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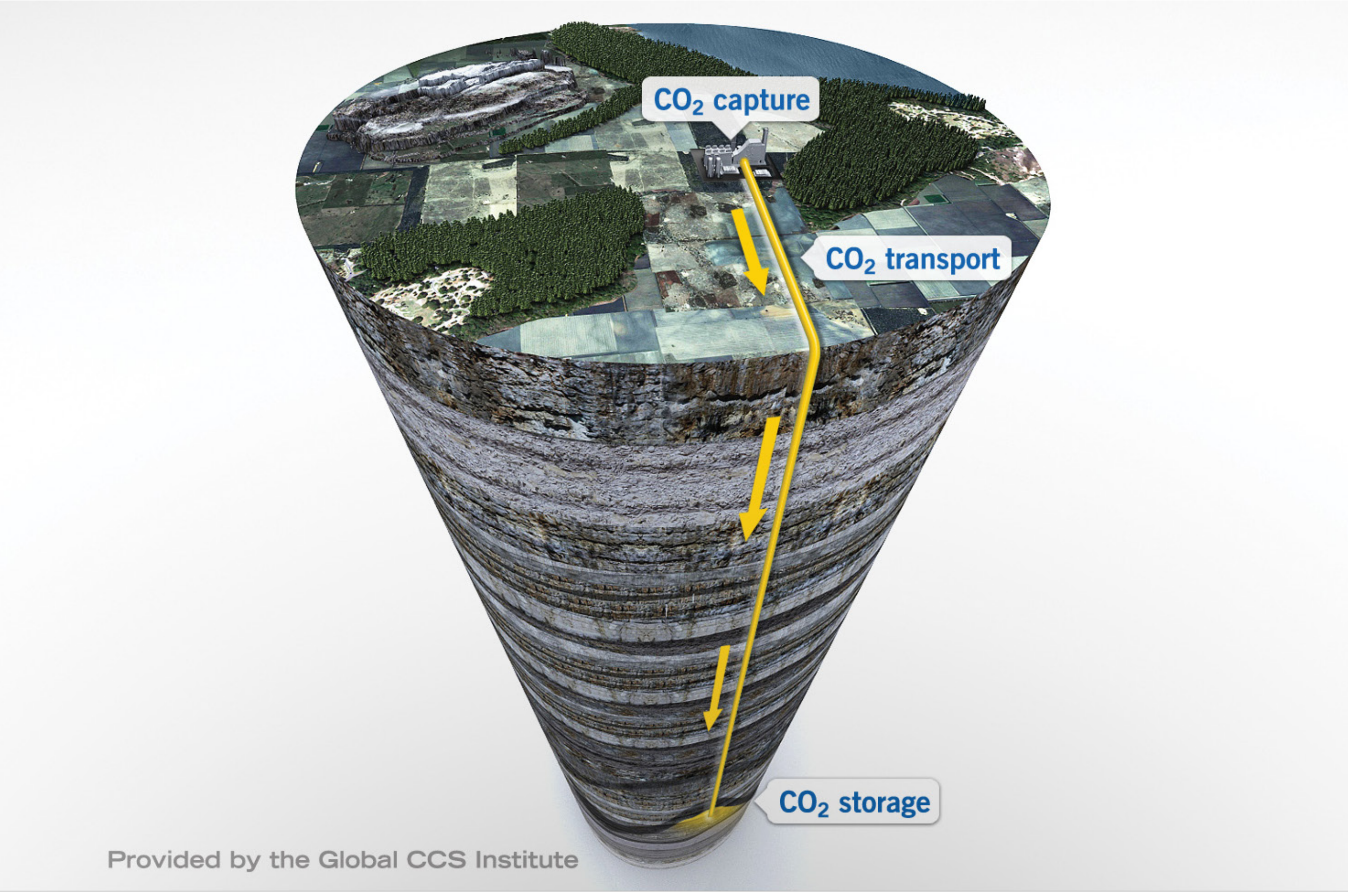
Geological Conditions and Environmental Hazards for Storing Captured CO_2 in the Nini West Field of the Danish North Sea

A Literature Review

Peter Gustafsson



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Geological Conditions and Environmental Hazards for Storing Captured CO_2 in the Nini West Field of the Danish North Sea – A Literature Review

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Abstract

The Nini West depleted oil field, located in the Siri Canyon in the Danish North Sea, is a potential storage site for CO_2 (Petersen et al., 2022). Depleted gas- and oil reservoirs are attractive for storing CO_2 since these aquifers proved their capability to store buoyant fluids over geological time (Duguid et al., 2021). The cap-rock overlaying the reservoir is almost 900 m thick and the reservoir sandstones have suitable permeability and porosity for CO_2 storage. Potential leakage pathways in injection wells or legacy wells present a risk to local benthic ecosystems by Ocean acidification. A regulated surveillance plan has to be implemented and leakage pathways must be continuously monitored.

Innehåll

Introduction

According to the Paris Agreement, global greenhouse gas emissions must be reduced by 2025 and decline by 43% by 2030 to limit global warming to 1.5°C (UNFCCC, 2015). Carbon dioxide (CO_2) is one of the greenhouse gases that significantly impact the global atmospheric temperature (Marshak, 2015). Preem, Sweden's biggest fuel company is evaluating options for a full-scale application of Carbon Capture and Storage (CCS), for some of their refinery units at both of their refineries in Gothenburg and Lysekil in Sweden (Fig.1). Preliminary calculations suggest that CO_2 emissions could be reduced by approximately 900 kt/a, which is about 40% of Preems total on-site emissions (Biermann et al., 2022).

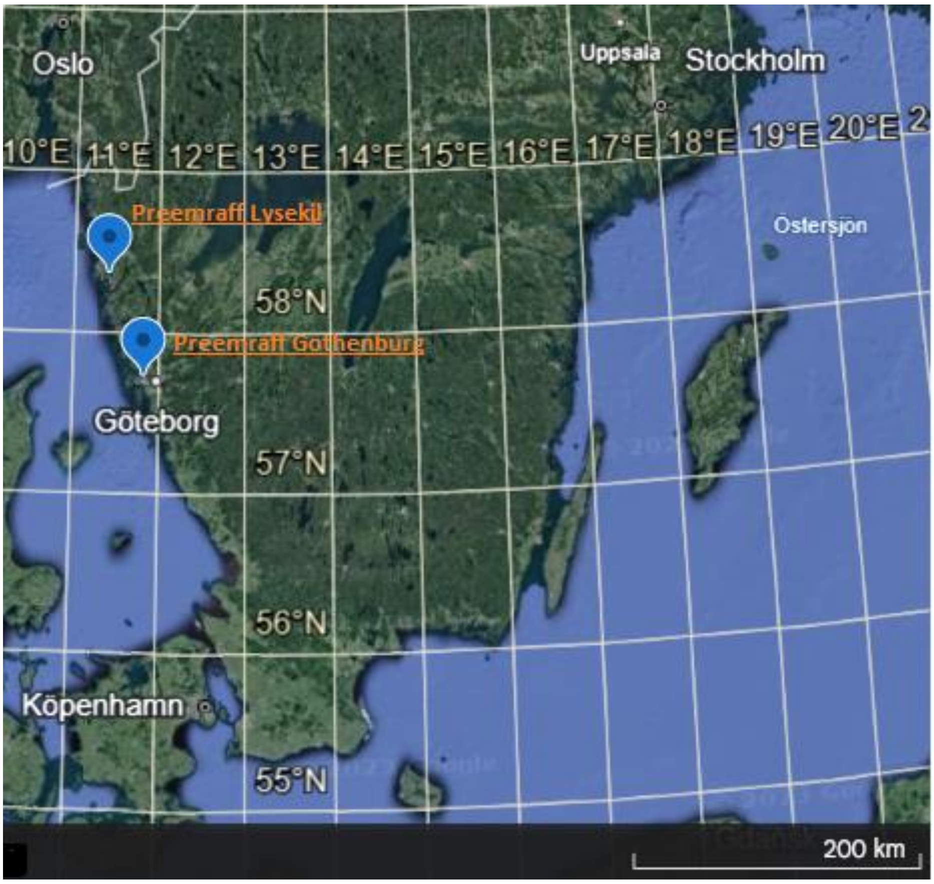

Figure 1 Map showing the refineries in Gothenburg and Lysekil (Created in GoogleEarth)

In a project called NORDICCS it was determined that for Sweden, Denmark and Norway, there is a potential to store approximately 120 billion tonnes of CO_2 in deep aquifers. Nearly 14 billion of these 120 billion tonnes could be stored in exhausted oil- and gas fields.

According to the Global CCS Institute (GCCSI) there were 22 full-scale CCS projects operative or being built worldwide by 2018 and many more are planned. In Europe ongoing and recently finished projects on CCS include active test sites, and pan-European surveys for identifying potential facilities. These include:

SACS (*Saline Aquifer CO_2 Storage):*

A project that started 1998 with monitoring the migration of CO_2 in the Utsiraformation in the North Sea. The project include among other things mapping of the aquifer, geochemical studies, injection through the Sleipnerplatform (Oilplatform) and seismic parameters. In 2002 the project entered phase 3 and continues with injecting and monitoring CO_2.

GESTCO (*Geological Storage of CO_2 from Fossil Fuel Combustion*):

This project that lasted from 1999-2003 mapped major CO_2 sources in Europe and their proximity to possible storage locations and their properties and capacity.

EU GeoCapacity:

This was a European Union overriding project that lasted 2006-2008, which compiled information from the European countries about emissions, infrastructure, potential storage locations and economical evaluations.

Sleipner:

Since 1996 they have been storing CO_2 in a deep aquifer by the Sleipnerfield in the Norwegian North Sea. Approximately 16.2 Mt has been injected between 1996 – 2016 in an aquifer at 800-1000 m depth where the temperature is around 37°C and the pressure 110 bar (Mortensen et al., 2017).

Regulations

The European Union has stated directives that establish a legal framework for the environmentally safe geological storage of CO_2 to prevent negative effects and risk to the environment and human health. These regulations cover exploration, site selection, storage permits, monitoring, reporting by the operator and measurement of leakage among other things. Sufficient data must be accumulated to construct a volumetric 3-dimensional model for the storage complex. The data must cover the following characteristics according to *ANNEX I - CRITERIA FOR THE CHARACTERISATION AND ASSESSMENT OF THE POTENTIAL STORAGE COMPLEX AND SURROUNDING AREA*:

- Geology, geophysics and hydrogeology with extra caution of existing groundwater intended for consumption.
- Volumetric calculations of pore volume for injection and storage capacity of CO_2. Geochemistry with focus on dissolution and mineralisation rates.
- Geomechanics such as permeability and fracture pressure.
- Seismicity and the presence of natural and man-made pathways such as wells and boreholes.

Furthermore, the following characteristics of the reservoir complex must be documented (European Union, 2009):

Domains surrounding the storage formation that may be affected. Population distribution in the region. Proximity to natural resources and ecosystems. Interaction between the ecosystems or natural resources with activities such as exploration, production or storage of CO_2. The geothermal use of aquifers and underground water reserves. Total potential of CO_2 storage and adequate transport networks.

Nini West Field

Preem is investigating alternatives for storing of CO_2 and one option could be in an exhausted oil- and gas field called Nini Field that lie's in the Danish North Sea (Biermann et al., 2022)(Fig. 3). The Nini west field has a potential of storing 0.5-1.5 Mt CO_2 per year by 2025 and possibly 4-8 Mt per year by 2030(Petersen et al., 2022). 5 reservoir boreholes are located within the boundary of the storage complex, 3 of which are legacy wells (pre-existing wells) and two newly drilled wells (Fig. 2) (Project Greensand, 2021). Schiøler et al. (2007) presents seismic data of the area in an article about the Lithostratigraphy of the Palaeogene – Lower Neogene succession of the Danish North Sea including: litostratigraphic schemes, well log data, chronostratigraphy, isopach and isochore maps.

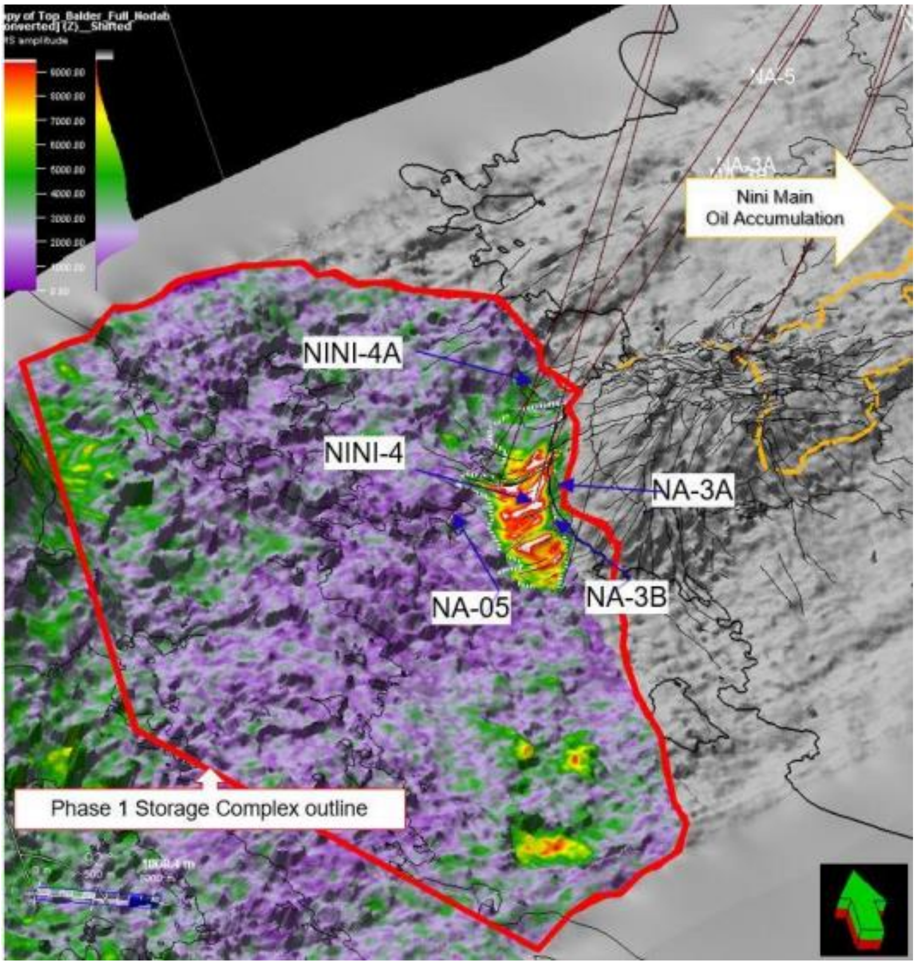

Figure 2 Outline of the Nini West storage complex and legacy wells (Nini-4, -4A,NA-3A, -3B and NA-05). The model shows RMS Amplitudes from seismic data indicating the presence of hydrocarbons with orange – red being high amplitudes and purple being low amplitude. Geomodel from Project Greensand Final Report (2021).

The single most important feature for storing CO_2 in a geological formation is the presence of an overlaying, thick and continuous layer of silt, clay or evaporite, referred to as cap-rock.

The caprock is a fine-grained rock of clay and silt that physically hinders the upward migration of CO_2 by a combination of capillary and viscous forces, meaning it has low permeability (Benson & Surles, 2006). Petersen et al. (2022) analysed the petrophysical and mechanical properties of the seal complex and included organic and inorganic data, physical properties, well logs and mud gas data.

Another prerequisite for a CO_2 storage site is porous and permeable reservoir underlying the cap-rock for the CO_2 to accumulate in (Mortensen et al., 2017). An economical aspect to be considered is the proximity of the aquifer to the source of the CO_2 to minimize transport costs (Metz et al., 2005).

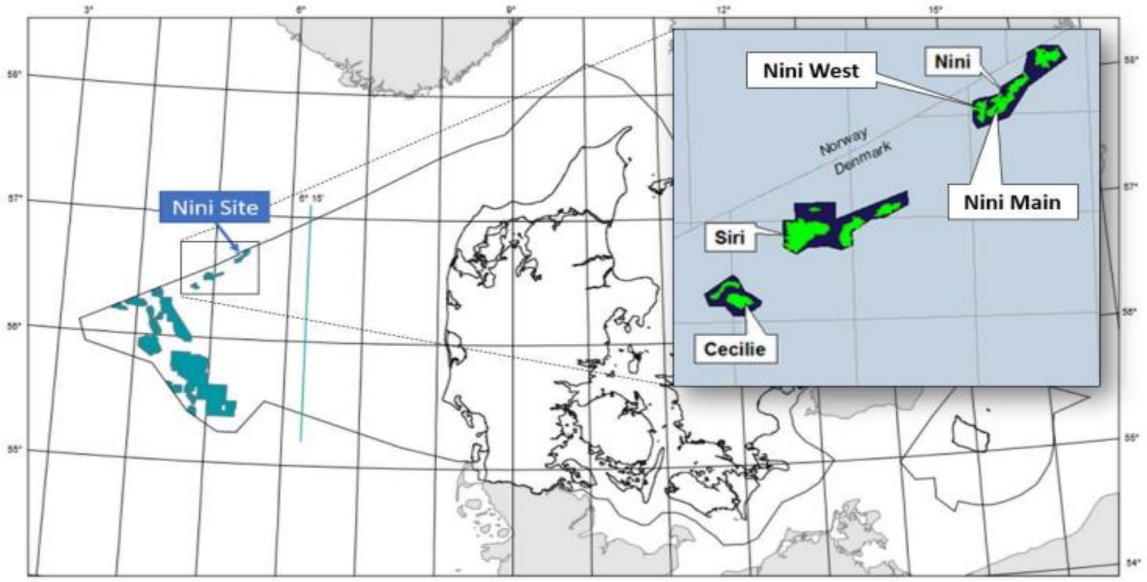

Figure 3 Location of the Nini west field (Project Greensand: End of phase 1 report)

Depleted oil- and gas fields have proved their capability of storing buoyant fluids over geologic time and therefor their risk of leakage is considered low. The most recognised pathways of leakage are the manmade boreholes used to extract the gas and oil (Duguid et al., 2021). Potential leakage of CO_2 from the storing location can drive strong local seawater acidification and impact the benthic ecosystems and biogeochemical processes (Rastelli et al., 2016). A specific concern in the North Sea is the health of the Plaice population. Plaice is one of the most abundant flatfish species in the North Sea and plays an important role in the benthic ecosystem (Madsen et al., 2013).

This paper aims to review (1) what makes a suitable storage location for CO_2, (2) seismic and well logging data as well as published geological maps on the geological setting at the Nini field area and assess whether it is appropriate for storing CO_2, and (3) the environmental risks to biological diversity in the event of leakage. I will limit (1) to depleted gas- and oil fields and what makes these suitable for storage and not consider other options such as brine filled geological formations or ocean storage for example (Benson & Surles 2006). For (2) I will restrict the data investigated to those defined in the introduction. Lastly, for the environmental risks (3) I will narrow it down to the possible local effects on the benthic ecosystem in or near the sediments on the ocean floor.

Method

The review is mostly conducted by analysing peer-reviewed scientific articles and reports with the majority being from the last decade. ScienceDirect (www.sciencedirect.com) was the main database. Additional information were gathered from organisations and companies such as SGU (Swedish Geological Survey), IPCC (International Panel on Climate Change), Preem and the Greensand Project. First, Preem and I established what they wanted to investigate with the review and how I could incorporate both the geology and sustainability aspect of CCS. Preem also provided connection with Greensand who shared published reports and some geological data on the area of interest that I could review. Later followed the review of papers on CO_2 storage in previous depleted oil- and gas fields to obtain more information and data on the subject. Lastly the geological setting and suitability of storing CO_2 in the Nini West Field was reviewed as well as the risk for local ecosystems with leakage. The most used search terms were: CCS, Nini West Field, Acidification, North Sea and Leakage.

Geologic Background

The Nini west field is a depleted oil and gas reservoir located in the Siri Canyon which extends approximately 120 km E-NE (Fig. 4) in the Danish North Sea (Biermann et al., 2022). According to BBC News (2014), the first licenses for oil and gas extraction in the North Sea was issued 1964. At 2014, 42 billion barrels had been produced, that equals approximately 6.677 billon m^3. Estimations at the time said there could be up to 3.815 billion m^3 remaining in untapped reserves.

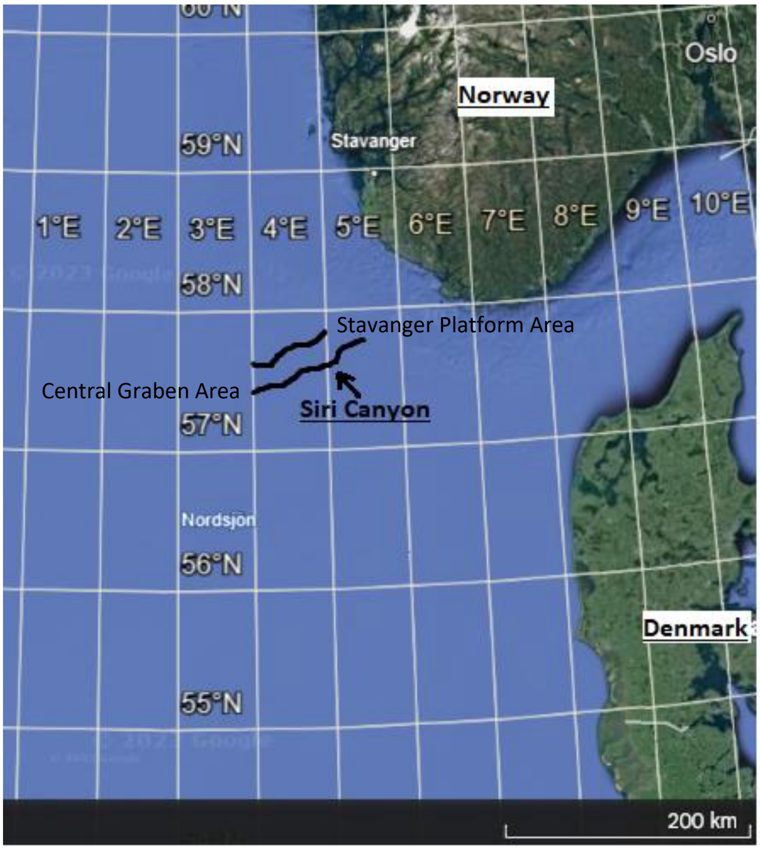

Figure 4 Map showing the location of the Siri Canyon (Created in GoogleEarth)

The Norwegian Petroleum Directorate made a summary on the geology of the North Sea:

In the Carboniferous – Permian period (359 Ma – 252 Ma) major rifting and volcanism caused reddish eolian fluvial sandstone to deposit. Two basins with thick evaporate sequences were developed and eventually younger sediment deposited over these sequences through halokineses (salt moving upwards by buoyancy). This was important for the formation of cap-rocks. In the Triassic period (252 Ma- 201 Ma) major N-S to NE-SW rifting with coarse thick fluvial sediments deposited along rift margins and finer-grained river and lake deposits towards the center of the basins. A widespread marine transgression from north and south took place in the transition from the Triassic to Jurassic (201 Ma – 145 Ma). Furthermore the growth of a volcanic dome followed this transgression which caused land-uplift and eventually erosion. During the late Jurassic – Early Cretaceous (145 Ma – 66Ma) some major block-faulting caused more uplifting and tilting which created local topography with sediment supply. Thick sequences of shale accumulated in anoxic basins which also is important for the formation of cap-rocks. Two different lithologies dominated the Cretaceous period, chalk to the south and siliclastic clay to the north. During the Cenozoic Era (66 Ma – 0 Ma) major tectonic movements have occurred, with sea floor spreading in the North Atlantic and mountain formation in the Himalaya at convergent plate boundaries. Deposition of chalk continued in the North Sea where uplift of basin margins by inversion produced submarine fans transported from the west. These sands mixed with marine shales in the Paleocene sandstones. Major uplift and glacial erosion led to the deposition of thick sequences into the North Sea which eventually buried the Jurassic source rocks that generated the hydrocarbons.

The primary source rock of the petroleum was organically enriched shale deposits (Kimmeridge clay) from the Jurassic period. The marine transgression in this period resulted in extensive anoxia and decreased clastic inputs which favoured marine biomass accumulation and preservation (Skarstein et al., 2022). There are three formations with oil accumulation In the Siri Canyon: The Sele and Balder Formations that were deposited during the early Eocene and the Lista Formation that was deposited during the late Paleocene (Fig. 6) (Zhou et al., 2015).

The cap-rock, or seal complex, of the Nini west field is almost 900 m thick. The mudstones comprising the cap-rock range from approximately 56-23 Ma in age and are of Horda formation and lower to mid Lark formation (Petersen et al., 2022). The Siri Canyon formed during the Paleocene and was filled by turbidite deposition as glauconitic sands were transported to the Danish Central Graben from the Stavanger Platform (Fig. 4).

Mudstone Formations from the Paleocene-Eocene Rogaland group seal the oldest sandstones which were transported by post-depositional fluidization. The youngest sandstones are sealed by the Eocene Horda Formation and Oligocene-Miocene Lark Formation that are approximately 1 km thick combined (Petersen et al. 2022).

The Horda Formation extends over the central and northern North Sea and was deposited between 53-33 Ma (Fig.6) (Schiøler et al., 2007, Petersen et al., 2022). It reaches a thickness of 906 m in the Central Graben, where the Siri Canyon is located, and thins towards the East and South East to about 100 m. The lithology of the Horda Formation is characterised by greenish grey fissile mudstone, limestone and thin layers of black mudstone at some levels and in the lowermost part red-brown mudstones. The depositional environment of the basal part was open marine, deposited in 1000 – 4000m in water depth under oxic bottom-water conditions. This is indicated by the diverse fauna of benthic (calcareous and agglutinated) and planktonic calcareous foraminifers. The upper part holds an abundant and diverse agglutinated foraminifer fauna with a very sparse or absent occurrences of calcareous foraminifers. This indicates a depositional environment of upper bathyal depths with dysoxic bottom conditions (Schiøler et al., 2007).

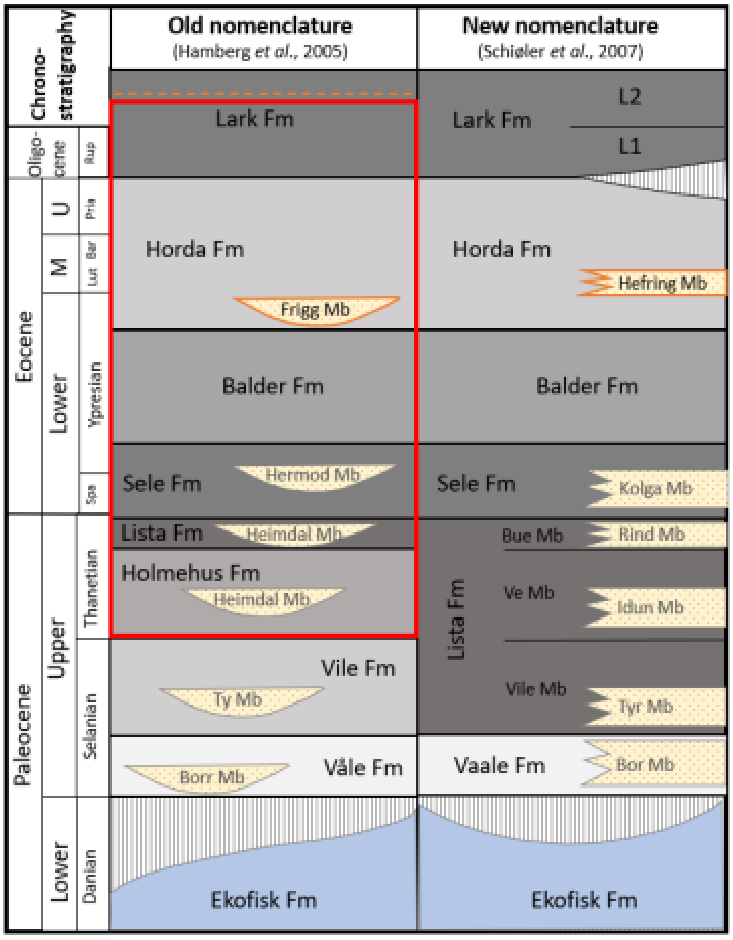

Figure 6 Litostratigraphy of the Siri Canyon. The red square defines the Nini west field complex. (Project Greensand: End of phase 1 report)

The Lark Formation also extends over the central and northern North Sea and was deposited between 35-13 Ma (Schiøler et al., 2007, Petersen et al., 2022). It reaches a thickness of 1194 m along the eastern boundary of the Danish Central Graben. The lithology is of dark, greenish gray, non-fissile mudstones and some thin layers of white or reddish brown carbonate in the upper layers. The depositional environment of the lower to middle part of the Formation is open marine, neritic – outer neritic setting with well oxygenated bottom water conditions. This is indicated by the proportion of agglutinated, calcareous planktonic and benthic foraminifers. The upper part is dominated by calcareous benthic foraminifers, indicating a neritic to middle neritic setting with oxic bottom water conditions (Schiøler et al., 2007).

Results

CCS Potential of the Nini West Field in the Siri Canyon

Depleted gas- and oil reservoirs are attractive for storing CO_2 since these aquifers proved their capability to store buoyant fluids over geological time (Duguid et al., 2021). For an aquifer to be suitable for CO_2 storage it should consist of porous and permeable bedrock, preferably sandstone down to approximately 2500 m depth. After this depth the sandstone generally becomes too dense (less porous) because of compaction. The reservoir must be overlain by an impermeable formation to trap the buoyant fluids. This is referred to as the cap-rock, and prevents CO_2 from migrating to and escaping from the seafloor (Mortensen et al., 2017).

A number of properties that need to be evaluated to determine if an aquifer is suitable for storing CO_2 (Mortensen et al., 2017) are the following:

1. Structural properties such as expansion and limitations of the sandstone as well as vertical and horizontal structure.
2. Physical properties including permeability, porosity, capillary forces and chemical properties.
3. The caprocks size, thickness, structure, physical and chemical properties.

Geometrical and Structural properties

Deeply located porous layers of sandstone with a thickness of at least 15 m are considered the most viable options for storing CO_2. Usually there are multiple layers of porous sandstone alternating with layers of mudstone, shale or limestone that combined forms a reservoir. A geological formation is defined as a sequence of similar facies and can be described by its heterogeneity (variation in size). The sand net/gross relationship defines the amount of sandstone suitable for storing CO_2 compared to the amount of unsuitable layers. The amount of sandstone (in meters) can be considered Net and the formations total thickness (in meters) is considered Gross (Mortensen et al. 2017). If the total thickness of a reservoir is 1000 m and the thickness of the permeable sandstone is 700 meters the net/gross relationship is:

$700/1000 = 0.7$

The value is between 0 and 1 and the higher it is, the more permeable and hydraulically well connected it tends to be (Olsen et al., 2017).

For sandstone to be considered suitable for storage, certain values of porosity (>10%), mud content and grainsize, are more favourable. Higher mud content generally leads to a tendency of favourable chemical reactions and smaller grainsize means higher surface area and more favourable reactions.

The most favourable formation for storage is a homogenous one with few individual layers of sandstone. This makes it more convenient to monitor the injected CO_2 and also more predictable to know where it will migrate. Completely isolated aquifers are very rare, however there are examples of more or less horizontally laying aquifers with overlying caprock. The Utsiraformation in the Sleipnerfield in the Norh Sea is an example of a horizontal aquifer that has shown that injected CO_2 remains in a relatively limited portion of the aquifer close to the injection-well (Mortensen et al., 2017).

Physical and chemical properties

In order to make CO_2 storage possible in a geological formation, there are some physical and chemical requirements. A fundamental requirement is that the CO_2 is kept in a supercritical state. This ensures that an optimal amount can be stored since the volume gets significantly less compared to gas. To achieve this, the aquifer has to be located at a minimum depth of 800 m below the seasurface. The storage capacity is determined by the volume of the aquifer and the porosity. In the project NORDICCS, a value of 10% porosity or above was set as a desirable condition for suitability. The actual storage capacity is usually considerably less than the theoretical because of the presence of faults, chemical conditions, heterogeneous bedrock or temperature, which are all affecting the storage capacity. The injectivity of the aquifer is another important factor for assessing suitability, this is a measurement of how easy the CO_2 can be injected into the aquifer and how fast it migrates. The definition of injectivity is the product of the aquifers permeability and volume and this is measured in darcymeters (Dm). In the NORDICCS, an injectivity of minimum 0.25 Dm and a permeability of at least 0.1 Dm is suggested as a prerequisite for CO_2 storage (Chadwick et al., 2008). Darcy's law is widely used by petroleum engineers and hydrologists to calculate fluid flow rate in various media:

$$v = -\frac{k}{\mu}\frac{dp}{dl}$$

Where *k* is the permeability, µ the viscosity, and dp/dl the pressure gradient (Chang et al., 2019). A permability of 1 darcy allows a flow of 1 cm^3/s of a fluid with 1 mPa viscosity under a pressure gradient of 1 atm/cm over an area of $1cm^2$.

Caprock

A significant prerequisite for safe storage, without negative effects on the surrounding environment, is a large and closed caprock. Typical caprocks are mudstone, muddy shale, or muddy limestone. The thickness and density are crucial for avoiding capillary migration as well as leaks in case of fractures or faults. Fractures are common in caprocks because they may be brittle, these fractures tend to expand because of chemical dissolution of bedrock caused by the acid made by CO_2 in contact with water ($CO_2 + H_2O \leftrightarrow H_2CO_3$). Semiplastic mudstones are the most suitable caprocks since they have the ability to repair themselves. In areas with tectonic activity, increased seismicity can lead to leakage by the activation of faults and fractures. The recommended prerequisites for a caprock is a continuous expanse with a thickness of at least 50 m, a lithology of muddy bedrock, low intensity of faults and the presence of multiple caprocks for additional limitation of upward migration (Mortensen et al., 2017).

Properties of the Nini West field

Geometrical and Structural properties

The evaluated storage unit from Project Greensand is the Lower Eocene Frigg Member of the Horda Formation (Figure 5), it is located in the Nini salt dome structure on the western flank at a depth of approximately 1700-1800 m. Highly porous and permeable glauconitic sandstones 12-30 m thick enclosed by very extensive lateral shale units are the constituents of the unit. Evaluation from a third party says that the storage potential of the Nini west field is 0.45 million tonnes (Mt)/year with a total potential volume of 5 Mt (Project Greensand, 2021). Petersen et al., 2022 suggest a storage potential of 4-8 Mt by 2030. The sandstones in the aquifer probably originate from the collapse of unstable shelf sands on the Stavanger Platform due to seismic shocks (Kazerouni et al., 2013).

Physical and chemical properties

The Frigg sandstones in the aquifer have been tested in a lab and are competent of and geochemically stable to CO_2 with a measured permeability of 0.1-0.3 Dm (Project Greensand, 2021). Stokkendal et al. (2009) and Kazerouni et al. (2013) collected samples from the Siri Canyon sandstones to perform a geochemical and petrographic study and electron microbe analyses respectively. The samples were strongly glauconitic, quartz and glauconite occurs in similar amounts (20-30% of the rock volume). Glauconite occurs as pellets and glauconitised mica which generally contains intragranular porosity or cement. All sandstones are fine-grained with the average grain size of 100 and 200 µm. 18 samples from depths of 2038.8-2160.7m were analysed with SEM-BSE micrographs to determine porosity. The results range from 0.3 – 21.6% with an average of 12.93% (Stokkendal et al., 2009). Kazerouni et al. (2013) suggest that the sandstones of the reservoir are very fine to fine-grained, poorly consolidated with porosity up to 30-35%, Project Greensand came to the same conclusion on the porosity of the sandstones (Table 1). They also suggest that the sandstones observed diagenetic changes appear to have occurred during early burial before hydrocarbon migration.

Table 1 Porosity of 3 samples from the Siri Canyon Reservoir Kh = horizontal permeability and Kv = vertical permeability (Project Greensand)

Well	Reservoir	Depth (m)	Porosity Original (%)	Porosity Corrected (%)	Average log porosity (%)	Kh Air (Dm)	Kv Air (Dm)
NINI-4	FRIGG	1772.2	34.8	37.1	36.7	1.277	0
NINI-4A	FRIGG	1930.2	39.0	37.4	37.5	1.091	0
SOFIE-1	FRIGG	1877.1	33.3	32.6	32.9	0.519	0.325

Caprock

The canyon in which the Nini west field lies is located in a geologically stable area, not close to active fault zones or subsiding areas and with low seismic activity (Petersen et al., 2022). According to the United States Geological Survey (USGS - Latest Earthquakes (usgs.gov)), no earthquakes occurred in the North Sea in the last 30 years. The primary seal is of the Horda and lower part of the Lark formations and has a thickness of more than 300m. The secondary seal is of the mid-upper Lark Formation and is approximately 550m thick. There is also a bottom seal of approximately 50 m thick shale (Project Greensand, 2021)(Petersen et al., 2022). The capacity of the seals can be confirmed by documented previous oil accumulations in the unit (Duguid et al., 2021). Petersen et al. (2022) collected 20 samples from the Nini-4 well and Nini-4A sidetrack (Fig.2) to determine particle size distribution, mineralogy and petrography (Table 2).

Table 2 Analysed samples from Nini 4 well and Nini 4a sidetrack modified from Petersen et al., 2022.

Sample	Well	Depth (m)	Formation	Clay <2 µm (wt. %)	Measured porosity (%)	Modelled permeability (Dm)
1	Nini-4	1600	Lark	50	-	$0.30 * 10^{-6}$
2	Nini-4	1620	Lark	53	-	$0.20 * 10^{-6}$
3	Nini-4	1640	Lark	63	-	$0.09 * 10^{-6}$
4	Nini-4	1660	Lark	60	-	$0.06 * 10^{-6}$
5	Nini-4	1680	Lark	63	-	$0.07 * 10^{-6}$
6	Nini-4	1700	Lark-Horda	57	-	$0.06 * 10^{-6}$
7	Nini-4	1710	Horda	59	-	$0.15 * 10^{-6}$
8	Nini-4	1716	Horda	67	-	$0.05 * 10^{-6}$
9	Nini-4	1725	Horda	47	-	$0.05 * 10^{-6}$
10	Nini-4	1734	Horda	-	-	$0.11 * 10^{-6}$
11	Nini-4	1740	Horda	52	-	$0.02 * 10^{-6}$
12	Nini-4	1755	Horda	48	-	$0.08 * 10^{-6}$
13	Nini-4	1762	Horda	50	18.2	$0.21 * 10^{-6}$
14	Nini-4	1821	Sele	58	18.7	$0.14 * 10^{-6}$
15	Nini-4	1749	Horda	59	18.6	$0.09 * 10^{-6}$
16	Nini-4a	1910	Horda	46	16.3	$0.16 * 10^{-6}$
17	Nini-4a	1915	Horda	53	19.2	$0.21 * 10^{-6}$
18	Nini-4	1801	Sele	38	21.2	$0.29 * 10^{-6}$
19	Nini-4a	1903	Horda	59	20.6	$0.09 * 10^{-6}$
20	Nini-4a	1956	Horda	<15	12.8	$1.93 * 10^{-6}$

Risks of leakage at CO_2 storage sites

If large amount of CO_2 were to leak from a storage site, this would cause a risk to the health of the local environment and harm ecosystems. Thick cap-rocks lower the risk of integrity loss and leakage even if faults and fractures occur since they can develop without transgressing the entire cap-rock. In the Salah CO_2 storage site in Algeria, there is an example of this where a fracture network reaches 100-200m into the cap-rock but still has no effect on the storage safety since the cap-rock is up to 950m thick (Petersen et al., 2022). More commonly, leakages develop from the injection well or from old wells that have not been properly sealed (Benson & Surles., 2006) (Fig.7).

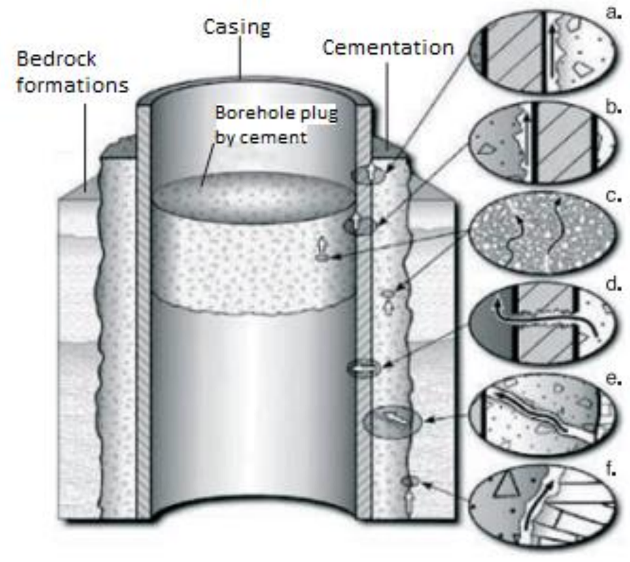

Figure 7 Potential pathways for leakage from a well, a) outside casing, in the zone between casing and borehole cement, b) inside casing, in the zone between casing and borehole plug, c) through porous and permeable cement, d) through damaged casing, e) through cracks and holes in the cement, f) in the zone between the cement and the bedrock (modified from SGU 2017).

In the European Parliament directives (2009) it is stated that no significant risk for leakage is allowed to be present for an aquifer to be used for storing CO_2. Parameters exist that are part of a surveillance-plan with the purpose of monitoring and controlling the CO_2 in the aquifer over time. In injection-wells the injection is being controlled with regards to the pressure in the well. The monitoring must be able to show magnitude, place and what type of leakage that is occurring (Mortensen et al., 2017).

There are a large number of parameters that need to be accounted for in the surveillance-plan (Fig.8).

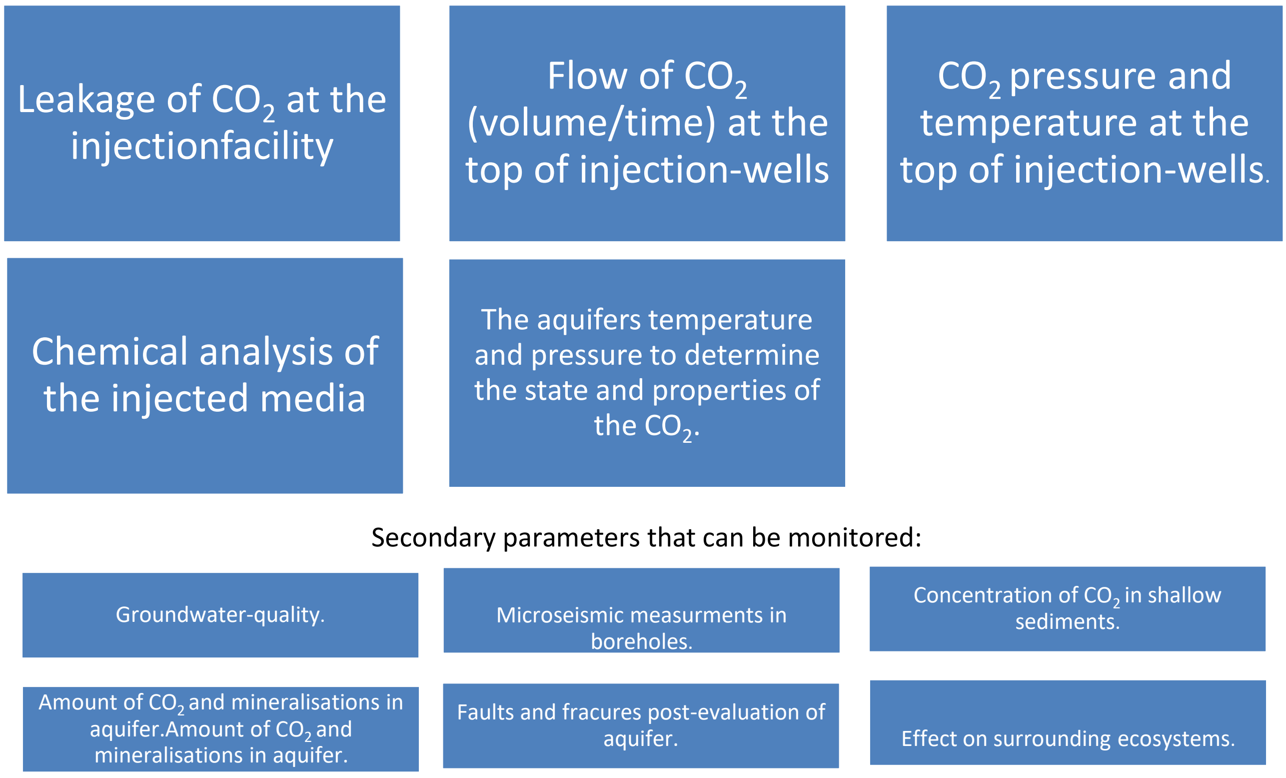

Figure 8: Parameters necessary for monitoring and controlling CO_2 storage and secondary optional parameters to consider (European Parliament Directives 2009).

The method used for monitoring should be the best available at the time of construction (Mortensen et al., 2017). A critical part of the Greensand phase 1 was to demonstrate that the site can be properly monitored. The monitoring plan constructed is based on the EU CCS Directive Guideline (Table 3).

Table 3 Intended parameters to be monitored based on the EU CCS Directive Guideline (Project Greensand Report, 2021)

Parameter	**Tools**	**Location**	**Frequency**	**Period**
Fugitive emissions of CO_2 at injection facility	Pressure and temperature gauges, laser technique for CO_2-detection	Ship, wellhead and connection pipes	Continuous	Pre-injection Injection phase Post-injection
CO_2 volumetric flow at injection wellhead	Pressure gauges->permanent gauges, temperature detector	wellhead	Continuous	Pre-injection Injection phase Post-injection
CO_2 volumetric flow at injection wellhead	flow meter	wellhead	continuous	Injection phase
CO_2 pressure and temperature at injection wellhead	Pressure gauges -> permanent gauges Temperature detector	Injection facility and wellhead	Continuous	Pre-injection Injection phase Post-injection

Parameter	Tools	Location	Frequency	Period
Wellbore (and well integrity) CO_2 pressure and temperature	Permanent Downhole Pressure Gauge (PDPG) Permanent Downhole Temperature Gauge (PDTG)	Downhole injection well At reservoir interval	Continuous	Pre-injection Injection phase Post-injection
Chemical analyses of injected material	Analytical sensor systems	Onshore	Per each ship transfer	Pre-injection Injection phase
Reservoir pressure and temperature (CO_2 phase behaviour)	PDPG PDTG Simulation	Downhole injection well, Monitoring wells, At reservoir interval	Continuous	Pre-injection Injection phase Post-injection
Location and migration paths of CO_2	Bottom hole pressure (BHP)-gauge Pressure testing of annulus Leakoff test	Injection well	Continuous	Pre-injection Injection phase Post-injection
Location and migration paths of CO_2	Seismic spot imaging Micro-seismicity	Water surface, seafloor, faults and fractures	Baseline	Pre-injection Injection phase Post-injection
CO_2 plume	PDPG Seismic spot imaging	Downhole injection well, at reservoir interval	Continuous	Pre-injection Injection phase Post-injection
Potential leakage pathway	Seismic spot imaging, Micro seismicity	Water surface, seafloor, faults and fractures	Baseline Continuous	Pre-injection Injection phase Post-injection

In the Risk Register created in Project Greensand Phase 1 the environmental risks for the storage facility is considered Acceptable to Tolerable. Key risks that will be further assessed in Phase 2 are cement integrity of wells, chemical degradation of cement and corrosion of tubulars in NA-3 and NA-5.Mitigation of scenarios regarding leakage is presented as: Monitoring in wells, sea-bed and specific faults. Stop injection, monitor leak and update injection strategy. Monitor oil-leakage outside of storage complex.

Benthic ecosystems

A diversity of ecosystem processes drive the production or degradation of organic matter in marine sediments, this is a major contributor to geochemical processes in the ocean. A leakage could drive strong local seawater acidification (lowering of pH). The pH of the surface sediment (1-5 cm depth) also reduces from the acidification, especially the top cm (Rastelli et al., 2016). It is possible that reduction of pH in the sediments and water affects the growth rate and lipid content of shrimps, which would also affect the higher trophic levels like plaice that eat shrimp. Multiple studies have shown that growth is impaired by the combined effect of warming and acidification (Maia et al., 2022) (Fig. 8).

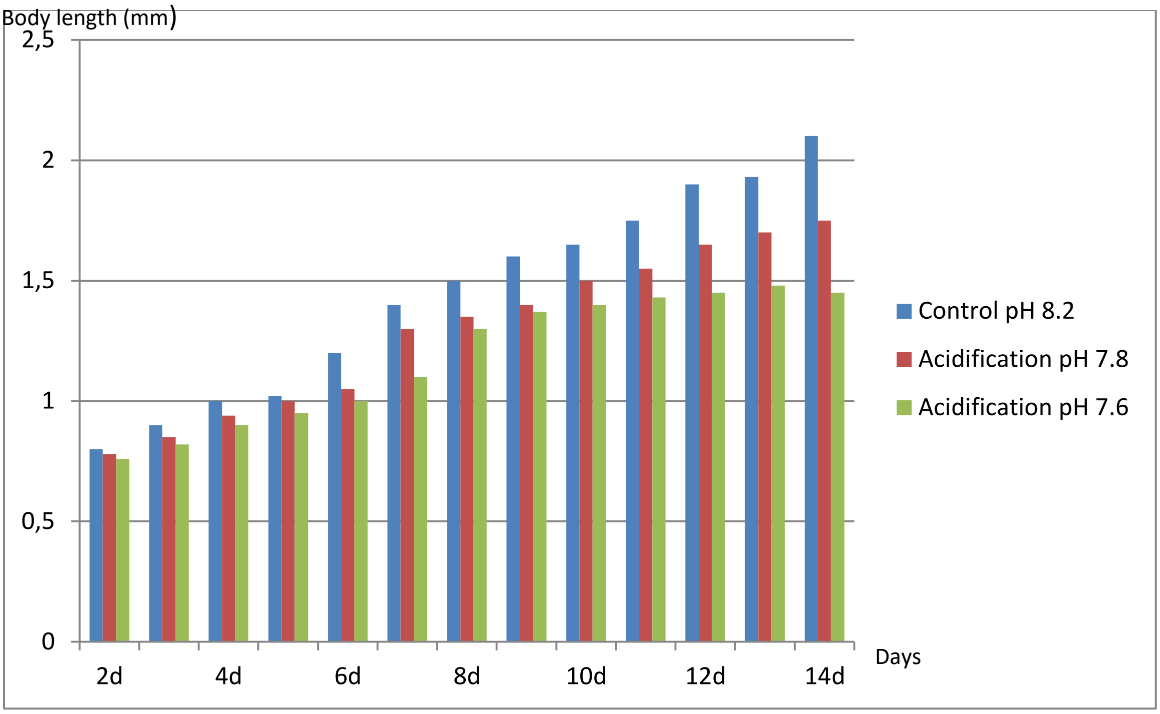

Figure 8: Body length of shrimp in acidified water driven by elevated CO_2 levels. X-axis shows amount of days and the Y-axis shows body length in mm (modified from Zheng et al 2014).

Meta-analyses also identified the significant negative effect on survival, development and abundance of marine organisms due to acidification caused by CO_2 (Augosto et al., 2018). It is of great importance to resolve the impact of acidification on crustacean habitats as it will affect the benthic ecosystem as well as the food security and economy of the world. The time of exposure is a well-known factor for the biological response to Ocean acidification (Weerathunga et al., 2023).

Minor leakage for 65 days

In an experiment with shrimp by Maia et al. (2022), exposure to low pH (7.4) initially lead to haemolymph acidosis (pH of the blood becomes acidic) after approximately 14 days. After 30 days, the shrimp adapted by extracellular acid-base regulation. This adaptation may increase the survival rates of the shrimp but it is an energetically costly process that can affect growth (Maia et al., 2022).

Major leakage (pH 7.0-7.4)

A similar experiment by Muralisankar et al. (2020) indicated that the acidic stress caused by lower pH can produce membrane damage in shrimps. This study also revealed that survival, growth and food utilization decreased significantly in CO_2 driven acidified water (Muralisankar et al., 2020).

Discussion

The data analysed and reviewed in this paper suggests that the Nini West Field is suitable for CO_2 storage with low risk for leakage from the aquifer. Petersen et al. (2022) have established that the sealing capacity of the caprock meets the prerequisites stated by Mortensen et al. (2017) in the report from the *Geologcal Survey of Sweden.* Duguid et al. (2021) also support the suitability by the statement that the capacity of caprocks can be confirmed by previous oil-accumulation in the aquifer, which is applicable to this aquifer. Data on the geometrical and structural properties suggest that the aquifer is big enough and lab tests shows that the sandstones have permeability and porosity suitable for containing CO_2. The data reviewed on the Nini West Field may suggest that it is suitable for CO_2 storage. However, based on the findings on CO_2 driven ocean acidification, the benthic ecosystems should be carefully monitored, by measuring pH near the seafloor near the aquifer, along with the potential leakage pathways around legacy boreholes.

The Greensand project entered phase 2 in 2021, which will aim to provide necessary information for the storage capacity in the Nini Field. This will be a full value chain pilot project that will deliver documentation and reports to prepare for a permit application by 2023 with qualified monitoring technology for environmentally safe storage of CO_2. The full-scale project is to be initiated in 2023 with storage allowed from the second half of 2025 (Project Greensand Phase 2).

The Nini West field seems to be quite similar to the In Salah region in central Algeria in terms of depth, cap-rock and permeability and porosity of the sandstone. The In Salah Gas Project started in 2004 and had successfully injected over 3 Mt of CO_2 by 2011 (Lopez et al., 2011).

Table 4: Comparison of the Nini West Field and In Salah region in central Algeria.

Formation and depth:	Nini West Field 1700-1800 m	In Salah 1800 m
Cap-rock thickness:	Up to 900 m	Up to 950 m
Permeability of sandstone:	0.1.0.3 Dm	0.15-1 Dm (Ringrose et al. 2011)
Porosity of sandstone:	13-30%	10-21% (Lopez et al. 2011)

The fact that the In Salah project has successfully been storing CO_2 for many years and the geological similarities to the Nini West field indicate that the probability for successful storage in the Nini West field should be high. Another indication for good suitability for the Nini West field is that all the properties meet the standards stated by the Geological Survey of Sweden.

Regarding the environmental aspect of acidification from potential leakage, there are multiple studies highlighting the potential risk to benthic ecosystems. The growth and even survival rate of shrimp is affected from a decrease in pH, which in turn affects the higher trophic levels like plaice and also humanity since we eat and fish for both shrimp and plaice.

Careful monitoring of the injection well must be implemented at the facility and preferably also the benthic ecosystem at the seafloor.

Ultimately a consideration must be made comparing the benefits of reducing CO_2 emissions to the environmental risk of leakage.

Conclusion

The prerequisites for a storage location for CO_2 are a geological formation at a minimum of 800 m depth below the sea surface with a cap-rock with continuous expanse at least 50 m thick and an underlaying permeable and porous sandstone reservoir for the CO2 to accumulate in.

According to the information and data gathered from the reviewed papers on the Nini West Field, the area has the desired geological setting and is suitable for CO_2 storage.

Regarding the environmental risk in the event of leakage there is a surveillance plan stated by the European Parliament covering control and monitoring of the CO_2. A risk register based on this surveillance plan has been conducted for the outcome that the risk for leakage is tolerable to acceptable.

Should however a leakage occur, this would contribute to local ocean acidification that affects the growth- and survival-rate of shrimp. This affects the higher trophic levels like plaice and eventually humans.

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