

# From Arrhenius to CO<sub>2</sub> Storage

## Part V: Underground Storage of CO<sub>2</sub>

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*"It is important that carbon storage is carefully regulated, that the process is transparent to the public, and that there is a clear accounting of what happened to the CO<sub>2</sub>. This is particularly true of underground storage, where there is always a small chance that pressurised CO<sub>2</sub> could escape."*

*Klaus Lackner,  
Director CNSE (Center for Negative Carbon Emissions)*

**By building on knowledge from the petroleum industry and experience over 23 years of storing CO<sub>2</sub> in deep geological formations, we can make a new value chain and a business model for carbon capture and storage in the North Sea Basin.**

Storage of carbon dioxide is about keeping the CO<sub>2</sub> secured underground in a geological reservoir. Carbon capture, transport and storage (CCS) is a process whereby carbon dioxide (CO<sub>2</sub>) is captured from energy production or industrial plants, transported in pipelines or by ships, and deposited so it will not enter the atmosphere. Deep underground storage is the only current means of disposing of large amounts of CO<sub>2</sub> safely and permanently.

### CO<sub>2</sub> Storage on NCS

A new CO<sub>2</sub> storage site is now under development on the Horda Platform, in the Johansen geological formation south of the Troll Field. This is part of the Norwegian government's initiative to develop a full-scale demonstration CCS project.

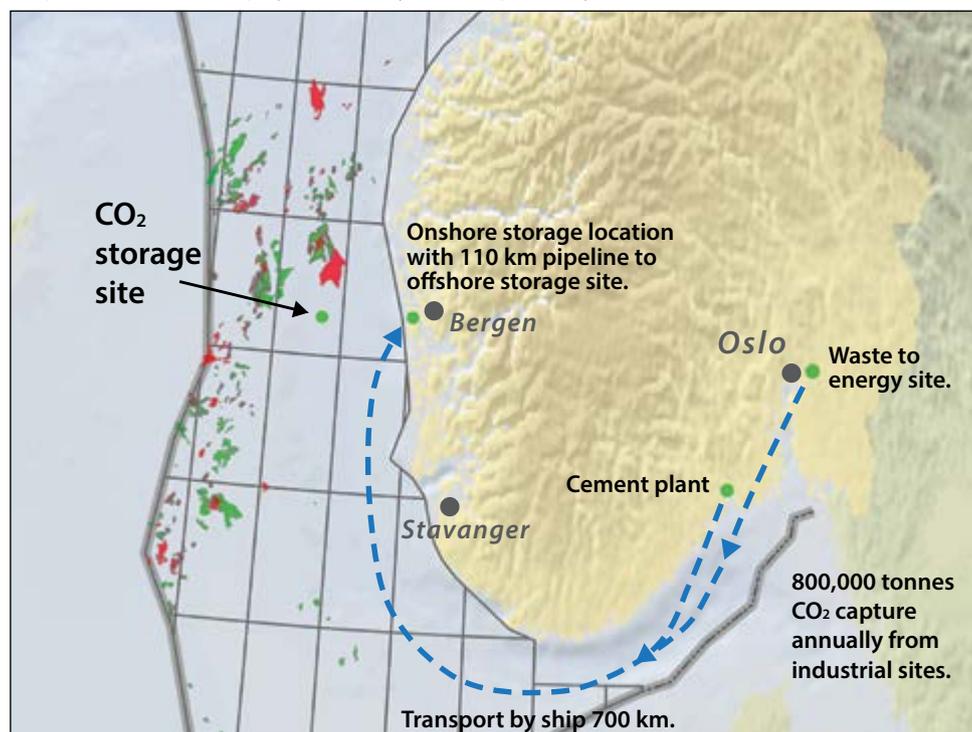
The government issued feasibility studies on CCS solutions in 2016 with the ambition of developing a full-scale CCS value chain in Norway. This project includes the capture of CO<sub>2</sub> from industrial sources in the Oslo Fjord region, ranging from cement and waste to energy, and the shipping of liquid CO<sub>2</sub> to an onshore terminal at Kollsnes on the Norwegian west coast. From there, the liquified CO<sub>2</sub> will be piped and injected into the Johansen Formation south of the Troll Field area for permanent storage.

This is the first industrial CCS project to develop an open access infrastructure with the intent and capacity to store significant

volumes of CO<sub>2</sub> from across the European continent. It was initiated when the Ministry of Petroleum and Energy awarded EL001, the first CO<sub>2</sub> exploitation licence on the NCS, to Equinor in January 2019. Together with partners, Shell and Total, the company is responsible for the transport and storage part of this government-initiated CCS project.

Two CO<sub>2</sub> storage sites have already been developed and are in operation on the Norwegian Continental Shelf today. These projects were established to meet the requirement for a maximum CO<sub>2</sub> content allowed in exported gas, and as a result of the CO<sub>2</sub> tax imposed on petroleum activity in 1991. The first project was designed to capture CO<sub>2</sub> from the produced gas at

*The planned full scale CCS project in Norway. (Base map courtesy NPD).*





Harald Petersen/Equinor.

Gas is piped from the Barents Sea Snøhvit field to the Melkøya LNG processing plant, where the CO<sub>2</sub> is separated out and sent back to be injected into the depleted reservoirs.

the Sleipner Vest gas field in the North Sea through the Sleipner T capture facility and inject it into the Utsira Formation; this was the world's first offshore CCS project. Today, three hydrocarbon fields capture CO<sub>2</sub> through the Sleipner T facility and inject through the same well. These fields are Sleipner Vest, which started CO<sub>2</sub> injection in 1996, the Gudrun Field, from 2014 and the Utgard Field, which started in 2019.

The second storage site was developed in the Snøhvit area in the Barents Sea, where CO<sub>2</sub> is captured from the separated gas at the onshore LNG processing plant at Melkøya in northern Norway, and then piped back offshore for injection through a subsea well.

### A Suitable Storage Site

To be suitable for CO<sub>2</sub> storage, reservoir formations need to have sufficient porosity and permeability to allow the defined volumes of CO<sub>2</sub> to be injected and stored, preferably in a supercritical state. No less important is the requirement of a caprock of good quality and integrity, in order to prevent leakage from the reservoir. The design and development of a good monitoring system is also of paramount importance.

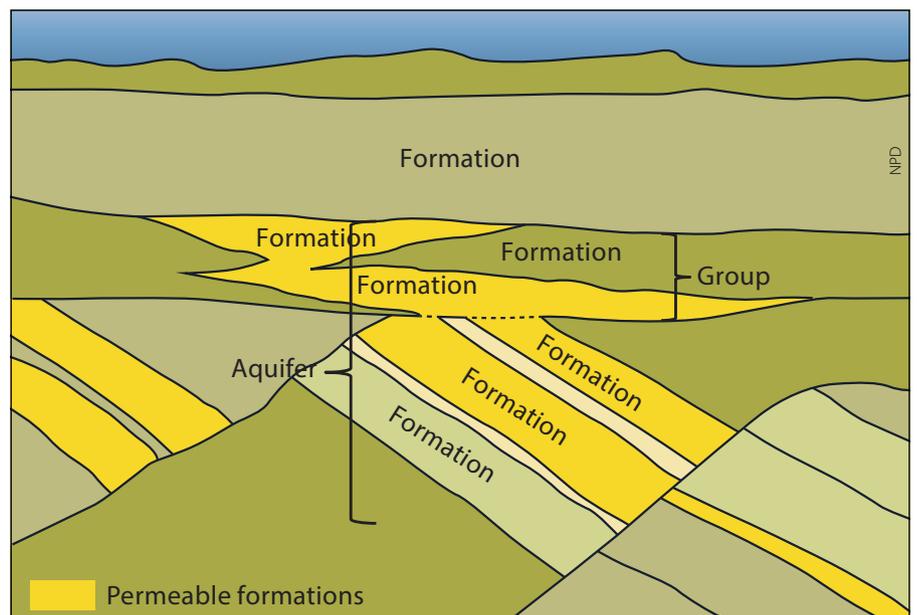
The CO<sub>2</sub> storage site selection process needs to demonstrate that the site has enough capacity to store the expected volumes and sufficient injectivity for the anticipated rate of CO<sub>2</sub> to be captured and supplied. The integrity of the site must also be assessed for the period required by the

regulator, to avoid any unacceptable risks to the environment.

Depending on their properties, several types of geological formations can be used to store CO<sub>2</sub>. On the NCS different aquifers and structures can be distinguished according to their geometry and storage efficiency; for example, they could include structured or dipping aquifers, drilled and water-bearing structures, or abandoned gas or oil fields.

Ultimately, CO<sub>2</sub> is held in place in a storage reservoir through one or a combination of five basic trapping mechanisms: stratigraphic, structural, residual, solubility, and mineral trapping.

The relation between geological formations and aquifers.



### Characterising Potential Sites

CCS has strong ties to the oil and gas industry. What we know about the offshore geology and its potential to store CO<sub>2</sub> builds on decades of research and experience from oil and gas activity. The Norwegian Petroleum Directorate (NPD)'s database, overviews and analysis make up a large and important information source based on more than 50 years of oil and gas activities and 23 years of CO<sub>2</sub> injection on the NCS. The Directorate has access to all data collected on the NCS related to petroleum activity and has a national management responsibility for these data, vested in the Norwegian Petroleum Law. The data available for the CO<sub>2</sub> storage studies covers 2D and 3D seismic, 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, are a good basis for characterisation and capacity estimation to help in the evaluation of suggested CO<sub>2</sub> storage sites.

The characterisation of potential sites is an important step in ensuring the safety and integrity of a CO<sub>2</sub> storage project. The methods used for characterisation of reservoir properties are similar to the well-established methods used in petroleum exploration. Characterisation of cap rocks and injectivity, for example, is typically conducted in field development studies and to some extent in basin modelling. Aquifers and structures can similarly be characterised in terms of capacity, injectivity, and safe storage of CO<sub>2</sub>. To complete the characterisation, the aquifers are also evaluated according to the data coverage and their technical maturity. Some guidelines have been developed to facilitate the characterisation.

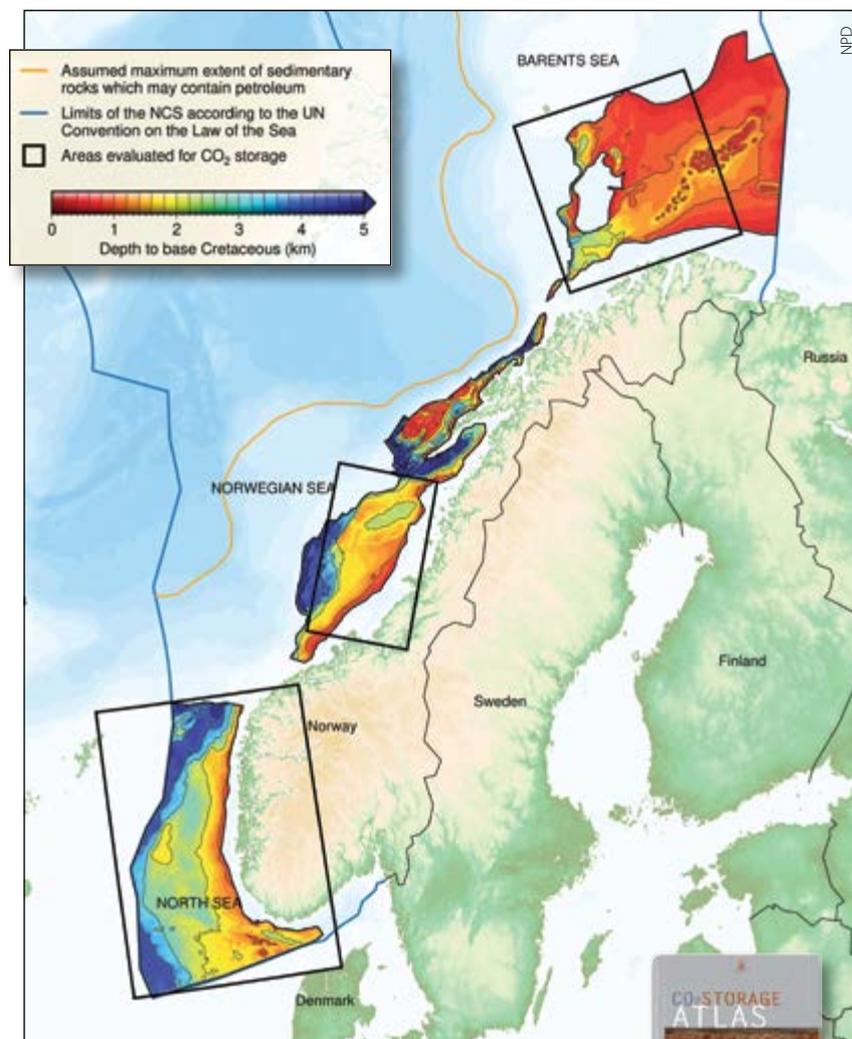
Those aquifers that may have a relevant storage potential in terms of depth, capacity and injectivity have been considered. The most attractive aquifers and structures were investigated by geomodelling and reservoir simulation. For estimation of storage capacity in all models, it is assumed that there will be no water production from the reservoir.

### The Norwegian CO<sub>2</sub> Storage Atlas

The NPD published a *CO<sub>2</sub> Storage Atlas* for the Norwegian Continental Shelf in 2014, the main objective of which was to identify safe and effective areas for long-term storage of the gas.

Pairs of potential aquifers and seals were identified, evaluated and characterised for their CO<sub>2</sub> storage prospectivity. Each parameter was rated with a score described in detailed checklists and summarised on the characterisation score chart for reservoir and seal.

Evaluation of faults and fractures through the seal, the



Areas on the NCS evaluated for CO<sub>2</sub> storage, as identified in the NPD's CO<sub>2</sub> Storage Atlas (inset).

thickness of the seal, number of seals, composition, faults zones and geometry needs a thorough evaluation, in addition to ensuring the integrity of existing wells penetrating the seal. For the evaluation of regional aquifers in CO<sub>2</sub> storage studies, the mineralogical composition and the petrophysical properties of the cap rocks are rarely well known, so they will then be based on knowledge of the regional geology.

The volumes of CO<sub>2</sub> that can be injected are constrained by the fracturing pressure, which is based on a large database of leak-off tests and observed pore pressures in exploration wells. Pressure differences across faults and between reservoir formations and reservoir segments are commonly observed in NCS exploration wells. Such pressure differences give indications of the sealing properties of cap rocks and faults.

Storage capacity depends on several factors, primarily the reservoir pore volume and the fracturing pressure. The relation between pressure and injected volume depends on the compressibility of the rock and the fluids in the reservoir. The solubility of CO<sub>2</sub> in the different phases will also play a part. It is important to know if there is communication between multiple reservoirs, or if the reservoirs are in communication with larger aquifers because the pressure will

increase when injecting fluid into a closed or half-open aquifer. Pressure increase can, however, be mitigated by production of formation water.

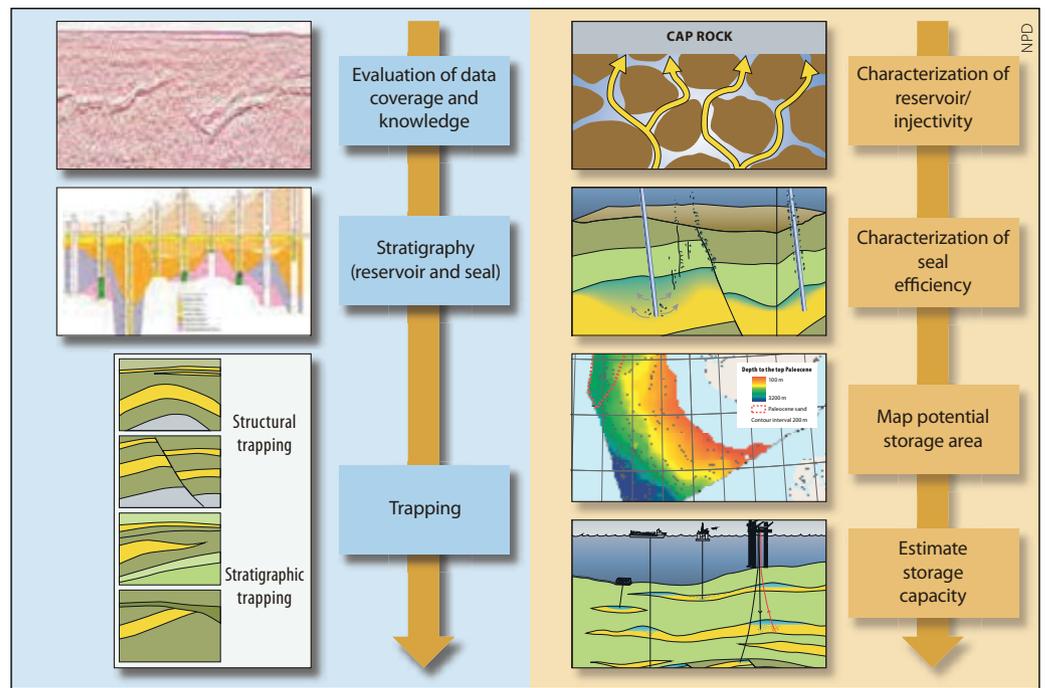
Based on this evaluation and characterisation, selected potential storage sites were mapped and the storage capacity was calculated for structures and aquifers. The evaluation presented in the CO<sub>2</sub> Storage Atlas does not provide an economic assessment. The storage capacities are presented in a pyramid diagram, where the highest level in the pyramid represents the capacity of sites that are already used for CO<sub>2</sub> storage, while the lowest level represents theoretical capacity in lesser-known aquifers.

### Monitoring

An important matter when injecting CO<sub>2</sub> is to ensure that the gas is contained in the reservoir according to plans and predictions and that there is no leakage to other geological formations or into the sea. When the aquifer is defined and characterised, the migration pathways and the plume development of the injected CO<sub>2</sub> can be modelled in the selected storage area.

Natural seepage of gas is observed in the hydrocarbon provinces in the NCS. 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 recognised by changes in biological activity and by free gas bubbles or, on seismic, by gas chimneys or pipe structures. The seepage rates at the surface show 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 conduits are established to the sea floor. Such conduits could be created along wellbores or by reactivation of faults or fractures. Established natural seepage systems are also regarded as a risk factor for CO<sub>2</sub> injection.

A wide range of monitoring technologies have been used by the oil and gas industry to track fluid movement in the subsurface and these techniques can be adapted to CO<sub>2</sub> storage. For example, repeated seismic surveying provides images of the subsurface, allowing the behaviour of the stored CO<sub>2</sub> to be mapped and predicted. Other techniques include pressure and temperature monitoring and down-hole sensors, as well as



Evaluation process for safe CO<sub>2</sub> storage sites.

seabed monitoring. An extensive programme to monitor and model the distribution of injected CO<sub>2</sub> in the Utsira Formation has been undertaken by a number of organisations (partly funded by the European Union). The Utsira monitoring programme includes a baseline 3D seismic survey and several time-lapse (4D) seismic surveys and they provide a good picture of how CO<sub>2</sub> moves horizontally and vertically.

### Regulation

NPD's evaluation of the geological formations, aquifers and structures for potential CO<sub>2</sub> storage will form the basis for any terms and conditions set for the development of a storage site offshore Norway. A new regulation for CO<sub>2</sub> transport and storage was published in 2014, regulating the exploitation and operation of a CO<sub>2</sub> storage complex, which adopted the EU CCS Directive and the regulatory system from the Norwegian offshore petroleum regulation. ■

