Greensand Focused Seismic Monitoring for Offshore CO_2 Pilot Injection

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Summary

The Greensand consortium, led by INEOS Energy Denmark, is preparing a CO_2 pilot injection to inject up to 15.000 tons of CO_2 into the depleted Nini West oil field, Danish North Sea. The operation lasts 90 days and include 14 shipments of CO_2 to the Nini site. The injection is cyclic and will be accompanied by three focused seismic acquisitions with the objective to detect and monitor the CO_2 plume.

Modelling done implies that the seismic surveys can detect injected CO_2 in the reservoir exceeding 4% saturation. The maximum CO_2 saturation at the injection well after the last injection cycle will reach up to 55% and will radially migrate up-dip, being dissolved in formation brine and trapped in the reservoir.

The objective of the planned spot seismic acquisition surveys is to proof the concept offshore of such focused and repeated seismic acquisitions which have the potential to replace conventional 4D seismic for CO_2 plume migration monitoring requirements, reducing the monitoring costs and environmental footprint during the entire storage field life.

If successful, this focused seismic monitoring concept would have positive impact on the commercial viability and environmental footprint of the Greensand project and possibly other offshore CCS site as well.

Introduction

The United Nation's Intergovernmental Panel on Climate Change (IPCC) points to CO_2 capture and storage as an effective tool for rapidly reducing our global CO_2 emissions. Denmark decided that CO_2 storage will be a key part in achieving their climate goals. Project Greensand is the most mature project for storage of CO_2 in Denmark with the possibility of storing up to 1,5 million tons of CO_2 per year in late 2025 at the Nini A well head platform and up to 8 million tons of CO_2 per year in 2030 in the entire Siri Fairway comprising also the still producing but depleting oil fields Cecilie, Siri and Nini East (Figure 1).

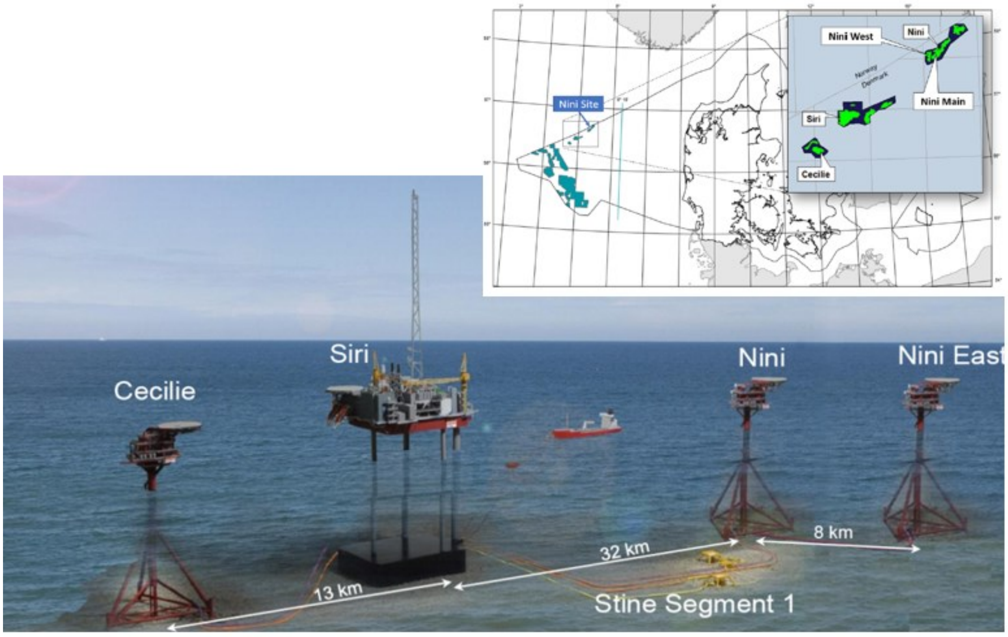

Figure 1 *Infrastructure in the Siri Fairway. INEOS Energy Denmark (Op.) and Wintershall Dea International GmbH (100% subsidiary of Wintershall Dea AG) are producing oil in the Siri Fairway since 2002. Production is envisaged until 2025. It is vision of INEOS and Wintershall Dea to convert the existing infrastructure and associated CO_2 storage capacity into permanent CO_2 storage sites, referred to be the Greensand project. Nini West Segment serves as the starting point for CO_2 storage.*

The Greensand Phase 2 Consortium is comprising of 23 cooperation partners, led by INEOS Energy Denmark, has been awarded a co-funding grant of the CCS funding pool in 2021 by the Danish Research and Development Programme EUDP. The work programme is designed to mature and de-risk the intended conversion of the depleted Nini West oil field into a permanent CO_2 storage site and is the direct continuation of the Greensand feasibility study (Greensand Phase 1 2020-2021) which was also co-funded by EUDP. The work of the feasibility study resulted in a Statement of Feasibility by DNV-GL that the depleted field has a capacity of 0.45 Mta for 10 years of CO_2 injection.

The Nini West segment was developed by one horizontal producer and one water injector for pressure support from the Nini A well head platform situated 2.5 km to the West. The injection well was used for water disposal from 2017 after the cease of oil production in the segment.

The key operational programme of the Greensand project is a CO_2 pilot injection of up to 15.000 tons of CO_2 via coil tubing through the active water injector well into the water leg of the reservoir. 14 shipments of CO_2 are foreseen in this operation. Each shipment will consist of 40 standard ISO-containers [2] each with 20 tons of capacity for liquid CO_2 delivered from the port of Antwerp. Injection will be for one day followed by shut-in of the well for 6 days allowing the vessel transits. This CO_2 pilot injection operation will take 90 days and is anticipated to commence at the end of 2022.

Seismic acquisition

According to the EU-Directive 2009 [1] for Carbon Storage and relevant ISO standards (ISO 27914, 2017; [2]), the injected liquid CO_2 and its plume migration and behaviour in the reservoir needs to be properly understood and forward modelled by reservoir simulation tools and confirmed by appropriate monitoring technologies. Any irregularity encountered in the monitoring requires an update of the reservoir model and needs to have mitigation measures in place. 4D seismic is the conventional reliable monitoring technology available which, however, has a very high impact on cost and environment. Considering value of information, if the storage containment area is well understood and delineated by existing 3D seismic, it is not mandatory to routinely acquire 4D seismic surveys just to repeatably image the CO_2 plume migrating conformably according to the predictions.

Focused seismic (or spot seismic, [3] Al Khatib et al., 2021) is a different approach to obtain dynamic subsurface seismic information than conventional 4D seismic. It is a single-source-single-receiver location acquisition and processing concept ([4] Morgan et al., 2020), regularly and repeatedly stacking the reflected seismic energy in one seismic trace over time and analyse the differences in the reflected seismic waves that were originated from the same reflection point (spot). Each spot location and timing of detection is directly driven by the forward simulation models ([5] Al Khatib et al., 2022). The method does not result in subsurface maps but in individual seismic traces containing information about the presence or absence of CO_2 in this spot location.

One source and respective receiver location can record seismic information about several meaningful spots, so the survey design and base line acquisition is key for success. The spots can be easily modified and adjusted to the moving plume by changing the source locations while keeping the recorders permanently on the ground. Permanent seismic recording stations and other monitoring sensors are another element of the monitoring research in the Greensand project but not relevant in this context. The method was applied successfully for CCUS onshore ([6] Brun et al., 2022), but has been tested for offshore CCS.

This injection operation will thus be accompanied by three focused seismic surveys, the base line acquisition pre-injection (mandatory as available 3D full field seismic was made before oil production) and the 1st and 2nd seismic monitor during and towards the end of the pilot injection in order to proof the concept of the focused seismic monitoring to be a viable technology to image and monitor CO_2 plumes.

One of the key objectives of the pilot is to demonstrate that focused seismic monitoring is able to detect injected CO_2 reliably in the reservoir, and thus be capable to confirm and calibrate the required conformity modelling during the injection lifetime and will be able to detect any irregularities. Further, it is the aim to demonstrate that focused seismic acquisition is not only lean and cost effective, but it can also be operated from a conventional offshore supply vessel passing by as the acquisition time is very limited. The focused seismic survey will be conducted from the ESVAGT INNOVATOR supply vessel with conventional low energy airguns, compressor equipment and personnel from Magseis Fairfield, both companies are consortium partners in the Greensand Phase 2 project.

Pilot modelling and monitoring planning

The field is covered by 3D seismic acquired in 1997 and reprocessed in 2002. Rock physical modelling (fluid substitution) implies that a CO_2 saturation exceeding 4% in the reservoir will create an impedance contrast strong enough to detect a difference in seismic reflection and cause a measurable time shift for the base reservoir reflection ([5] Al Khatib et al., 2022).

The cyclic CO_2 injection was simulated using ECLIPSE compositional model according to the planned pilot injection operation. After three injection cycles, equal to approximately 2250 tons of injected CO_2, the plume reaches 50 m radius away from the well exceeding the saturation detectability threshold of 4% which would be confirmed by the 1st seismic monitor (Figure 2). The 2nd seismic monitor is planned after the 12th shipment to not exceed the 90 days battery lifetime of the ocean bottom nodes deployed.

The post-injection CO_2 plume is expected to reach a 300m lateral extension, with a slight South-West anisotropy.

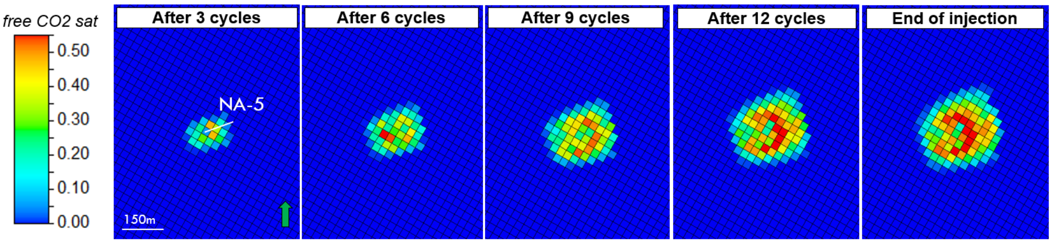

Figure 2 *Modelled free phase CO_2 saturation showing propagation of the plume after each injection cycle (indicated with the number) – 750 t of CO_2 injected in a day followed by 6 days of shut-in.*

The migration of CO_2 is driven by the top reservoir topography maintaining radial spread with partial dissolution and capillary trapping on its way, reaching a distance of 200m after one year (Figure 3B). Buoyancy force drives a lighter CO_2 up, resulting in higher saturations within top two meters. Parts of the CO_2 will dissolve directly in the aquifer and hence not be visible anymore in the seismic.

After storage site development in 2024 and 2025, the CO_2 plume of the pilot injection volumes will continued to be monitored, being part of the simulation models and the monitoring plan of the Nini West storage field.

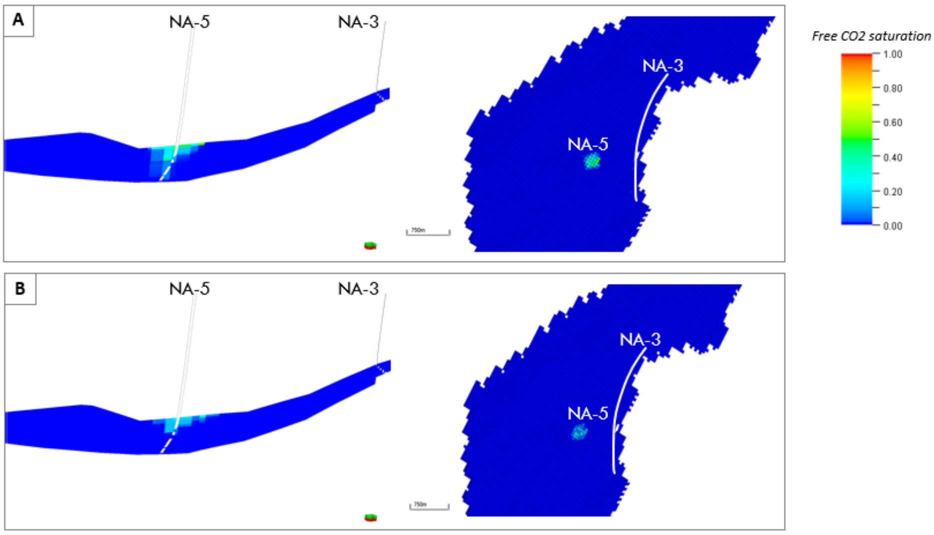

Figure 3 *Modelled free CO_2 saturation during post pilot injection period, showing plume migration after half (A) and one (B) years, accounting for progressive CO_2 dissolution in brine.*

To perform the monitoring, 25 ocean bottom nodes provided by Magseis Fairfield will be used, some of which will be retrieved during the operation for quality control. 7 source locations are planned, focussing on various spots placed at the injection location (perforation) and along the near well bore area of the injector well, see Figure 4.

With this static geometric acquisition and recording pattern similar to permanent seismic layout, it is ensured that even slight changes of saturations can be detected and possibly allow to calibrate the seismic trace to the modelled plume migration in high accuracy with regards to saturation, plume migration velocity and other variables.

If successful, this concept would have positive impact on the commercial viability and environment of the Greensand project. Furthermore, the flexibility of the concept allows to accommodate for future obstructions like windfarms, platforms or pipelines, ensuring operability for decades of monitoring.

Conclusions

The proposed focused seismic monitoring concept for carbon storage sites has the potential to replace 4D full field seismic as routine monitoring technology hence reducing the environmental footprint and monitoring costs significantly. Focused seismic increases the value of seismic information, by acquiring new data where and when needed as per the model. With this method, 4D seismic will only be triggered when the simulation model doesn't match the spot seismic detection outside the defined containment area. One of the objectives of the pilot CO_2 injection into the Nini West reservoir is to demonstrate the seismic detectability of CO_2 saturations exceeding 4% in the reservoir by the planned low energy lean seismic acquisition approach. Simultaneously the consortium learns to acquire focused seismic from the ESVAGT supply vessel which also serves other transports and logistics in the yet ongoing E&P business for INEOS Energy Denmark.

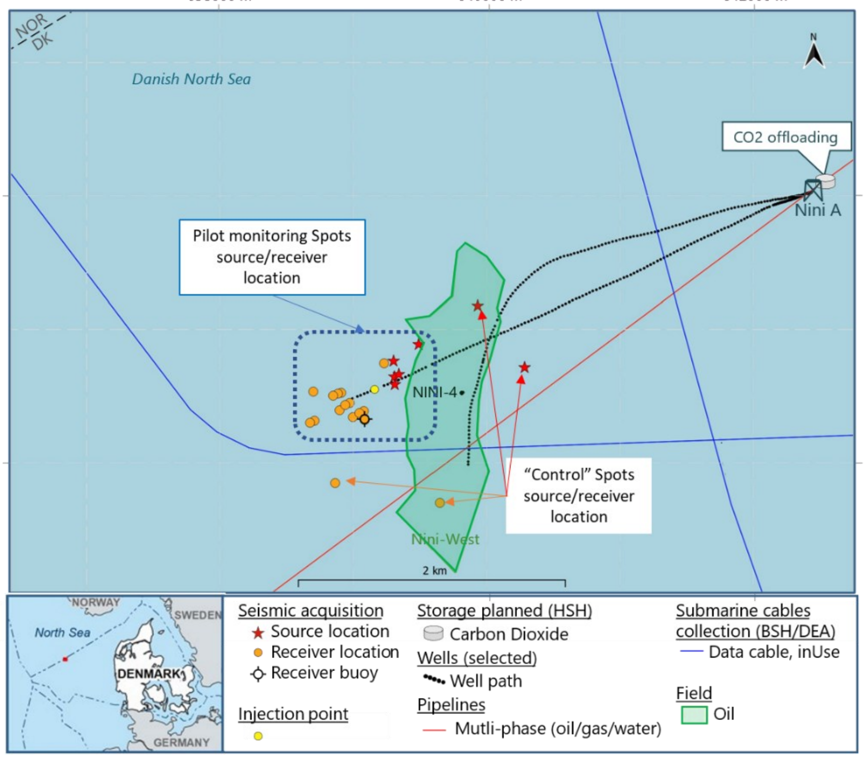

Figure 4 *Layout of the focused seismic acquisition at the Nini West segment. The central source/receiver locations were designed to monitor the CO_2 pilot injection. The remaining 2 source/receiver pairs locations are "control spots" where no CO_2 detections are expected.*

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