-P50-P90), but the reserves or capacity will be estimated by the need for a defined CO_2 volume to be stored. The Authorities regulations for safe and feasible storage site will be evaluated based on the characterization system developed in this study and the project economy will be a part of the total CCS development.

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