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Measurement, Monitoring & Verification (MMV) Framework to Enhance Sustainability of Decarbonization Plan in the North Sea Area

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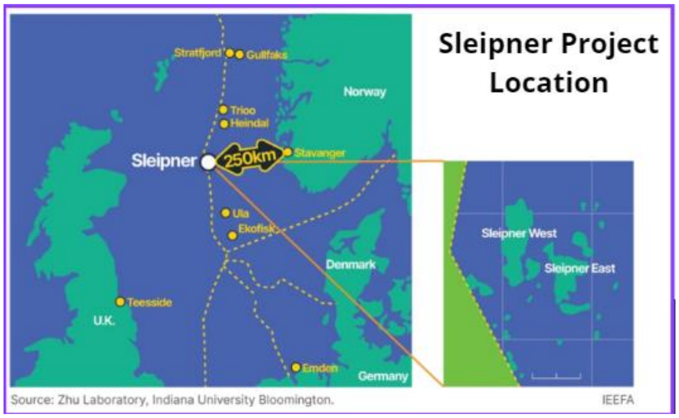
Abstract

The Sleipner CCS gas power station was designed with the intention of capturing, compressing, and transporting CO_2 emissions offshore. These emissions were then intended to be injected into the Utsira Formation at a consistent rate of 1 million tonnes per year for a duration of up to 20 years. The establishment of site selection, characterization, and engineering designs is widely recognised as the primary approach to assuring the long-term security of CO_2 storage. However, to validate their effectiveness, a complete Measurement, Monitoring, and Verification (MMV) programme is employed, which is based on a risk assessment framework. The Sleipner MMV programme was developed based on a comprehensive evaluation of storage containment risks particular to the site. Its primary objectives are to validate the effectiveness of containment measures, ensure compliance through continuous monitoring, gather data for accurate emission accounting, and facilitate the transfer of long-term responsibilities associated with storage. The design process employed by MMV involved the identification of a collection of suitable monitoring jobs and the corresponding monitoring technologies required to execute them. These determinations were made through the conduct of thorough feasibility studies that were tailored to the specific characteristics of the site in question. The objective of this method is to establish a comprehensive monitoring strategy that adheres to EU laws and incorporates various containment and environmental monitoring techniques.

Keywords: Carbon Capture Storage, Containment, Monitoring, Risk

Introduction

The Sleipner Vest gas field (Figure 1) was discovered in 1974, and put on stream in 1996, in a combined development with the Sleipner Øst condensate gas field (Furre et al, 2017). It is located about 250km offshore from Norway in the North Sea, encompassing two significant gas fields. Operated by Equinor (formerly Statoil), it has been operational since 1996 and is noteworthy for its environmental and technological advancements. Based on Hauber, 2023, the extracted gas from Sleipner has a CO_2 content ranging from 4% to 9%, which necessitates reduction to below 2.5% to align with stringent environmental regulations. This adherence to environmental standards is further reinforced by a carbon tax, set at over US$ 41 per ton, underlining the economic impetus for sustainable practices.



Source: Zhu Laboratory, Indiana University Bloomington.

Figure 1 Sleipner Project Location (Hauber, 2023)

The Sleipner project is globally recognized as the first commercial application of CO_2 storage in deep saline aquifers. It sequesters between 0.85 and 1 million tons per annum (mtpa) of CO2, a substantial contribution to reducing greenhouse gas emissions. The targeted injection site for this CO2 is the Utsira Sand, a regional saline aquifer. The Utsira reservoir has a depth ranging from 500 to 1500m and covers an area of 2.6 x 104 km^2 (Torp The reservoir is underlain by a shale layer that is between 50-100m in thickness and extends beyond the existing boundaries of the injected CO_2 (Figure 2). Shales possess extremely low permeability, which means that the shale layer will effectively prevent the injected CO_2 from escaping. The cap rock layer has numerous localized domal and anticline structures, which serve as effective traps and conduits for CO_2 migration inside the reservoir.

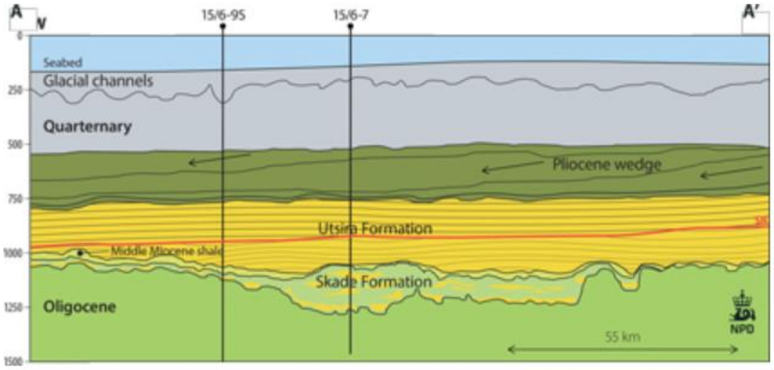


Figure 2 Cross section Formation in Sleipner Area (Norwegian Offshore Directorate)

The project entails the extraction of CO_2 from its sources, followed by its compression and delivery to the Utsira Formation for safe storage. In addition, it is crucial to have a monitoring and verification system in place during CO_2 injection operations to ensure the accuracy of risk assessment analysis and sensitivity. Therefore, it is necessary to predict the CO_2 capacity, model the reservoir, and plan the sustainability project for estimating purposes.

Methods

CO_2 storage is monitored for operational, safety, social, economic, and environmental protection purposes. Monitoring storage is crucial for guaranteeing the extended separation of anthropogenic CO_2 from the atmosphere. It is important to oversee the operations of the warehouse, both on land and in maritime and subterranean environments. When devising a monitoring strategy for the decisions that rely on the unique geological and engineering conditions of each warehouse, it is important to consider factors such as the shape and depth of the deposit, the anticipated expansion of the CO_2 front, potential migration routes, geological composition of the roof, pumping conditions, flow rate, and surface characteristics including topography, population density, infrastructure, and ecosystems.

The investigation of MMV scenario commences with two distinct analyses, encompassing both surface and subsurface characteristics. To effectively distribute CO_2 to the target well, it is crucial to identify the sources of CO_2 and the route of transportation, based on the surface type. Next, the second aspect concerns to the subterranean region. It comprises three analyses: geology, geophysics, and reservoir characteristics. The examination of geology and geophysics in this research is limited to the MMV scenario, hence it does not provide extensive detail. However, these analyses yield a static model and provide insights for constructing a dynamic model.

Furthermore, the analysis of reservoir features encompasses the examination of petrography, reservoir properties, and petrophysics. The collaboration involves the analysis of petrography, reservoir characteristics, and dynamic models used for calculating CO_2 storage. Moreover, the petrophysics analysis will determine the sealing capacity. These studies would have an impact on determining the monitoring, measurement, and verification processes during the study itself, as well as on forecasting and evaluating risk assessment.

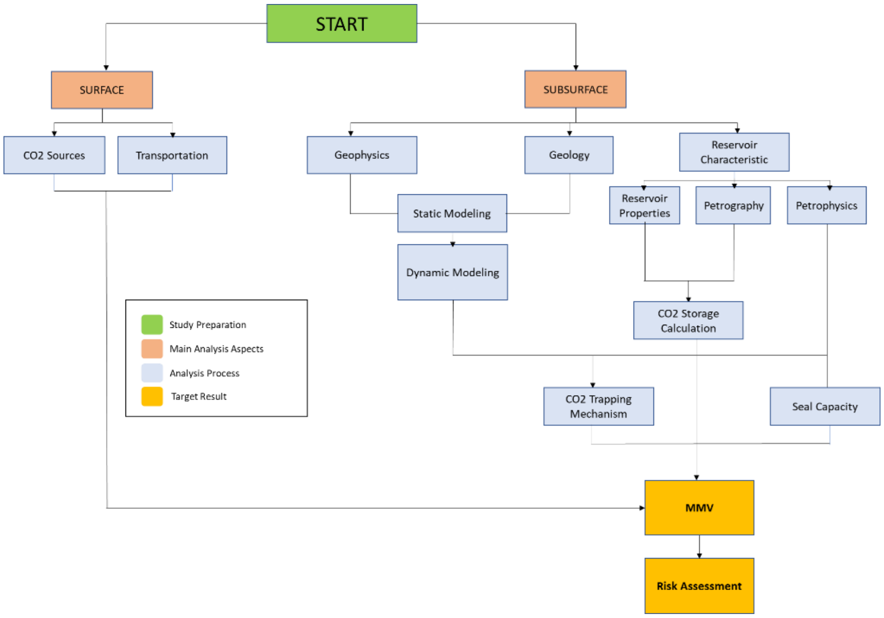
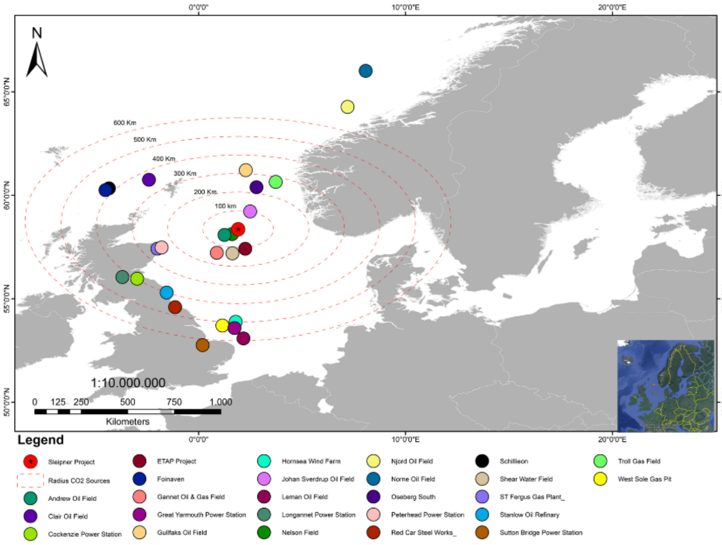


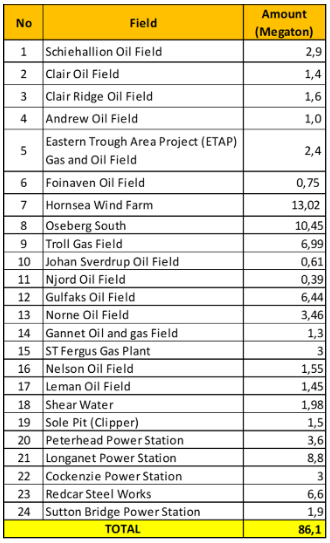
Figure 3 Methodology Identification

Results

CO_2 Sources and Transportation

The Sleipner Project is situated in close proximity to various sources of CO_2, such as an oil field, wind farm, gas plant, and power station. These sources are located within a radius of 100 to 600 kilometers from the project site, as shown in Figure 4. By conducting this study, it has been shown that there are twenty four potential sources of CO_2 in the North Sea area, with an estimated annual emission of around 86.1 megatons.





No	Field	Amount (Megaton)
1	Schiehallion Oil Field	2,9
2	Clair Oil Field	1,4
3	Clair Ridge Oil Field	1,6
4	Andrew Oil Field	1,0
5	Eastern Trough Area Project (ETAP) Gas and Oil Field	2,4
6	Foinaven Oil Field	0,75
7	Hornsea Wind Farm	13,02
8	Oseberg South	10,45
9	Troll Gas Field	6,99
10	Johan Sverdrup Oil Field	0,61
11	Njord Oil Field	0,39
12	Gulfaks Oil Field	6,44
13	Norne Oil Field	3,46
14	Gannet Oil and gas Field	1,3
15	ST Fergus Gas Plant	3
16	Nelson Oil Field	1,55
17	Leman Oil Field	1,45
18	Shear Water	1,98
19	Sole Pit (Clipper)	1,5
20	Peterhead Power Station	3,6
21	Longanet Power Station	8,8
22	Cockenzie Power Station	3
23	Redcar Steel Works	6,6
24	Sutton Bridge Power Station	1,9
TOTAL		86,1

Figure 4 CO2 Sources Map and Sources Estimation

To continue the CO_2 distribution, it requires to consider type of transportation. In previous study of Sleipner Project, it well known as The Northern Light. The Northern Light JV was launched in March 2021, detailed well planning was performed and the drilling and completion programs for the phase 1 injection well A-7 AH and contingent well C-1 H were finalized. Speak about decarbonization, CCS stands as an indispensable solution for decarbonizing industrial processes and achieving net-zero objectives. Northern Lights is actively crafting a versatile and accessible infrastructure designed to convey CO_2 from capture sites via ships to a reception terminal in western Norway for interim storage. Subsequently, the CO_2 is then transported through pipelines for secure and enduring storage in a reservoir positioned 2,600 meters beneath the seabed. The initial phase of this project focuses on the transportation and storage component of Longship, which is the Norwegian Government's comprehensive carbon capture and storage initiative. Longship seeks to showcase the viability of this decarbonization method to both Europe and the global community (Figure 5).

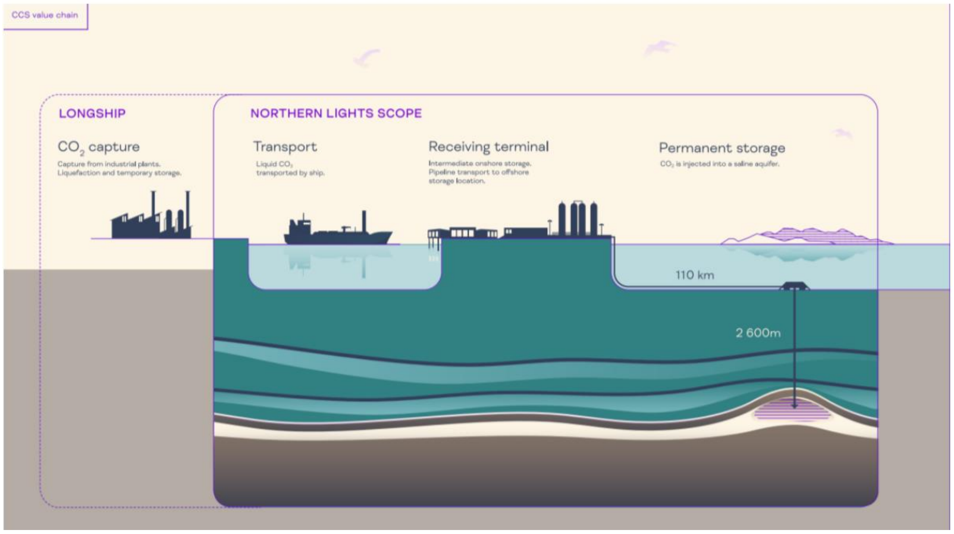


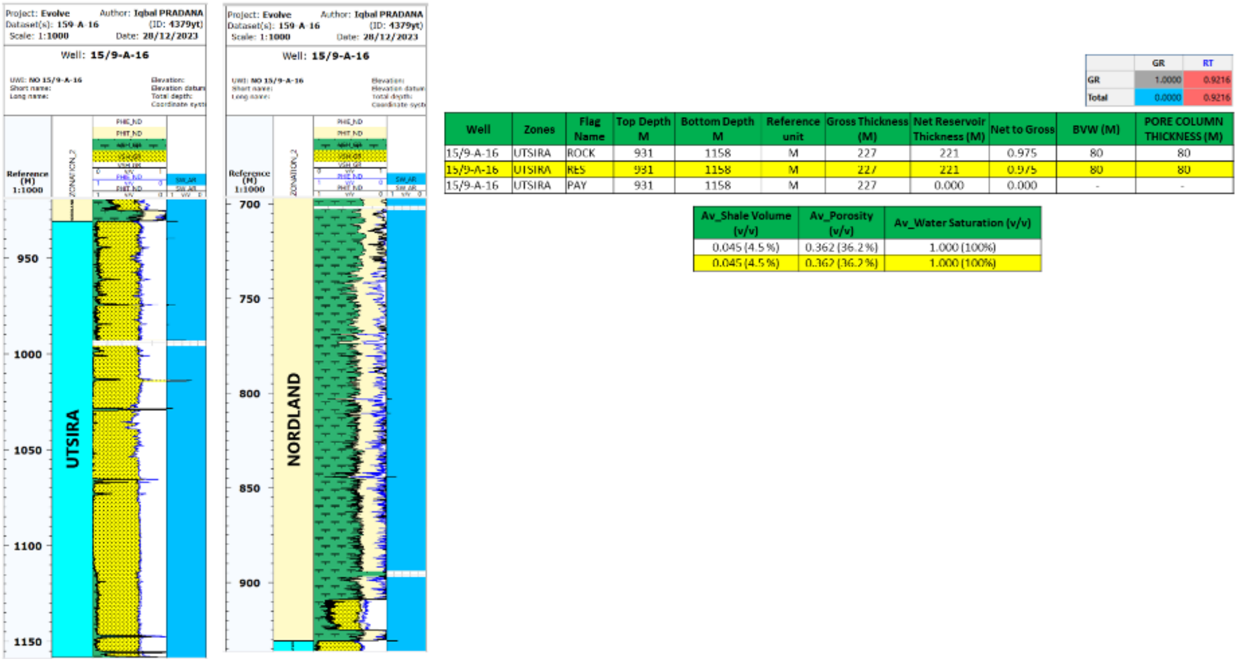
Figure 5 Northern Lights Planning (https://norlights.com/what-we-do/)

Through the establishment of an open-source infrastructure for CO_2 transport and storage, Northern Lights aspires to play a pivotal role in fostering a commercial CCS market in Europe. With operational readiness targeted for 2024, Northern Lights aims to be the pioneer in providing cross-border CO_2 transport and storage services. There are 3 key points of CCS Northern Lights, the first is Captured at the emission sources (power, industry, waste), the second is CO_2 is transported by ship or pipeline to the injection facility, and the third is Storage CO_2 that injected and stored safely at depths typically >1 km By addressing those 3 points, Northern Lights facilitates the reduction of unavoidable industrial emissions and expedites the process of decarbonizing European industry.

Geology, Geophysics, and Petrophysics Analysis

The petrophysical analysis for the Utsira Formation yields significant findings for the Sleipner CCS Project. Using a set of cutoff parameters, including a maximum volume of shale (Vshale) of 0.35, a minimum porosity of 0.1, and a maximum water saturation (SW) of 0.65, the calculated average Vshale for the reservoir is approximately 4.5%. This confirms the Utsira sand as a relatively thick and clean sand, with an average porosity of around 36.2%, predominantly considered as unconsolidated sand. The thickness of the reservoir is measured at approximately 221 meters true vertical depth (TVD) (Figure 8).

Given the limited geometry and favorable petrophysical properties of the Utsira sand, it is considered an excellent candidate for CO_2 storage. However, to refine the assessment and determine the potential column that the seal can hold, additional capillary pressure data is recommended. This data will provide crucial insights into the seal's ability to contain CO_2 and contribute to a more comprehensive understanding of the reservoir-seal system, supporting informed decision-making for the Sleipner CCS Project.



	GR	RT
GR	1.0000	0.9216
Total	0.0000	0.9216

Well	Zones	Flag Name	Top Depth M	Bottom Depth M	Reference unit	Gross Thickness (M)	Net Reservoir Thickness (M)	Net to Gross	BVW (M)	PORE COLUMN THICKNESS (M)
15/9-A-16	UTSIRA	ROCK	931	1158	M	227	221	0.975	80	80
15/9-A-16	UTSIRA	RES	931	1158	M	227	221	0.975	80	80
15/9-A-16	UTSIRA	PAY	931	1158	M	227	0.000	0.000	-	-

Av_Shale Volume (v/v)	Av_Porosity (v/v)	Av_Water Saturation (v/v)
0.045 (4.5 %)	0.362 (36.2 %)	1.000 (100%)
0.045 (4.5 %)	0.362 (36.2 %)	1.000 (100%)

Figure 6 The summary of petrophysical analysis

The petrophysical analysis for the Utsira Formation yields significant findings for the Sleipner CCS Project (Table 1). Using a set of cutoff parameters, including a maximum volume of shale (Vshale) of 0.35, a minimum porosity of 0.1, and a full water saturation (SW) of 0.65, the calculated average Vshale for the reservoir is approximately 4.5%. This confirms that the Utsira sand is relatively thick and clean, with an average porosity of around 36.2%, predominantly considered unconsolidated sand. The thickness of the reservoir is measured at approximately 221 meters of actual vertical depth (TVD).

Table 1 Petrophysical Result and Summary

Well	Zones	Flag Name	Top Depth M	Bottom Depth M	Reference unit	Gross Thickness (M)	Net Reservoir Thickness (M)	Net to Gross	BVW (M)	PORE COLUMN THICKNESS (M)
15/9-A-16	UTSIRA	ROCK	931	1158	M	227	221	0.975	80	80
15/9-A-16	UTSIRA	RES	931	1158	M	227	221	0.975	80	80
15/9-A-16	UTSIRA	PAY	931	1158	M	227	0.000	0.000	-	-

Given the limited geometry and favorable petrophysical properties of the Utsira sand, it is considered an excellent candidate for CO_2 storage. However, additional capillary pressure data is recommended to refine the assessment and determine the potential column that the seal can hold. This data will provide crucial insights into the seal's ability to contain CO2 and contribute to a more comprehensive understanding of the reservoir-seal system, supporting informed decision-making for the Sleipner CCS Project.

Petrophysical data is then used to build the static model. The model is made exclusively from Utsira base formation up to thick shale on Nordland Group. The facies model was constructed with the Sequential Indicator Simulation algorithm, and to control the facies distribution on the target formation, Colored inversion generated by amplitude inversion was used as trend distribution. The model is managed with variation distribution NNE-SSW and NNW-SSE direction and low dip, under 10°, configuration. The facies model shows a promising result since it shows a clear contrast between formations. Sandstone-loose sand dominates the Utsira formation and also has interbedded shale, and it shows the Nordland group shows a very thick shale with very low sand competition. The facies model was then used for the base porosity modeling with the promising result of effective porosity ranging from 0.1% to 30%. The static model shows underestimated result with the pore volume of 0.4 billion m^3 of volume that can store CO^2 plume.

Table 2 Volume Result

Bulk volume[*10^6 m3]	Net volume[*10^6 m3]	Pore volume[*10^6 rm3]
9755	5853	406

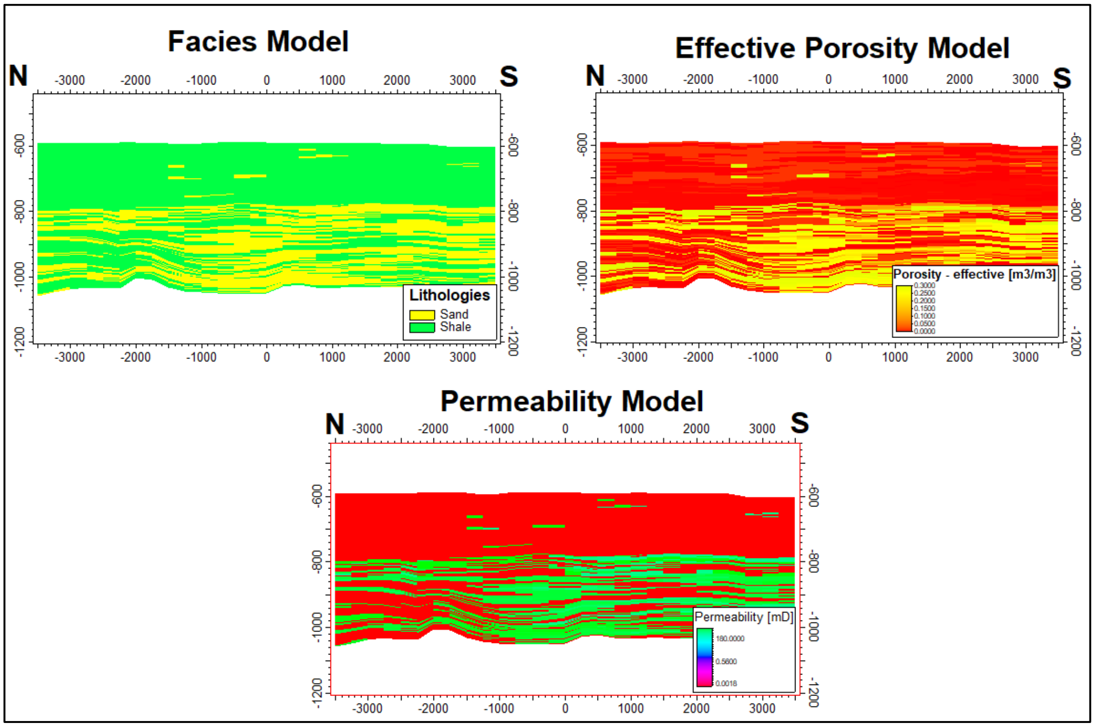


Figure 7 Static Model of the Sleipner

MMV Performance Assessment

In the Pore Pressure to Monitoring, Measurement, and Verification (MMV) analysis for Zone 1 in the Sleipner CCS Project, the primary focus lies in assessing the hydrostatic or normal gradient conditions. The analysis begins with a thorough examination of pressure values, scrutinizing them against the expected normal gradient range of 8.4-8.5 ppg (Figure 10). To ensure consistency, these pressure values are meticulously converted to psi at specific depths, confirming their alignment with the anticipated hydrostatic pressure gradient. The objective is to validate the pore pressure interpretation and establish a reliable foundation for reservoir characterization.

In parallel, a critical step involves the identification and removal of abnormal pressure readings attributable to lithological variations outside of shale formations. This process enhances the accuracy of the analysis by isolating the effects of lithology on pressure values. Subsequently, the interpretation is further validated through cross-referencing with data from pressure tests, Leak-off Tests (LOT), and Drill Stem Tests (DST). Pressure tests provide direct measurements of formation pressure, while LOT and DST data offer insights into pressure behavior during operational phases. The iterative nature of this analysis ensures a robust and accurate understanding of the pore pressure dynamics in Zone 1, facilitating informed decision-making and contributing to the success of the Sleipner CCS Project.

The identification of a suspected transition zone from a normal pressure gradient to a higher gradient in Zone 1 of the Sleipner CCS Project necessitates a comprehensive validation process within the framework of Monitoring, Measurement, and Verification (MMV). The initial step involves a meticulous examination of pressure values in the transition zone, comparing them to the expected normal gradient range of 8.4-8.5 ppg and converting them to psi at specific depths. The objective is to ascertain whether the observed pressure values align with the anticipated hydrostatic pressure gradient, providing a foundation for understanding the subsurface conditions. Concurrently, the analysis includes the removal of abnormal pressure readings associated with lithological variations outside of shale formations, ensuring that the focus remains on accurately characterizing the transition zone.

To further validate the suspected transition zone, the MMV plan incorporates multiple data sources and validation techniques. These include pressure tests, Leak-off Tests (LOT), and Drill Stem Tests (DST). Pressure tests directly measure formation pressure, while LOT and DST data offer insights into pressure behavior during different operational phases. By cross-referencing pressure data with these independent datasets, the MMV process aims to strengthen the reliability of the transition zone interpretation. Transparent communication of findings and continuous monitoring plans will be essential, allowing for ongoing adaptation of the interpretation as new data becomes available. This robust MMV strategy ensures the accuracy of reservoir characterization in the transition zone, contributing to the overall success of the Sleipner CCS Project by mitigating risks associated with pressure variations.

In the Pore Pressure to Monitoring, Measurement, and Verification (MMV) analysis for Zone 2 within the Sleipner CCS Project, attention is directed towards investigating a suspected deviation from a slightly above normal pressure gradient. The analysis begins by meticulously examining pressure values and assessing their correlation with the expected increase in pressure gradient, typically followed by an analogous trend in fracture pressure. However, in this case, there is a notable observation of a reduced distance between Pore Pressure (PP) and Fracture Gradient (FG) at deeper depths, warranting a thorough validation process.

To enhance the accuracy of the interpretation, abnormal pressure readings associated with lithological variations outside of shale formations are systematically removed. This step aims to isolate the impact of lithology on pressure values, ensuring a more precise characterization of the subsurface conditions. Subsequently, the MMV analysis includes validation measures such as cross-referencing with pressure tests, Leak-off Tests (LOT), and Drill Stem Tests (DST). Pressure tests provide direct measurements of formation pressure, while LOT and DST data offer insights into pressure behavior during various operational phases. The comprehensive validation process ensures that the interpretation of Zone 2's pore pressure dynamics aligns with the observed trends and is supported by multiple data sources, contributing to the reliability of reservoir characterization in the Sleipner CCS Project.

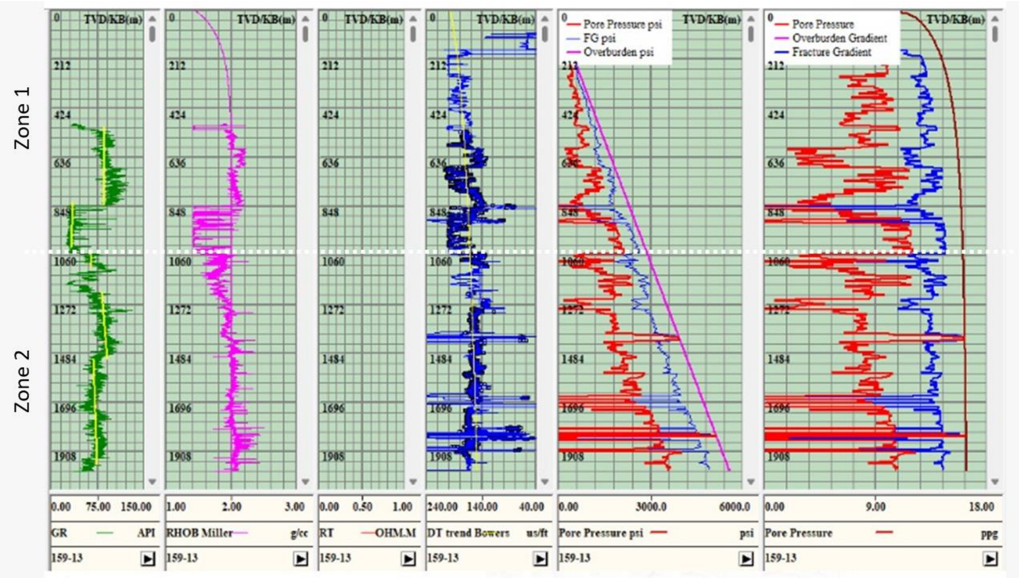


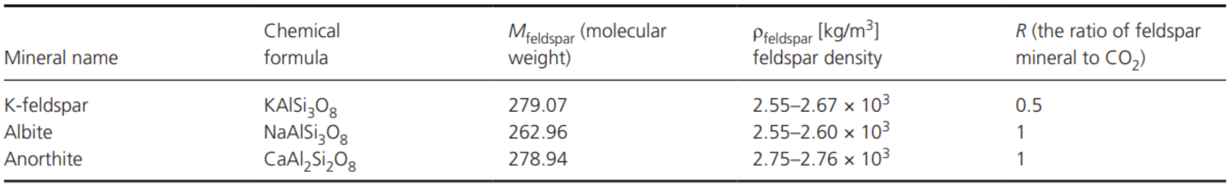
Figure 8 Pore Pressure Fracture Gradient Analysis

The other approach to look the performance of storage is through mineral identification. The process of mineral trapping is considered the most secure method, as it involves the conversion of CO_2 into secondary minerals through geochemical reactions. It is alternatively described as "perpetual confinement". The presence of mineral entrapment is demonstrated by the outcome of transport reactive modeling, facilitated by an abundance of comprehensive geological data. Over the course of millions of years, the ability of minerals to trap substances varies across different places.

The storage capacity of mineral trapping is limited by the mineral compositions of reservoir rocks and the chemical compositions of formation waters. Based on Jin, et al (2017), the sandstone is the predominant kind of reservoir for capturing CO_2 in continental oil and gas operations. Typically, sandstone consists of quartz, feldspar, lithic fragments, clay minerals, and occasionally carbonate cements, specifically calcite. Calcite, being highly unstable, has its initial reaction with acidic formation water following the injection of CO_2. The transient trapping of CO_2 occurs due to the inherent instability of bicarbonate and the reversible nature of equation.

Hence, the carbon dioxide (CO_2) that is sequestered by calcite is not accounted for in the capacity of mineral trapping. The physical characteristics and CO_2 consumption rates of three common feldspar minerals, namely K-feldspar, albite, and anorthite, are being examined (Table 3). The interaction between acidic fluid and feldspar minerals results in irreversible entrapment.

Table 3 Investigate the physical characteristics and carbon dioxide consumption of feldspar minerals (Jin, et al, 2017)



Mineral name	Chemical formula	$M_{feldspar}$ (molecular weight)	$\rho_{feldspar}$ [kg/m^3] feldspar density	R (the ratio of feldspar mineral to CO_2)
K-feldspar	$KAlSi_3O_8$	279.07	$2.55–2.67 \times 10^3$	0.5
Albite	$NaAlSi_3O_8$	262.96	$2.55–2.60 \times 10^3$	1
Anorthite	$CaAl_2Si_2O_8$	278.94	$2.75–2.76 \times 10^3$	1

The equation illustrates the calculating procedure for mineral trapping.

$$m_{CO_2 K-feldspar} = \frac{\rho_{k\ \ feldspar} \cdot V \cdot (1-\phi) \cdot C_{fragments} \cdot C_{feldspar} \cdot X_{K-feldspar} \cdot a \cdot M_{CO_2} \cdot R}{M_{K\ \ feldspar}}$$

mCO2 [Mt] = the total CO2 storage capacity of mineral trapping
ρfeldspar [kg/m3] = the average density of feldspar mineral
Vfeldspar [km3] = the total volume of feldspar mineral, MCO2 [g/mol]
Mfeldspar [g/mol] = the molecular weight of CO2 and feldspar mineral
R = the ratio of feldspar mineral to consumed CO2
E =the storage efficiency factor

The petrography analysis of the Utsira Formation indicates the existence of many minerals, such as quartz, plagioclase, feldspar, chlorite, kaolinite, biotite, muscovite, hematite, sylvite, and halite (Figure 11). According to the percentages, the majority of the composition is comprised of quartz, which accounts for over 20% of the total content. Plagioclase makes up slightly more than 15%, while k-feldspar contributes roughly 10% (Asbjornsen, 2015). The previously mentioned minerals will be employed in the calculation estimation of capacity, with specific emphasis on feldspar's ability to sequester CO_2 using the aforementioned formula. The activity entails calculating the mineral content and subsequently evaluating the formula. The Utsira Formation has the capacity to sequester a total of 97.73 megatons of CO_2 (Table 4).

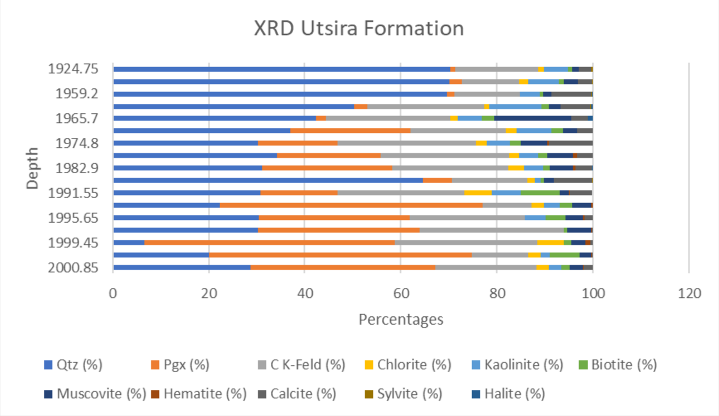


Figure 9 Utsira Formation Mineral Identification

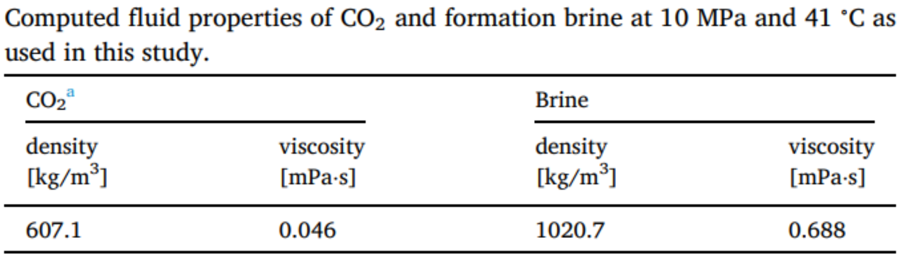
Table 4 Mineral identification from sample in Utsira Formation

Depth	Qtz (%)	Pgx (%)	C K-Feld (%)	Chlorite (%)	Kaolinite (%)	Biotite (%)	Muscovite (%)	Hematite (%)	Calcite (%)	Sylvite (%)	Halite (%)	Cfrag (%)	ρfeldspar (kg/m3)	V (km3)	(1-Por)	E (%)	MCO2 (g/mol)	R	Mfelds (g/mol)	MCO2 (MT)
2000.85	28.67	38.54	21.02	2.586	2.72	1.57	2.85	0.15	1.88	0	0	78.966	2550	260	0.688	2.16	44.01	0.5	279.07	5.85
2000.3	20.1	54.73	11.71	2.64	1.9	6.22	2.45	0.14	0.11	0	0	88.29	2550	260	0.688	2.16	44.01	0.5	279.07	3.64
1999.45	6.66	52.13	29.7	5.43	0	1.57	2.92	1.06	0.53	0	0	70.3	2550	260	0.688	2.16	44.01	0.5	279.07	7.36
1996.6	30.24	33.75	30.03	0	0	0.6	5.02	0.13	0.24	0	0	69.98	2550	260	0.688	2.16	44.01	0.5	279.07	7.40
1995.65	30.37	31.49	23.96	0	4.39	4.13	3.62	0.37	1.67	0	0	76.04	2550	260	0.688	2.16	44.01	0.5	279.07	6.42
1995.4	22.22	54.81	10.26	2.51	3.29	2.57	4.06	0.29	0	0	0	89.75	2550	260	0.688	2.16	44.01	0.5	279.07	3.24
1991.55	30.79	16	26.49	5.58	6.08	8.15	1.97	0.09	4.67	0	0	73.33	2550	260	0.688	2.16	44.01	0.5	279.07	6.84
1983.4	64.57	6.16	15.58	1.57	1.29	0.62	2.16	0	7.91	0.13	0	84.41	2550	260	0.688	2.16	44.01	0.5	279.07	4.63
1982.9	31.04	27.23	24.17	3.16	4.05	1.39	4.86	0.56	3.46	0	0.09	75.84	2550	260	0.688	2.16	44.01	0.5	279.07	6.46
1979.25	34.16	21.66	26.73	2.18	3.89	1.96	5.28	0.82	3.32	0	0	73.27	2550	260	0.688	2.16	44.01	0.5	279.07	6.90
1974.8	30.23	16.67	28.78	2.22	4.89	2.24	5.47	0.41	9.09	0	0	71.22	2550	260	0.688	2.16	44.01	0.5	279.07	7.22
1967.95	37	24.95	20.01	2.18	7.28	2.42	2.82	0	3.34	0	0	79.99	2550	260	0.688	2.16	44.01	0.5	279.07	5.64
1965.7	42.35	2	25.95	1.58	5.05	2.51	16.09	0	3.41	0	1.06	74.05	2550	260	0.688	2.16	44.01	0.5	279.07	6.77
1959.65	50.35	2.72	24.25	1.18	10.81	1.53	2.5	0	6.09	0.18	0.4	75.76	2550	260	0.688	2.16	44.01	0.5	279.07	6.47
1959.2	69.67	1.46	13.7	0	4.18	0.65	1.75	0	8.18	0.21	0.2	86.3	2550	260	0.688	2.16	44.01	0.5	279.07	4.17
1952.5	70.16	2.59	11.88	1.93	6.42	1.05	2.87	0	2.88	0.24	0	88.14	2550	260	0.688	2.16	44.01	0.5	279.07	3.69
1924.75	70.23	1.18	17.23	1.21	5.01	0.85	1.44	0	2.48	0.37	0	82.77	2550	260	0.688	2.16	44.01	0.5	279.07	5.02
																			TOTAL	**97.73**

Dynamic modeling is necessary to validate the monitoring and measuring process. The dataset utilized in this work was obtained from the offshore Norway Sleipner CCS project, specifically the Sleipner 2019 Benchmark Model. This project entails the injection of CO2, which has been recovered from natural gas obtained from a gas field located 200 km inland and approximately 1 km beneath the ground, into the Utsira formation. The Utsira formation is a salty aquifer (Akai, T. 2021). CO2 injection commenced in 1996. An individual injector, specifically the 15/9-A16, releases approximately 0.8 million tonnes (Mt) of carbon dioxide (CO2) on a yearly basis. Akai, T. (2021) states that the Utsira Formation consists of shallow, loose sands that were deposited as marine low stand deposits in a confined basin. These sands have porosities ranging from 35% to 40% with permeability above 1 Darcy. Figure 1a displays the gamma-ray reaction acquired from vertical exploration well 15/9-13. The Utsira formation has a thickness that varies between 200 and 300 meters in the studied area. The Utsira Formation is overlaid by a caprock formation with a thickness of 100 meters, serving as an effective barrier for containing and storing CO2.

In addition, the flow simulation employs Darcy's law, and we resolved the mass conservation of components in many phases using the CMG compositional simulator (GEM version 2022), a commercially available reservoir simulator. We examined a gas/liquid system consisting of two phases (CO2-rich and aqueous) that maintained a constant temperature. The system comprised five components: CO2, H2O, sodium chloride, calcium chloride, and calcium carbonate. While the other constituents are only found in the liquid state, both CO2 and H2O can exist in both the gaseous and liquid states.

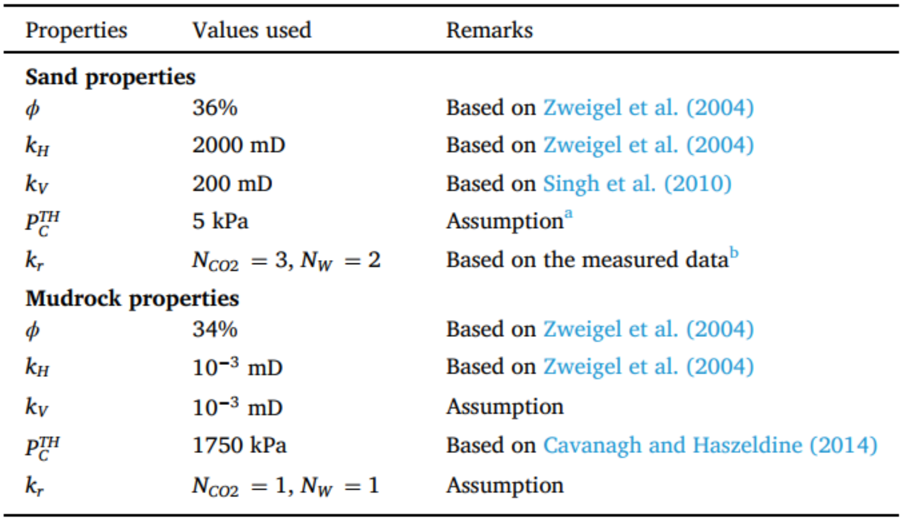
Table 5 Fluid properties of CO2 and formation brine



Computed fluid properties of CO_2 and formation brine at 10 MPa and 41 °C as used in this study.

CO_2[a]		Brine	
density [kg/m^3]	viscosity [mPa·s]	density [kg/m^3]	viscosity [mPa·s]
607.1	0.046	1020.7	0.688

Table 6 Sand and Mudrock properties (Krevor et al, 2012)



Properties	Values used	Remarks
Sand properties		
ϕ	36%	Based on Zweigel et al. (2004)
k_H	2000 mD	Based on Zweigel et al. (2004)
k_V	200 mD	Based on Singh et al. (2010)
P_C^{TH}	5 kPa	Assumption[a]
k_r	$N_{CO2} = 3, N_W = 2$	Based on the measured data[b]
Mudrock properties		
ϕ	34%	Based on Zweigel et al. (2004)
k_H	10^{-3} mD	Based on Zweigel et al. (2004)
k_V	10^{-3} mD	Assumption
P_C^{TH}	1750 kPa	Based on Cavanagh and Haszeldine (2014)
k_r	$N_{CO2} = 1, N_W = 1$	Assumption

A compositional reservoir simulator requires a higher computing load compared to a black oil reservoir simulator, as it solves the mass balance of each phase. However, because it can accurately model the movement of CO2 in water and include chemical reactions, we decided to use a compositional reservoir simulator. In the instance of the Sleipner storage site, it was seen that the later factor (referring to a previous mentioned factor) had less importance. This was because the brine, which included dissolved CO2, remained unsaturated for a long period of time.

The dynamic model input parameter constructed a simulation grid model utilizing these surfaces. The handling of the model's boundary conditions was as follows. In order to maintain the mass conservation of the components in the model, a closed boundary constraint was imposed on each border. Hence, a model was created to depict the process of CO2 diffusive mass movement in brine towards the cap rock situated above it. However, our work did not simulate the process of mass diffusion towards a subsurface formation. The outside two grid blocks had a large pore volume, which allowed the accumulation of fluid components that reached that area.

The composition of the formation brine was determined by analyzing saltwater with a salinity of 35,000 parts per million. The initial reservoir pressures inside the formation were determined by considering the hydrostatic pressure gradient of the formation brine and a reference pressure of 10 MPa at a depth of 1000 meters. Our assumption of an isothermal temperature of 41∘C was based on the findings of Bickle et al. (2007), notwithstanding the presence of a temperature gradient across the target formation. At these pressure and temperature settings, CO2 exists in the formation brine either as a dissolved component or as a supercritical phase. The compressible density of CO2 was calculated using a modified Redlich-Kwong equation of state (Spycher and Pruess, 2005; 2010), while viscosity was calculated using the models proposed by Fenghour et al. (1998) and Vesovic et al. (1990).

The grid blocks were represented as active grid blocks, meaning that both the caprock layers and the thin intraformational mudrock layers were modeled as active grid blocks with poor permeability and high capillary pressure. The assignment of grid block attributes was determined by referencing values available in the literature and consolidating them in Table 2. Table 2 demonstrates our utilization of identical reservoir parameters to those documented in Singh et al. (2010) and Sleipner 2019 Benchmark Model (2020a), with the exception of the relative permeability. The drainage relative permeability of the Sleipner benchmark model can be found in Singh et al. (2010). However, for our study, we utilized the relative permeability data from Krevor et al. (2012), which was obtained from sandstone samples with comparable permeability. This data was collected for a CO2/water system, and it exhibited a similar drainage relative permeability pattern to that observed in the Sleipner storage site sample (Singh et al., 2010).

The relative permeability should be taken into account while considering the hysteresis of the material. The empirically determined relative permeability was directly utilized in our simulation without any up-scaling, as the Utsira formation exhibits a high degree of homogeneity and permeability. We considered the impact of the intraformational mudrock barriers on the movement of the CO2 plume by comparing its simulated and seismically observed morphologies. Two simulations were conducted: one applying the sand properties from Table 6 to the other layers, including the intraformational mudrock layers (case 1), and the other applying the mudrock properties to both the intraformational mudrock layers and the caprock layers (case 2).

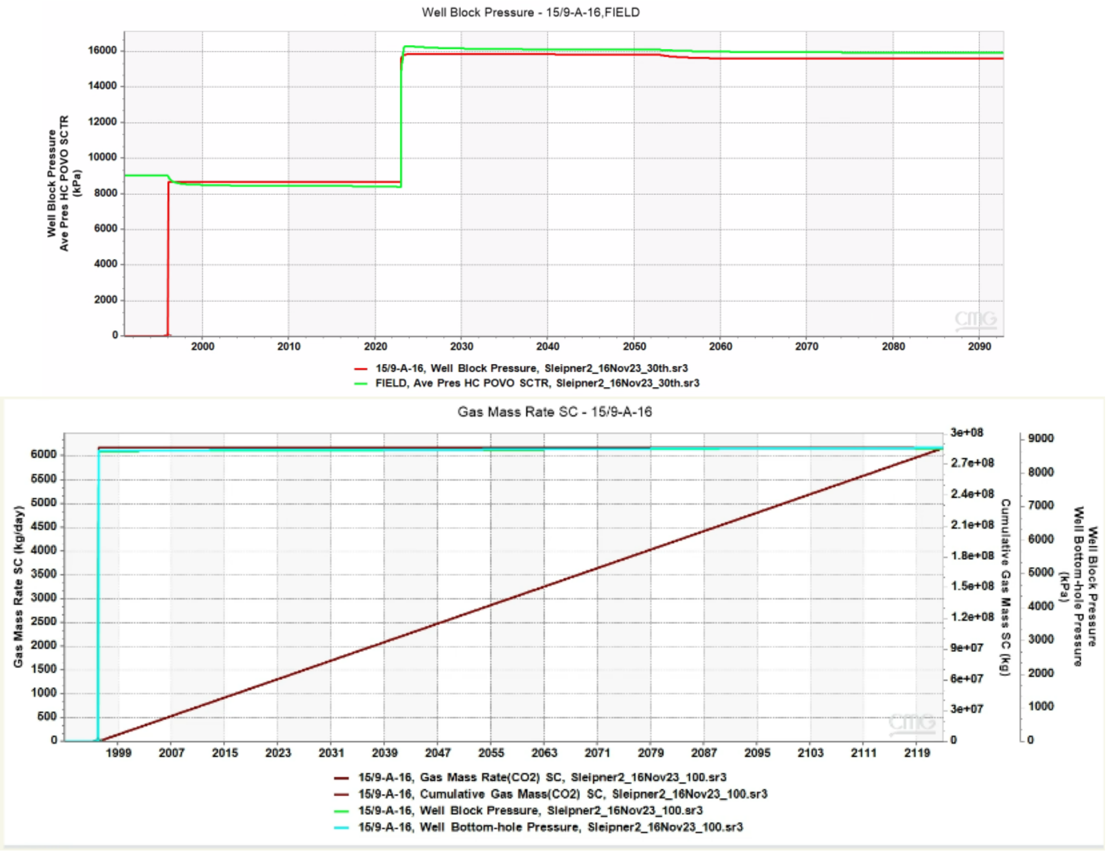


Figure 10 Well Block Pressure and Gas Mass Rate

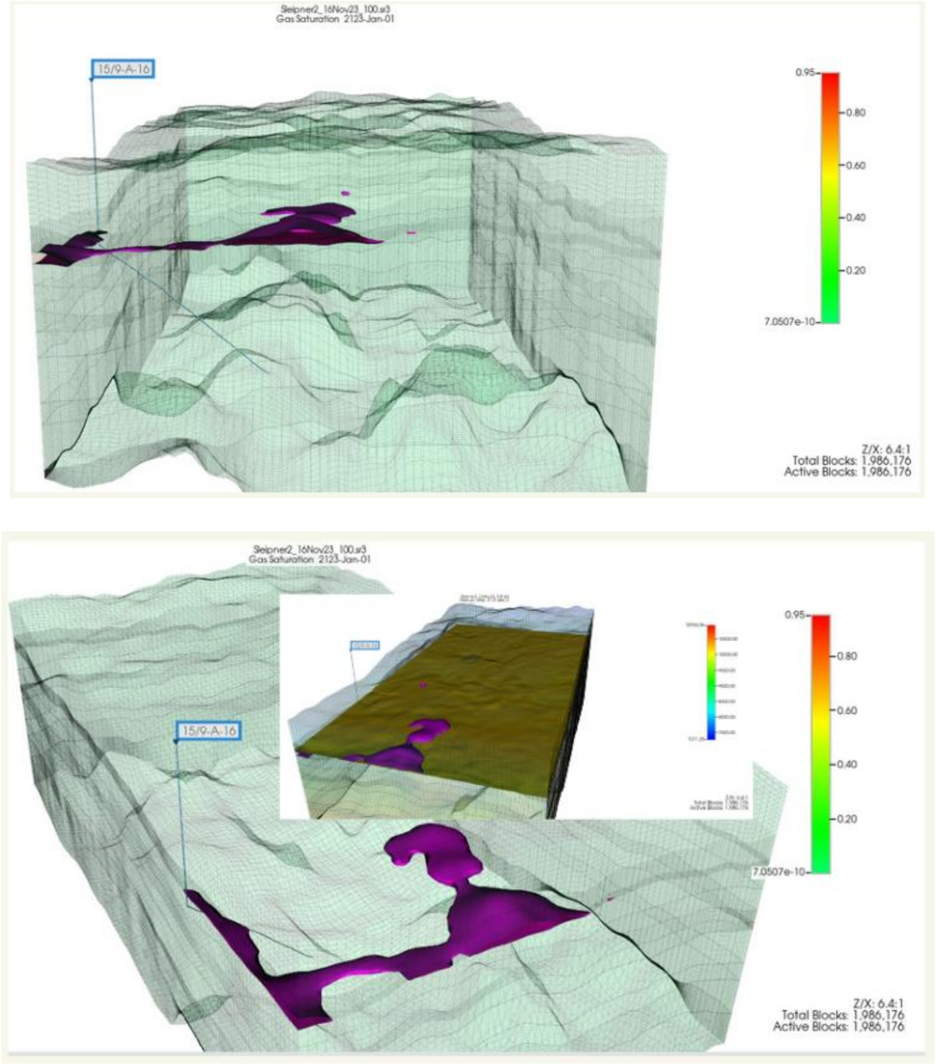


Figure 11 Dynamic modeling from CO_2 plume migration overview in Utsira Formation

The change in the average reservoir pressure and the pressure of the grid block where the injection took place (well, the grid block pressure) can be seen from the temporary result. The pressures were adjusted to a datum depth of 1000 meters. The well grid block showed the greatest pressure change, as would be expected. Within a year of injection, it dropped below 10.2 MPa, having begun at about 10.5 MPa, which was 0.5 MPa higher than the initial reservoir pressure of 10 MPa. The well's injectivity increased during this time due to an increase in gas relative permeability caused by an increase in gas saturation of the grid blocks surrounding the injector. Both pressures progressively increased until the injection was stopped after a year. When the CO2 injection was finished, the well block pressure increased to 10.23 MPa, the highest average reservoir pressure recorded being 10.1 MPa.

The sensitivity simulation looks at how simulation input parameters affected the storage mechanisms over an extended length of time. To comprehend the general behavior of the model, this was done. In certain cases, intraformational mudrock barriers were left in place for a millennium without additional CO_2 injection in order to examine the effects on long-term storage mechanisms. Recall that case 1's intraformational mudrock layers had sand-like characteristics, whereas mudrock and sand layers had distinct capillary and permeability values.

For the simulation management strategy used a compositional reservoir simulation model with five fluid components using a simulation model made up of 64 × 118 × 154 grid blocks (i.e., approximately 1.2 million grid blocks) to model the Sleipner storage site, which has an area of about 20 km2 and a thickness of about 200 m. It took 25 hours to simulate the 12-year injection period and an additional 36 hours to simulate the 1000-year post-injection period using 16 CPUs. With a desktop simulation environment, this computational cost might be reasonable for the small number of sensitivity simulations that we have demonstrated here. However, a high performance computing (HPC) environment would be required if numerous simulations (> 100 runs) were needed (for example, an automated history matching study (Nilsen et al., 2017) and a sensitivity study for a wider range of uncertain parameter space).

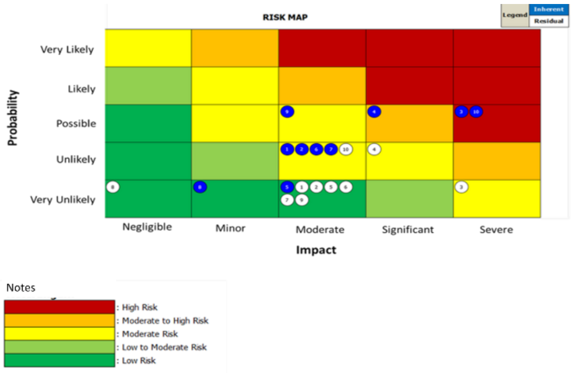
Risk Assessment

Carbon Capture and Storage (CCS) is a technology aimed at reducing greenhouse gas emissions, but it carries various risks that need careful assessment. These risks include potential CO_2 leakage from geological storage sites, health and safety hazards during capture, transport, and storage, transportation accidents, and high implementation costs. Additionally, CCS faces challenges in regulatory and legal frameworks, public perception, long-term liability issues, and potential environmental impacts. Mitigating these risks involves thorough site selection and monitoring, stringent safety and environmental regulations, effective public engagement, and ongoing technological innovation. Furthermore, assessing the economic viability and ensuring alignment with broader climate goals are crucial. Overall, a multidisciplinary approach is essential to address the complex challenges associated with CCS and to harness its potential benefits in combating climate change.

In this cases, there are 10 hazards that can be potential during the project based on surface and subsurface (Table 7). Based on several potential, it could be calculated the level of impact and probability shown below. The crucial issue addressed by existing pipeline corrosion and environmental incidents that signed by red color in map.

Table 7 Risk Assessment during project

No	Hazard Potential	Cause	Consequences	Mitigation
1	Existing pipeline corrosion	Corrosion levels higher than expected, existing pipeline unsuitable for CO2 service	Cost/schedule impact of having to repair/replace corroded pipeline section	Confirm the integrity of the pipeline
2	Existing Well Corrosion	Unexpected combination of ions in the water caused by CO2 interactions	The possible occasional presence of oxygen and/or solvent degradation products could react with the metal and cause corrosion and failure of the well components	By selection of appropriate well components to minimise corrosion risk, performing corrosion experiments and adopting a suitable sparing strategy
3	Existing Infrastructure failure	Existing site infrastructure which is planned to be used to supply utilities to the carbon capture process is not fit for purpose over the required lifetime of	Requirement for repair/replacement, exposure to liabilities for loss of availability	Assessed the suitability of the existing plant before considering necessary upgrade and life extension works.
4	CO2 migrates above primary seal via flow behind injection casing	Loss of cement bond	Forced to cease using injection well, leading to well intervention and abandonment of well. Possible license issues, increased monitoring costs	Cement quality logging
5	Failure of CO2 gas detection	CO2 detector failure due to temperature drop	HSSE exposure, unable to inject CO2, potential health impact.	Review and testing of CO2 technology
6	Procurement process Delays in: - Procurement process - LLI delivery - CO2 injection equipment -Long Lead Item	1. Un-available tools in shorebase / field 2. Difference spesification required	Late project execution	1. Communication to vendor in weekly progress 2. Plan backup for vendor's candidate
7	Competition complexity causes project delay and budget over-run	The magnitude/scale and complexity of the overall project (i.e. the long chain from the operating power plant to inject in target reservoir) and complexity of bid process	Project delay and budget overrun, leading to stakeholder concerns over deliverability of project	Time schedule and prepare for emergancy cost
8	Seawater & CO2 injection test execution / operation issues	Improper CO2 handling/storage due to unfamiliarity in CO2 handling process	- Delay project - Re-inspection	- Proper communication with providers - Pre job inspections
9	Injectivity estimate not achieved	- Poor saline aquifer quality - Thin layer saline aquifer - Compartmentalization - Pressure constraint	Unexpected volume CO2 storage	Re-run model through fine out the uncertainties Building optimistic, base, and pesimistic case
10	Environmental incidents	- CO2 leaking during transportation - Seal leaking	- Public complain - Project would be stopped by government	- Execution based on working procedure - Monthly or yearly monitoring program



Environmental, Sustainability, and Governance (ESG)

ESG investing is becoming increasingly popular in the financial sector due to its positive impact on the environment, society, and corporate governance. ESG investing reward companies that emphasize sustainability, social responsibility, and good governance. In order to identify the ESG scheme in the Sleipner Project, the primary objective is to ensure that the emissions from operations do not exceed 80 megatons of CO_2 during the project. This is crucial since the amount of CO_2 emitted during operations must be lower than the amount of CO_2 injected. Furthermore, the project's sustainability is ensured by maintaining a consistent injection rate and pressure, which helps to sustain the project. Moreover, the governance part primarily concerns the formulation of policies and the development of a communication plan for stakeholders. In this section, the policy would provide comprehensive support for this program in order to effectively mitigate greenhouse gas emissions, which contribute to global warming.

Additionally, a stakeholder study is necessary to assess and determine the degree of knowledge, concerns, issues, commitment, support, or resistance of relevant and significant stakeholders involved in the CCS Sleipner Project. Data will be gathered via interviews and Focus Group Discussions (FGDs) as part of the social site characterisation process. The stakeholder analysis facilitates the identification of stakeholders that may not be immediately apparent to the CCS Sleipner team. It also allows for the observation of stakeholders' perceptions of the project and the collection of subtle indications of societal concerns. Finally, upon completion of the procedure, the project can familiarize important stakeholders with the concept of the CCS Sleipner Project.

During the initial phase of stakeholder identification, it is important to conduct a communication process in order to gain a comprehensive understanding of the project context and provide support for the project. The early engagement of stakeholders is vital for ensuring the project's social acceptance. The important stakeholders can be categorized into four groups, the local administration in the vicinity is associated with nearby villages, community representative associated with non-governmental organization, and media sources.

Discussion

Two perspectives are involved in conducting this project: surface analysis and subsurface analysis. The surface assessment reveals that there are twenty-four potential sources of CO_2 in the North Sea area, emitting approximately 86.1 megatons of CO_2 annually. These emissions are transported through the Northern Lights accessible infrastructure, which is specifically designed to transport CO_2 from capture sites via ships to a reception terminal in western Norway. The CO_2 is then stored temporarily in this terminal before being transported through pipelines for safe and long-lasting storage in a reservoir located 2,600 meters below the seabed.

Furthermore, the geophysics assessment, which relies on subsurface analysis, examines the velocity model of the Utsira interval in the Sleipner area. It indicates that this interval is unlikely to have experienced significant tectonic deformation, as there are no noticeable amplitude discontinuities or displacements that would classify it as a fault zone. Proceed further the calculated expansion rate of the CO_2 plume within the Top Utsira Sands, measured in terms of area, is around 0.278 square kilometers per year.

In order to evaluate the efficacy of the MMV procedure, there are multiple data points available to substantiate the analysis. One of the methods involves conducting petrophysical studies on the Utsira Formation. This study utilizes the reservoir's average volume of shale (Vshale) is around 4.5%, based on specific cutoff characteristics. These parameters include a maximum Vshale of 0.35, a minimum porosity of 0.1, and a maximum water saturation (SW) of 0.65. The Utsira sand is confirmed to be a relatively thick and clean sand, with an average porosity of approximately 36.2%. It is mostly classified as unconsolidated sand. This data is used to determine the performance assessment of MMV, namely the pore pressure fracture gradient. The outcome of this data. To identify a probable transition zone from a normal pressure gradient to a greater gradient in Zone 1, the first step entails a thorough evaluation of pressure readings in the transition zone, comparing them to the expected normal gradient range of 8.4-8.5 ppg. Furthermore, the analysis for Zone 2 is examining a suspected departure from a pressure gradient that is somewhat higher than the typical range.

Additionally, the initial method for the MMV program involves identifying minerals to determine the estimated amount of CO_2 sequestration prior to modeling and management. The Utsira Formation is predominantly composed of quartz, which makes up more than 20% of the total material. Plagioclase constitutes slightly over 15%, whilst k-feldspar accounts for approximately 10%. By utilizing these minerals, it is possible to calculate that the Utsira Formation has the capacity to store around 97.73 megatons of CO_2. Moreover, in order to validate the preliminary research for MMV, it is necessary to use dynamic modeling in this study. According to the parameter input, the well grid block exhibited the most significant alteration in pressure, as one would anticipate. After one year of injection, the pressure decreased to less than 10.2 MPa from an initial value of around 10.5 MPa, which was 0.5 MPa greater than the original reservoir pressure of 10 MPa. The injectivity of the well improved during this period due to an elevation in gas relative permeability resulting from an increase in gas saturation of the grid blocks surrounding the injector. Both pressures steadily escalated until the injection was halted after a year. Upon completion of the CO_2 injection, the pressure in the well block rose to 10.23 MPa, with the highest recorded average reservoir pressure being 10.1 MPa.

To ensure the project's sustainability and mitigate potential threats, it is crucial to categorize the risk assessment. The present pipeline corrosion and environmental accidents address a major issue, as explained. Nevertheless, this challenge can be surmounted by prioritizing the preservation of the system's integrity and adequately preparing for the expenses associated with repairs. Moreover, once the various components have been analyzed, it is necessary to proceed with the development of an environmental, sustainability, and governance program. This program establishes connections with society and stakeholders to guarantee the project's safety throughout its operation.

Conclusions

The project entails a thorough examination of carbon dioxide (CO_2) emissions in the North Sea, encompassing surface and subsurface analyses. Surface assessment identifies 24 potential CO_2 sources emitting 86.1 megatons annually, with transportation facilitated through the Northern Lights infrastructure. Subsurface geophysics assessment indicates a low likelihood of tectonic deformation in the Utsira interval. The Monitoring, Measurement, and Verification (MMV) procedure involves petrophysical studies revealing the Utsira Formation's capacity to store approximately 97.73 megatons of CO_2. Dynamic modeling of injection processes shows changes in pressure and improved well injectivity. Risk assessment addresses pipeline corrosion and environmental concerns, emphasizing system integrity and preparedness for repairs. The project's sustainability is underscored by the development of an environmental, sustainability, and governance program, fostering connections with society and stakeholders to ensure ongoing safety during operation.

References

Akai, T., Kurivama, T. Kato, S., Okabe, H. 2021. Numerical Modelling of Long-Term CO2 Storage Mechanisms in Saline Aquifers using the Sleipner Benchmark Dataset. International Journal of Greenhouse Gas Control. https://doi.org/10.1016/j.ijggc.2021.103405

Asbjornsen, E. Sedimentology, petrology, and diagenesis of core 16/1-13 from the Edvard Grieg Field, Utsira High, Norwegian North Sea. 2015. Master Thesis in Geoscience.

Bickle, M., Chadwick, A., Huppert, H., Hallworth, M., Lyle, S. 2007. Modelling carbon dioxide accumulation at Sleipner: Implications for underground carbon storage. Earth and Planetary Science Letters. https://doi.org/10.1016/j.epsl.2006.12.013

Fenghour, A., William, A., Wakeham, Vesovic, V. 1998. The Viscosity of Carbon Dioxide. Journal of Physical and Chemical Reference Data. https://doi.org/10.1063/1.556013

Furre, A., Eiken., Alnes, H., Vevatne, J., Kiaer, A. 2016. 20 Years of Monitoring CO2 Injection at Sleipner. 13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland. Energy Procedia 114 (2017) 3916 – 3926.

Hauber, G. 2023. Norway's Sleipner and Snøhvit CCS: Industry models or cautionary tales? Institute for Energy Economic and Financial Analysis. https://ieefa.org

https://norlights.com/what-we-do (access at January 2024)

Jin, C., Liu, L., Li, Y., Zeng, R. 2017. Capacity assessment of CO2 storage in deep saline aquifers by mineral trapping and the implications for Songliao Basin, Northeast China. Energy Science & Engineering. doi: 10.1002/ese3.151

Krevor, S., Pini, R., Zuo, L., Benson, S. 2012. Relative Permeability and Trapping of CO2 and Water in Sandstone Rocks at Reservoir Conditions. Water Resource Research.

Nilsen, H., Krogstad, S., Andersen, O., Allen, R., Lie, K. 2016. Using sensitivities and vertical-equilibrium models for parameter estimation of CO2 injection models with application to Sleipner data. 13th International Conference on Greenhouse Gas Control Technologies. doi: 10.1016/j.egypro.2017.03.1478

Norwegian Offshore Directorate. The Utsira and Skade Aquifer. https://www.sodir.no/en/whats-new/publications/co2-atlases/co2-atlas-for-the-norwegian-continental-shelf/ (access at January 2024)

Singh, V., Cavanagh, A., Hansen, H., Nazarian, B., Iding, M., Ringrose, P. 2010. Reservoir Modeling of CO2 Plume Behavior Calibrated Against Monitoring Data from Sleipner, Norway. Paper presented at the SPE Annual Technical Conference and Exhibition, Florence, Italy, September 2010. https://doi.org/10.2118/134891-MS

Sleipner 2019 Benchmark Model, 2020. URL: https://co2datashare.org/dataset/sleipner-2019-benchmark-model. 10.11582/2020.00004

Spycher, N., Pruess, K. 2005. CO2-H2O mixtures in the geological sequestration of CO2. II. Partitioning in chloride brines at 12–100°C and up to 600 bar. Geochimica et Cosmochimica Acta. https://doi.org/10.1016/j.gca.2005.01.015

Vesovic, V., Wakeham, A., Olchowy, G., Sengers, J., Watson, J., Millat, J. The Transport Properties of Carbon Dioxide. Journal of Physical and Chemical Reference Data. https://doi.org/10.1063/1.555875