Final report

February 2023 – Picture snapshot taken from the Greensand Phase 2 Monitoring and CO_2 Injection pilot trial operation at the Nini West platform in the Danish North Sea

A EUDP funded project delivered by a strong consortium of Partner:

The Greensand Phase 2 Consortium Partnership

Funded by the European Union

NextGenerationEU

Table of contents

1. Project details

Project title	Project Greensand Phase 2 – Enabling environmentally safe and long-term storage of CO_2 by 2025
File no.	64021-9005
Name of the funding scheme	EUDP
Project managing company / institution	INEOS E&P A/S
CVR number (central business register)	73349613
Project partners	Wintershall Dea INEOS Oxide SEMCO Maritime Noble Corporation (Initially *Maersk Drilling* and merged with Noble) Energy Cluster Denmark Danish Technological Institute GEUS Ramboll Geelmuyden Kiese DHI Aker Carbon Capture DTU Chemistry Welltec BLUE WATER SHIPPING SeaPeak (Initially *EverGass* and acquired by Seapeak) Esvagt University of Southampton National Oceanography Centre Spotlight Earth Wind Power Lab Resen Waves TGS (Initially *Magseis* and acquired by TGS)
Submission date	09 September 2024

2. Summary

English version

This phase, Project Greensand Phase 2, has further matured the storage assessment of the Nini field and has deliver the required technical documentation and reports, which will be used for a CO_2 Storage Site Permit Application by 2024. Moreover, the project has qualified the monitoring technologies enabling environmentally safe storage. This is required to maintain the ambitious target of providing storage by end 2025/early 2026. All work done is in compliance to the existing international standards, to allow subsequent approvals from regulators and authorities to be as swift as possible.

The project has successfully conducted an injection pilot in Nini West reservoir. 7 batches have been injected in total, equally to approx. 4,100 tonnes of CO_2. Next step is to further mature Project Greensand into a full-scale project of minimum 0.3 mtpa by late 2025/early 2026 and scaling through further projects to 4-8 mill tonnes CO_2 by 2030 if justifiable in the depleted oil fields of the Greensand Area.

On March 8th, 2023, Project Greensand initiated the world's first cross-border offshore CO_2 storage intended to mitigate climate change. This storage was officially celebrated at the exclusive First Carbon Storage event in Esbjerg, Denmark, in the presence of His Royal Highness Crown Prince Frederik of Denmark, Danish Minister for Energy-, Climate-, and Utilities Mr. Lars Aagaard - and with a pre-recorded address from President of the European Commission Ms. Ursula von der Leyen. Based on findings from the Global Status of CCS 2022 report, it can be concluded that Project Greensand conducted the world's first cross-border offshore CO_2 storage intended to mitigate climate change.

The consortium in Project Greensand Phase 2 was constituted by the most experienced companies and institutions within offshore industry operations and CCS in both Denmark and Northern Europe. With this multifaceted consortium, Project Greensand has moved the CO_2 Storage in the Nini Field from its current TRL 5 to TRL 8 during the project period.

Danish version

Project Greensand Phase 2 har modnet gennemførligheden af CO_2 lagring i Nordsøen og har leveret den nødvendige tekniske dokumentation, som efter projektet vil blive brugt til en ansøgning om CO_2-lagringstilladelse i 2024. Desuden har projektet kvalificeret monitoreringsteknologierne og muliggør dermed dokumentation for en forsvarlig og sikker lagring af CO_2 i udtjente olie- og gasfelter. Dette er nødvendigt for at fastholde det ambitiøse mål om at levere lagringsfacilitet allerede i sen 2025/tidlig 2026. Arbejdet er sket i overensstemmelse med de eksisterende internationale standarder, som skal bane vejen for efterfølgende godkendelser fra de relevante myndigheder så hurtigt som muligt.

Projektet har med succes gennemført en injektionspilot i Nini Vest reservoiret. Der er injiceret 7 batches i alt svarende til ca. 4.100 tons CO_2. Næste skridt er at fortsætte med at modne Project Greensand til et fuldskalaprojekt på minimum 0.3 mtpasent 2025/tidlig 2026 og via yderligere projekter at modne lagerkapacitet op til 4-8 mio. ton CO_2 i 2030 i udtjente olie- og gasfelter i Greensand området.

Den 8. marts 2023 påbegyndte Project Greensand verdens første grænseoverskridende offshore CO_2-lagring med et klimhensyn. Den første injektion af CO_2 blev officielt fejret ved det eksklusive First Carbon Storage-arrangement i Esbjerg, Danmark, hvor bla. Hans Kongelige Højhed Kronprins Frederik af Danmark, Danmarks Energi-, Klima- og Forsyningsminister Lars Aagaard deltog - og med en pre-optaget tale fra formanden for Europa-Kommissionen Ursula von der Leyen. Baseret på Global Status of CCS 2022-rapporten kan det konkluderes, at Project Greensand har udført verdens første grænseoverskridende offshore CO2-lagring.

Konsortiet i Project Greensand Phase 2 er blevet sammensat af de mest erfarne virksomheder og institutioner inden for offshore industrien og CCS i både Danmark og Nordeuropa. Med dette mangefacetterede konsortium har Project Greensand flyttet CO_2-lagring i Nini-feltet fra dets nuværende TRL 5 til TRL 8 i projektperioden.

3. Project objectives

Objectives

The purpose of Project Greensand Phase 2 was to deliver a CO_2 storage pilot test, in the Nini Field, Danish North Sea, and hence, moving CCS on Danish territory closer to a storage site of 0.3 MTPACO_2 by 2025 and 4-8 mill tonnes CO_2 by 2030 in the depleted oil fields of the Siri Area. Thereby, Project Greensand allows Denmark to reach its ambitious climate target in 2025 and 2030 and will also provide significant growth and employment in the green industries, especially for a part of the workforce which else would be difficult to offer a just transition.

The Project Greensand Phase 2 maturation was related to obtaining Statement of Endorsement and Acquisition and Modelling of Environmental Data needed for a subsequent Storage Site Permit. In addition, Phase 2 conducted further de-risking of the technical risks identified in Project Greensand Phase 1. This work constitutes vital parts of the important decision base for the Final Investment Decision (FID) for a full-scale CO_2 storage project. The identified risks, handled in Phase 2, can largely be grouped into three:

- Materials in the reservoir and wells
- Offshore CO_2 Injection in relation to ship-transport and offshore discharge of CO_2
- Monitoring technologies for environmentally safe CO_2 Storage Sites

All work throughout the project period, as well as the main documents has been organized within the three areas defining the structural setup of Project Greensand Phase 2.

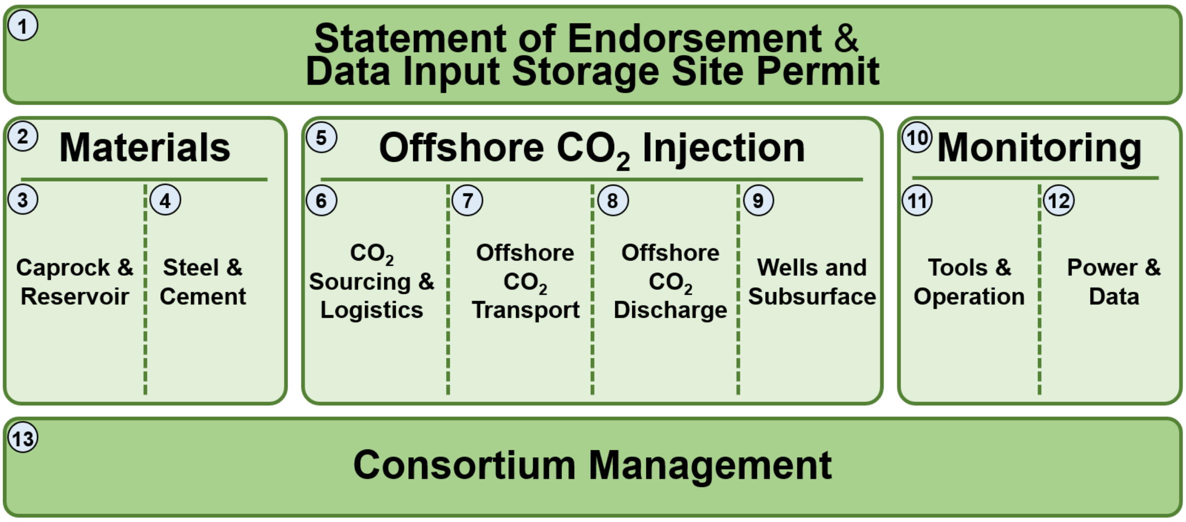

Figure 1: Overview of the main areas of Project Greensand Phase 2. Numbers in blue circles refer to the work packages described in this application.

Project Greensand has provided the necessary development and demonstration within safe and environmentally sound storage of CO_2 in the Nini Field. In Project Greensand Phase 2, CO_2 was captured in Antwerp, Belgium, and transported in ISO containers by ship to the Nini Platform, where the CO_2 was pressurized and injected into the NA-05 well of the Nini West reservoir (Figure 2).

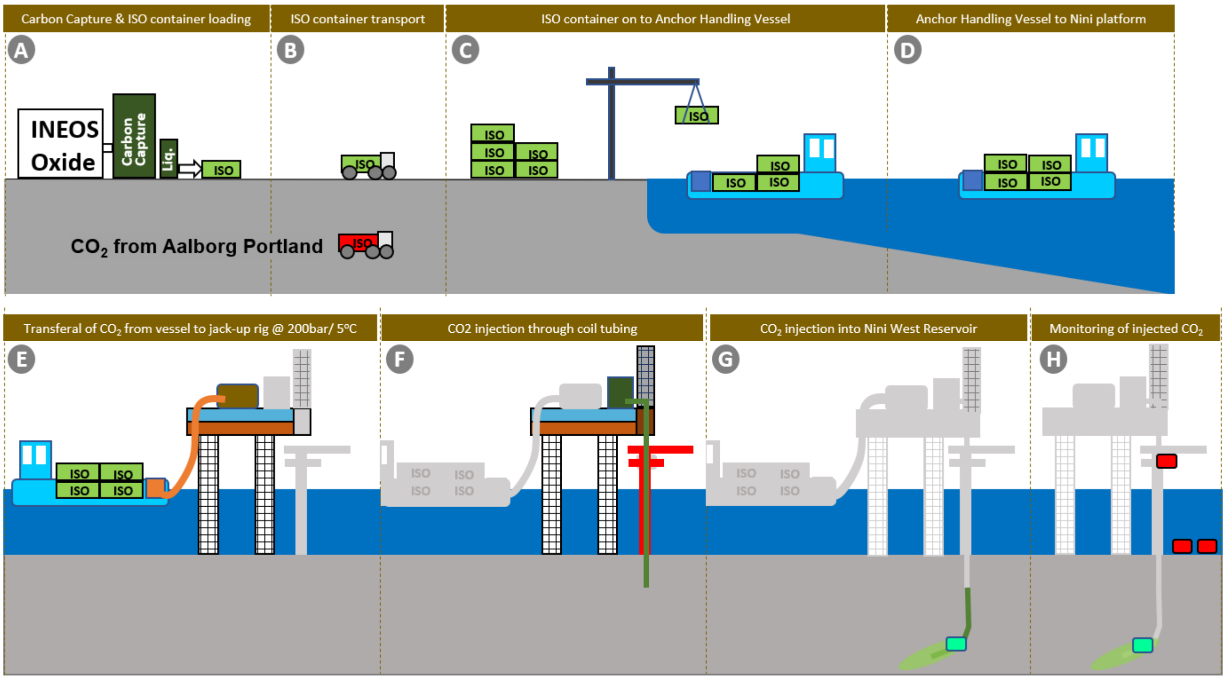

Figure 2: Purpose of Project Greensand Phase 2 is to make a system prototype demonstration in operational environment. CO2 from Antwerp will be shipped to the Nini Platform and injected into the Nini West Reservoir. Additional CO2 will be provided by Aalborg Portland (red truck in (B)), and additional monitoring technologies will be qualified (red boxes in (H))

By integrating the full value chain of the technical elements of CCS, Project Greensand is a world leading pilot project and is being recognized as such in the CCS Community, and lately recognized internationally for advanced development of CCS in the Global Status of CCS 2022 by the Global CCS Institute. This inclusion of the entire value chain did offer a series of benefit: Seamless knowledge sharing and rapid adoption of new insight, lower total project cost as project management, governance etc. was handled centrally and thus more cost-effectively. By having the storage part as the core of the project, the monitoring technologies were tested in a real operational environment.

4. Project implementation

Overall, the project is considered to have been a great success for the consortium partners and in terms of moving CCS closer to the market. The project met the overall project goal to perform an offshore CO_2 injection operation and matured the necessary monitoring program to document a safe and permanent storage of CO_2 in a depleted oil field in the Nini field. By that the project has produced novel insights and practical experience along the full value chain of CCS, that can be further developed, matured, and commercialized across the entire value chain and forthcoming CCS industry.

However, there have also been several challenges. The project was originally applied with a larger scope. Originally, it was intended that Danish CO_2 captured from Aalborg Portland's production facilities in Aalborg would be included in the project's overall demonstration of the CCS value chain. However, the project did not receive the full grant, and therefore, CO_2 capture, and evaporation of CO_2 from Aalborg Portland and parts of the monitoring program were taken out of the project scope. It also meant that a handful of partners withdrew from the project.

Furthermore, the offshore pilot was carried out during February-March 2023, and because of that, the project was challenged by bad weather conditions which postponed the departure of the Noble Resolve rig from Port of Esbjerg to the Nini field in the North Sea. Since the CO_2 storage could only take place with a temporary permit for offshore CO_2 storage, this meant that the amount of CO_2 stored in the pilot was less than expected. Even so, the amount of CO_2 was sufficient to verify work processes for safe offshore operations in regard to injection of CO_2 and the CO_2's impact on the reservoir. Consequently, enough and adequate data was obtained to generate the necessary decision-making basis regarding Final Investment Decision (FID) towards large-scale CO_2 storage in the North Sea.

Due to disruptions in the supply chains directly related to the COVID-19 pandemic and the war in Ukraine, the scope of the monitoring program was changed. Important components for constructing the wave buoy arrived so late in the project period that the buoy could not be included in the test and demonstration practices of the monitoring program in due time. However, all in all the monitoring program was successfully demonstrated as nodes and sensors were provided with a battery solution, and by that, data could be acquired. However, this meant that the wave buoy to power the nodes and sensors unfortunately became irrelevant during the project period, and therefore the subsequent development activities related to the buoy were stopped.

5. Project results

WP1 Storage Site Endorsement and Data Acquisition

The objective of WP01 has been to integrate all the cross disciplinary results from the various work packages required to conduct a Third-Party verification and obtain a Storage Site Endorsement on the Nini West storage complex. The verification was conducted by DNV according to the recommended practice (DNVGL-RP-J203) and ensured that the work is following the ISO 27914:2017 standard.

Containment and facilities risk assessment, data acquisition and subsequent modelling of environmental data was furthermore covered by WP1.

Early in the Greensand project the operator involved DNV as third-party verifier to certify the storage site feasibility. This scope was extended during the Greensand Phase 2 pilot to include independent advisory and verification of safety and compliance aspects of infrastructure and facilities within the regulatory framework of Danish Offshore legislation, Danish Offshore Safety Act verification of Safety and Environmental Critical Elements as well as EU Directives' accredited certification.

A Storage Endorsement verification was set as a final delivery of the Greensand Phase 2 and this was later supplemented by a Storage Site verification as result of the project status.

The verification followed the two industry standards:

- DNV-RP-J203 (2021) – Geological storage of carbon dioxide.
- ISO 27914:2017 – Carbon dioxide capture, transportation and geological storage – Geological storage.

The DNV verification of conformance with these standards were provided following the DNV-SE-0617 and DNV-SE-0473. The overall aim of the verification is to provide independent assurance to support stakeholder confidence in that CCS projects are developed and executed in accordance with applicable legislation, standards and industry best practice. The figure below provides a schematic overview of the main stages of the development of a CO2 storage project and the corresponding verification that are offered by DNV, including both reservoir, wells and facility aspects.

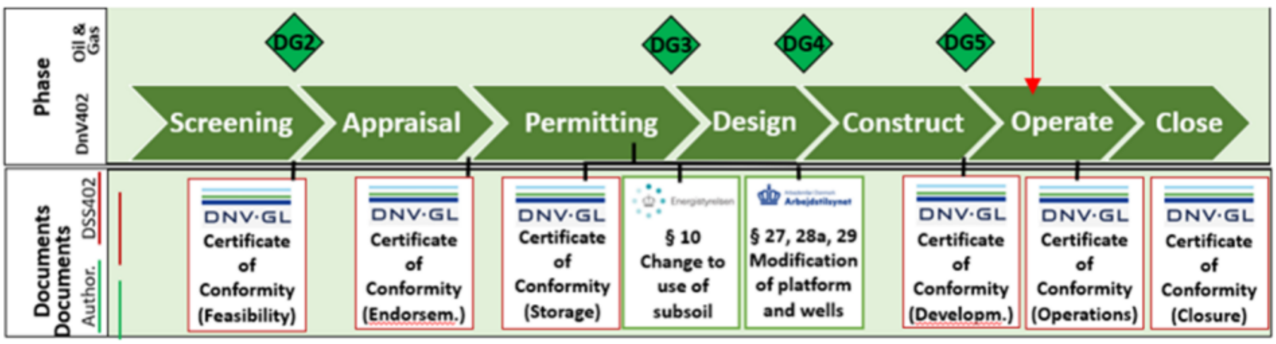

Figure 3 : CCS project stages where DNV offer independent 3rd party verification.

Back in 2020 DNV conducted the first verification on Project Greensand: **Site Feasibility Certification of Nini West (2020)**. This verification confirmed that DNV considers that storage of 0.45 million tonnes CO2 per annum (Mtpa) over 10 years in Nini West is conceptually feasible.

Further site characterization was, however, required to establish the necessary confidence that the storage site has the required characteristics to allow safe and effective geological storage.

This work was performed as part of Project Phase 2 and in 2022 DNV verified that the **Greensand Phase 2 pilot** could be safely executed with the proposed execution plan.

Based on several Phase 2 deliverables from WP01-WP12 a final verification was performed of the Nini West storage site covering all requirements for a "Certificate of Conformity – Site Endorsement". Due to the progressed project timeline the subsequent minor "Certificate of Conformity – Storage Site" was also included.

The basis for this verification comprised the following:

Management Planning*				
Risk Management Plan	Monitoring & Verification Plan (M&V)	Plan for Public & Stakeholder engagement	Storage facility design plan	Operation and Maintenance (O&M): • Policy for use of O&M plan • Operational protocols • Communication plan • Safety plan • Security plan Provisional Closure Plan

*Table 1: *Includes environmental considerations in line with national regulations and EU directives, e.g. Miljøvurderingsloven & CSRD Directive.*

As the first of its kind in the emerging CCS industry - the verification concluded that DNV considers that the storage site operator has developed appropriate plans to allow environmentally safe and effective geological storage of CO2 at Nini West in accordance with ISO 27914, project objectives, and relevant Danish and European legislative requirements.

Data modelling on environmental impact was conducted by DHI and Rambøll and included a baseline seabed survey.

In July 2022, the monitoring was initiated by a baseline seabed survey performed by DHI at positions with increasing distances from locations where CO2 could be released, by accidental release or continuous leakage, and lead to an acidification of the environment. The survey was performed by "Esvagt Server" and a number of seabed samples were taken and preserved to identify different species. An underwater robot was used to take video footage of the seabed and the animals living on the seabed like hermit crabs, snails, and fish. Sediments were also sampled to analyse for metals and nutrients and all results were summarised in a baseline report.

The conclusion of the baseline report is that the seabed is inhabited by species well-known to the North Sea and although oil and gas activities have taken place for decades, the Nini West seabed is relatively natural and undisturbed. Sampling showed a high similarity of benthic fauna for all stations except one, where the substrate was coarse sand instead of muddy sand. Investigations of the sediment chemistry showed that although trace concentrations of several of the analysed variables were found, all aliphatic groups were under the detection limit and the same was applicable for the BTEX components. Statistical analyses of those variables which are of concern to e.g., OSPAR and HELCOM showed that all PAHs and metals was close to the reference conditions. In conclusion, the seabed conditions, seen through the chemistry, can be considered very low in pollution and this is most likely due to the fact, that the establishing of the Nini field took place several decades ago without any discharges or new sub-sea development in the meantime. Recent seabed sediment research in the North Sea has shown that over the last 20 years, a general decline in the concentration of pollutants like PAH, PCB and other substances has been observed and the low concentrations found around Nini are in line with this study.

The baseline study provides a solid background for future assessments of changes in the seabed, which could be related to leakage of CO_2. Based on available Metocean data from the Nini field area, DHI generated a template for modelling the 'plume' of water impacted by possible released CO_2.

The modelling included the acidification of the environment and possible impacts on organisms mainly in the seabed where the direct effect is a change in the solubility of calcium carbonate due to increases in the concentration of dissolved CO2 and bicarbonate ions. A reduction in available calcium carbonate is critical as it is the primary material in the shells and hard skeletons of many marine organisms.

The assessment was carried out by DHI utilizing existing MIKE Powered by DHI modelling technology. In this context, substantial development was required to describe the chemical reactions affecting the pH and hence, the acidification impacts of dissolved CO_2. Both a hydrodynamic and a transport model was used to assess two worst-case scenarios. A Blow-out scenario where the plume of CO_2, oil, gas and water reaches the surface in a few seconds and less than one percent of the gas is dissolved, while the remaining amount is released to the atmosphere at the sea surface.

Due to the short duration of a blowout the impact is estimated to have insignificant impact to the environment. The potential pH reduction is expected to occur close to the sea surface and will therefore not be critical for the benthic community.

Also, a scenario where CO2 is leaking continuously from a well was evaluated. In this scenario all CO2 bubbles are expected to be dissolved at a short distance above the seabed. The calculations showed a potential PH decrease of 1.5 in close to 50% of the simulations and concluded a limited impact on benthic organisms and food chains close to the leakage.

Based on the data acquisition, leakage modelling and further noise modelling Rambøll conducted an assessment of the environmental impact from a Greensand CO2 storage project on Nini West.

A technical and commercial appraisal plan, based on the Green Phase 2 full scale maturation results stemming from the various relevant work packages has been construed and used as a storage site application for the Nini West reservoir. This is the foundation and the plan upon which the relevant Danish authorities can approve the first commercial CO_2 storage project in the Greensand area.

An accounting and reporting plan for handled and permanently stored CO2 has been developed to describe how the Nini Joint Venture as operators account for and report avoided emissions of CO2 for regulators and/or emissions trading schemes. This will be used as basis for discussion and agreements with future Greensand emitters (customers) as well as input to discussions in various relevant forums.

A Risk Management Plan (RMP) was developed in a collaboration between the INEOS, Risktec & Rambøll.

The objective of the RMP was to assess and provide assurance on the expected security of the storage complex and to confirm that there is no significant risk of leakage or harm to the environment or human health. The ISO 27914:2017 standard: "Carbon dioxide Capture, Transportation and Geological Storage – Geological Storage" was applied as a structure for the RMP.

The risk assessments followed the RMP, identified and evaluated the potential leakage paths from the facilities, subsurface storage complex based on leak scenarios and associated risk leading to the definition of prevention and mitigation control measures.

The assessment of the facilities covered the offloading of CO_2 from the ship and operations on the Nini platform. Rambøll led risk the assessment workshops (HAZID, Bowties & ALARP's) and analysis, with the Operator.

The assessment of containment risk covered the reservoir and wells through several risk scenarios:

- S1: Vertical leakage of CO_2 through the caprock
- S2: Lateral leakage of CO_2 from the storage complex
- L1: Leakage of CO_2 associated with on-structure wells with legacy P&A
- L2: Leakage of CO_2 via on structure shut in well not P&A'd during injection
- LA1: Leakage of CO_2 via on structure well with modern abandonment
- I1: Leakage of CO_2 via injector well internal pathways
- I2: Leakage of CO_2 via injector well external pathways
- I3: Leakage of CO_2 after injection via P&A injector well

Risktec was contracted to conduct the containment risk assessment workshops and analysis with the Operator. The risk assessments led to the definition of risk reduction prevention and mitigation control measures.

A Public Engagement strategy plan detailing relevant stakeholders, communication (incl. knowledge sharing) plans and engagement strategies was developed to support the next phases of the Greensand project. The plan has been based on the learnings from the Greensand Phase 2 and underlines the importance of prober external communication stakeholder management. The stakeholder groups in the various phases of the next commercial project, Project Future, that is standing on the learnings from The Greensand Phase 2, are illustrated in below table 2 and figure 4

		Phase 1: Financial Close	Phase 2: First Storage	Phase 3: Building Commercial Scale
Stakeholder Group		Key activities		
Knowledge	All	Showcase Project Future concept, planning and results to spread and harvest knowledge		
	Research institutions	• Create awareness of the project and the innovation height. • Ensure high activity to gain and provide knowledge for future scaling.	• Ensure high activity to gain and provide knowledge for future scaling. • Collaborate to enable outreach in preparation of next phase	• Bilateral dialogues. • Knowledge sharing by participation in conferences and seminars. • Regular media updates accessible to scientific individuals and continuous dissemination of results to relevant research institutions.
	Universities	• Create awareness of the project and the innovation height. • Ensure high activity to gain and provide knowledge for future scaling.	• Ensure high activity to gain and provide knowledge for future scaling. • Collaborate to enable outreach in preparation of next phase.	• Bilateral dialogues. • Knowledge sharing by participation in conferences and seminars. • Regular media updates accessible to scientific individuals and continuous dissemination of results to relevant universities.
	NGOs	• Create awareness of the project and the innovation height. • Ensure high activity to gain and provide knowledge for future scaling.	• Ensure high activity to gain and provide knowledge for future scaling. • Collaborate to enable outreach in preparation of next phase.	• Bilateral dialogues. • Knowledge sharing and continuous dissemination of results to NGO organisations.
Industry	All	Showcase ambitions and projects while preparing industry players to scale CCS		
	Emitters, logistics & transport, and ports	• Align on project foundations and bilateral talks to reach FID. • Negotiations with potential partners in the project's value chain. • Showcase thoughts leading to actual discussions with the European stakeholders.	• Share knowledge and learning to prepare for scaling. • Include a broader scope of stakeholders to acquire additional partners.	• Active and practical engagements.
Civil	All	Ensure project understanding in terms of safety and efficiency		
	Citizens	• Safe and efficient messaging on the potential. • Ensure understanding of the project.	• Address concerns and communicate the value drivers for the civil stakeholders of the Greensand Future Project.	• Address concerns and communicate the value drivers for the civil stakeholders of the Greensand Future Project.
	Media	• Communicating that INEOS is part of green transition while providing necessary energy for Europe. • Ensure understanding of the project.	• Communicate developments in project towards operations.	• Communicate and achieve a broad reach to show the first real proof that it works at scale.
	Unions + Associations	• Ongoing dialogues on CCS in general and project development. • Provide and gain industry insights.	• Ongoing bilateral dialogues • Facilitate sparring through a sounding board.	• Facilitate an active sounding board. • Active participation of the job creation within the EU that CCS creates.
Policy	All	Ensure feasibility and influence future regulatory environment		
	Policy-makers and	• Make FID possible. • Talk towards sharing thoughts	• Participate in dialogues on CCS European regulatory	• Share lessons learned and ideas to enable Greensand Future Pro-

Table 2: Table showcasing the purpose and key activities to engage with stakeholders across the phases of the project.

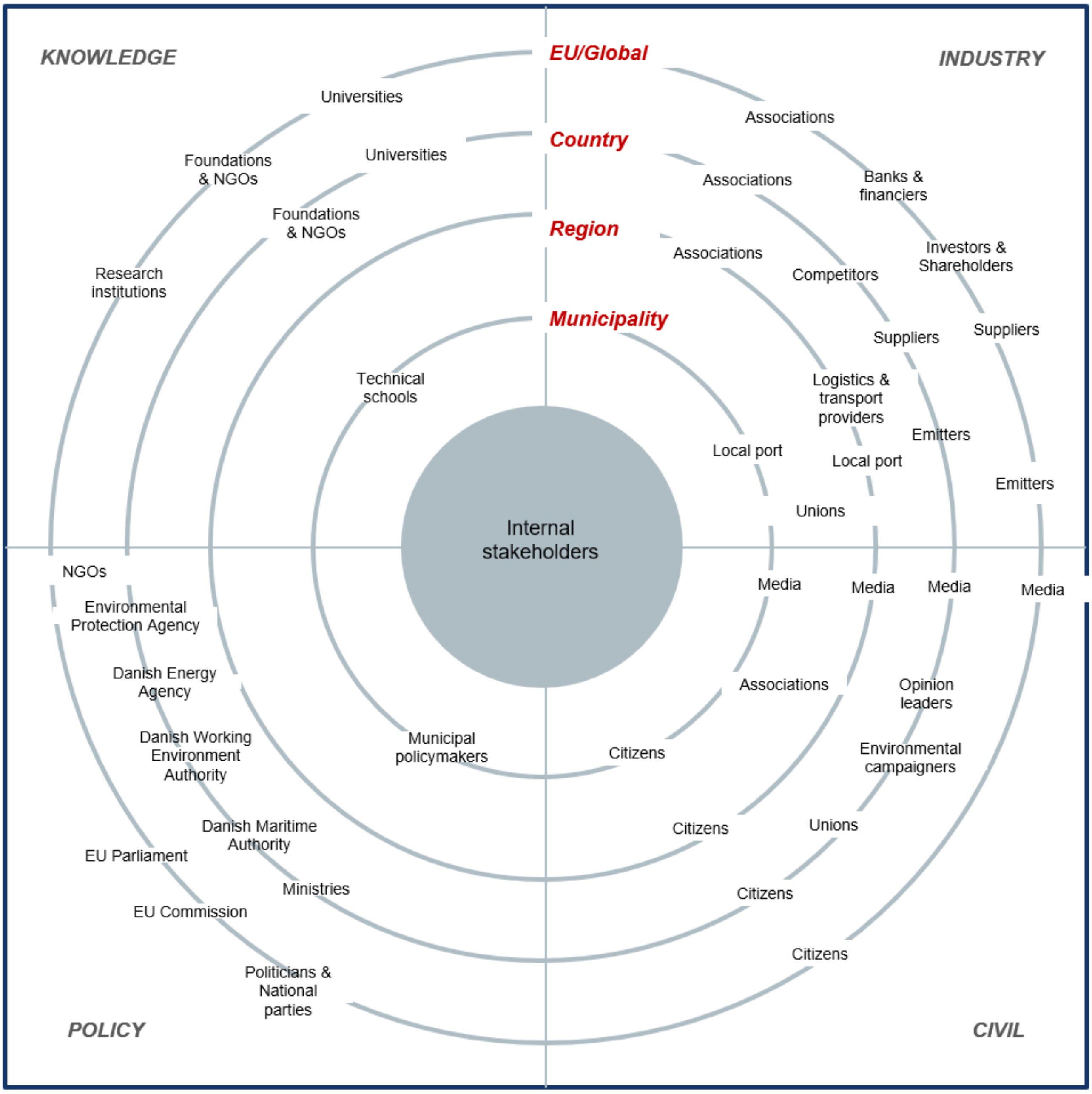

Figure 4 4 : Diagram displaying the landscape of stakeholders relevant to the project split across each stakeholder group (Knowledge, Industry, Policy and Civil) and geographical proximity to the project site

A Storage site closure plan used to describe the closure requirements for a given storage site and the qualification process that will be used by the Operator to demonstrate fulfilment of these requirements was developed in Greensand Phase 2. In addition, a Predictive Maintenance Plan was described for long-term stewardship with reference to the Monitoring Plan defined based on WP10 work results.

WP2 Materials

WP2 has functioned as a bridge between WP3 and WP4 and has from the start of the project facilitated coordination, and knowledge and data sharing between the work packages. This has included mapping of interdependencies of data within WP3 and WP4, dependencies of deliverables between the two WPs, and involvement in creating a basis of design table. The WP2 has on a weekly basis participated in a coordinating meeting with the WP3 and WP4 leads and has accordingly followed up on outstanding issues by reaching out to specific sub-task leads to clarify or resolve uncertainties. WP2 also organized the first WP3 workshop to facilitate data sharing.

WP3 Seal and Reservoir

The core aim of WP3 was to assess and counteract potential challenges related to inadequate injectivity, storage capacity, and unintended consequences of rock matrix alterations and residual oil. This objective was predominantly achieved through extensive CO_2 flooding experiments, carried out under various injection configurations. Comprehensive laboratory analyses of core materials and fluids, both pre- and post-flooding, reinforced our findings. By integrating these data into a hybrid numerical flow model, we were better positioned to predict the subsurface behaviour of CO_2. This enabled a more informed risk assessment for the operational design and continuous monitoring during the full field CO_2 injection process.
However, project execution was not without deviations from the original plan, which brought about some pivotal modifications:
Change in CO_2 source: Initially, the project intended to utilize CO_2 captured from a specific Danish emitter. Due to its unavailability, we switched to using a generic pure and impure CO_2 for our flooding experiments. This change was not merely a workaround. It offered a broader perspective on the potential impurity levels in CO_2, accommodating variability from multiple emitters rather than a single source. The selection of impurities to test against the reservoir was driven by an extensive literature review and expert insights into probable future mixtures.
Effluent Analysis Adaptation: The original plan involved analysing effluent from core floods to discern oil compositional changes, which would aid in identifying suboptimal CO_2 flow and provide input to dynamic reservoir modelling. Faced with the technical complexities of this endeavour, we integrated a novel pyrolysis technique (Extended Slow Heating©, ESH), which yielded proxy data on saturations of movable and non-movable hydrocarbons and their occurrence in the reservoir matrix.
Adjustments in Experimental Plans: Our ambitious analytical core-flooding scheme faced temporal constraints, leading to a reduction in the scope. While the number of experiments was curtailed, the core objectives remained uncompromised. Additionally, unforeseen delays in procuring essential components mandated a redesign of certain experimental plans.
In summary, while the trajectory of WP3 witnessed several amendments, the principal objectives were steadfastly pursued and successfully achieved.

<u>*Main technological results and milestones*</u>

Flooding experiments mimicking near- to far-wellbore flow, in conjunction with other flooding experiments. Flooding experiments comprised both unsteady-state and steady-state tests, conducted either in a 3-phase system (oil, brine, and supercritical (sc)CO_2) or a two-phase system (brine and scCO_2). These experiments were designed to emulate both near wellbore conditions with high flow rates and large pore volumes (PV), and far wellbore conditions characterized by lower flow rates. In the near wellbore tests involving oil, scCO_2 effectively displaced the oil without any loss in injectivity. Contrasted with earlier tests, the high PV scCO_2 tests displayed markedly increased injectivity, attributed to improved water displacement. The experimental setup featured complex sequences of alternating scCO_2 and brine injections. A crucial insight was the consistent brine permeability both before and after scCO_2 injections, aligning with results from earlier tests. Supercritical CO_2 permeability varied but was prominently high when juxtaposed with initial air permeability during three-phase flooding. It also paralleled oil permeability under initial water saturation conditions. Notably, there was a significant decrease in oil saturation following scCO_2 flooding, and brine saturation diminished as more scCO_2 was injected.

Intriguingly, the Greensand Phase 2 experiments indicated a minimal occurrence of fine production and migration. This might be attributable to the presence of oil and the utilization of preserved samples. As for salt precipitation, its potential effect on porosity did not seem to harm permeability, particularly in the two-phase flow experiment. Supercritical CO_2 flooding during this test enhanced scCO_2 permeability to nearly 75% of the initial air permeability.

Conditions and relative permeabilities for both near and far wellbore tests were determined and then simulated. They were subsequently history-matched to ascertain the relative permeability for the oil/brine and CO_2/brine systems. Near the wellbore, H_2O vaporization into scCO_2 may result in drying out, leading to increased injectivity that approaches brine permeability.

The effects on salt precipitation were directly studied using a method termed a "long tube apparatus" to enhance the understanding of salt precipitation when injecting scCO_2, addressing limitations found in traditional core flooding techniques. Numerical simulations were also conducted to validate the experimental results and to refine critical simulation parameters essential for predicting salt deposition under varying reservoir conditions.

Determination of the impact of impurities. A geochemical model was developed based on a theoretical knowledge and calibrated to core experiments to understand the intricate reactions resulting from scCO_2 injection with impurities (NO_x and SO_x). From our model we simulated the chemical reactions in various regions around the injection well, deepening our understanding of the complex geochemical processes. We found that rapid chemical reactions occur near the well highlighted the effectiveness of the CO_2 injection in interacting with the surrounding environment. Over a 10-year injection cycle, the model anticipates a transformation in the rock structure, offering potential insights for future optimization and understanding rock-fluid interactions. The findings provide valuable insights and offer a solid foundation for further refining and optimizing the CO_2 injection process.

Full compositional description of the effect of CO_2 flow on the residual oil. The scCO_2 flow's impact on the residual oil in the Nini West reservoir reveals intricate interactions that are vital for assessing the site's feasibility for CO_2 sequestration. Upon exposure to scCO_2, certain fractions of the remaining oil dissolve while others, specifically solid bitumen and asphaltenes, predominantly remain immobile. These non-movable hydrocarbon components demonstrate a notable affinity towards glauconite clasts. This adherence of solid heavy hydrocarbons to the glauconite clasts is particularly intriguing. Glauconite, a greenish, iron-rich clay mineral, has potential risks associated with it in CO_2 storage scenarios. Under certain conditions, glauconite may swell or disintegrate, leading to reservoir clogging and consequent issues in CO_2 injectivity. However, the observed preference of heavy hydrocarbons, especially asphaltenes, to adhere to glauconite clasts appears to offer a protective layer. This adherence can effectively mitigate potential glauconite swelling and disintegration, thus potentially enhancing the reservoir's integrity and ensuring smooth CO_2 injection. Furthermore, concerns often arise regarding asphaltene precipitation when introducing scCO_2 into oil reservoirs, as this can severely hamper reservoir permeability. However, in the context of the Nini West reservoir, our findings indicate that the risk of asphaltene precipitation is minimal. This low risk is pivotal, as any significant asphaltene precipitation could lead to pore clogging, reducing CO_2 storage capacity and efficiency. In summary, $scCO_2$ flow's interaction with the residual oil in the Nini West reservoir underscores the complex interplay of geochemical reactions. Notably, the strong adherence of solid hydrocarbons to glauconite clasts not only safeguards against potential glauconite-related challenges but also emphasizes the low risk associated with asphaltene precipitation in this particular reservoir setting.

Completed seal complex analysis, including petrophysical model. An in-depth examination of the geological seal parameters at Nini West potential CO_2 storage site yielded encouraging results. Using a multidisciplinary framework, the seal's quality was comprehensively assessed and showed that both the primary and secondary seals demonstrate exceptional sealing capacities, providing strong assurance for the containment of CO_2. The primary seal's high capacity ensures a secure overhead for CO_2 storage, while the secondary seal stands as a reliable backup, further enhancing safety. The robustness of the Nini West Seal Complex underscores its potential for dependable, long-term CO_2 sequestration. Overall, these findings are promising future of CO_2 storage in the Siri Canyon and elsewhere in the Danish North Sea and mark a step forward in CO_2 storage technology.

Reactive flow and geostatic models and uncertainty analysis for input to the overarching numerical model. Remapping of the Nini West Frigg reservoir unit formed the basis for a new extended geostatic model including the full extent of the hydraulic unit. The model was created in Petrel and populated with data from core and petrophysical evaluation. An extensive uncertainty analysis was carried out before handing the geostatic model to the dynamic modelling team.

A numerical flow model was built in the Eclipse software and populated with data from literature and core flooding analysis. The model was initially history matched to data from the former oil production and water injection period of the Nini Field. The first version of the flow model was used to predict the pressure changes in the reservoir prior to the Greensand Project CO_2 Pilot injection, thereby defining the operational window for safe operations. In addition, the model was used to predict the subsurface extent and concentration of the CO_2 plume in the reservoir forming the background for geophysical modelling and spot seismic monitoring activities.

The final model was updated with data collected during the CO_2 Pilot injection and form the basis for evaluation of total storage capacity, pressure and temperature changes in the reservoir and long-term plume migration. A fine-grid sector model was created as a subsection of the full field model and forms the basis for near well bore simulations evaluating injectivity and salt precipitation in the reservoir.

In summary WP3 provided the expected results. However, based on our preliminary assumptions in the WP, we did not foresee the notable impact of impurities in the CO_2 stream, pointing to a potential need for mitigation strategies. Additionally, while it was initially thought that introducing oil into the experiment might influence injectivity, it appears that oil presence may actually enhance it and curtail undesired mineral reactions and fines migration. This last point is of importance since injection in Nini will be within the oil depleted parts of the reservoir and thus that these data show better performance that experiments made on the reservoir that did not include oil.

The modelling workflow was successful in predicting the reservoir pressure and temperature changes in the reservoir during the CO_2 Pilot injection thereby validating the model. With the new integrated flow model total storage capacity and injection rates have been confirmed. Long term simulation runs (up to 500 years) predicting the migration of CO_2 in the reservoir after the end of injection has been used to constrain the monitoring plan (WP10).

<u>*Main Commercial Results and Milestones*</u>

Evaluation of the impact of residual oil and cyclic injection of pure and impure CO_2 on geochemical reactions, fines migration and clay swelling. In the Nini reservoir, where injections are planned to occur in the oil-depleted zone, our experiments showed that for pure $scCO_2$ then the presence of residual oil appeared to limit unwanted mineral reactions and possibly enhanced injectivity. During cyclic injection, the geochemical model developed

suggested alternating drying and wetting phases around the injection well. These cycles would lead to halite precipitation and increased NaCl concentrations. For impure CO_2 (with NO_x and SO_x impurities) then our findings indicated that NO_2 and SO_2 react swiftly near the well, primarily forming H_2SO_4 and gaseous nitrogen species. As the distance from the well increased, NO_x's reaction with SO_2 slowed, eventually leading to the formation of HNO_3 and HNO_2. The rapid production of acid near the injection site could quickly dissolve carbonate minerals, lowering the pH values to extremes. Such harsh environments are potential concerns for infrastructure integrity and transmissivity around the injection sites. Changes in the geochemical environment, particularly with impure $scCO_2$, might lead to fines migration and/or clay swelling due to pH alterations, affecting the overall porosity and permeability of the reservoir rock. The presence of impurities such as NO_x and SO_x, combined with cyclic injections, could thus alter the geochemical balance and cause clay minerals to swell or shrink. This, in turn, could influence the overall flow dynamics within the reservoir.
While the impact of impurities in the $scCO_2$ stream was more significant than initially anticipated, the presence of residual oil in the reservoir showed potentially beneficial effects on geochemical reactions and injectivity. Given the importance of CO_2 sequestration for mitigating climate change, these findings provide valuable insights into the complexities involved in the subsurface injection of CO_2, whether pure or impure.
Full assessment of caprock sealing capacity of the primary and secondary seal. The evaluation confirmed the high seal capacity found in the lower part of the seal also applied to the upper part of the seal section. Porous beds in the upper seal were mapped and their flow properties assessed. The evaluation entails that the seal consists of multiple layers providing independent seal to the Nini West Storage site thus adding additional safety to safe storage of CO_2.

Dissemination of WP3 Results

The importance of disseminating the outcomes of WP3 has been recognized, especially in the context of enhancing the awareness of Carbon Capture and Storage (CCS) in Denmark and aiding the site permit approval process.

To the scientific community then results from WP3 have been published in three peer-reviewed journals. Furthermore, several papers are either in preparation or submitted to international journals. In addition, 16 abstracts showcasing WP3 findings have been presented at several different technical conferences notably the EAGE annual conferences and the EAGE GET conferences. This direct communication with the broader scientific and technical communities have facilitated feedback and exchange of knowledge. In addition, more than ten internal reports have been prepared with WP3 results that will serve as basis for documenting workflows and data.

Scientific papers (peer reviewed or submitted)

Narayanan, P., Khosravi, M., Weibel, R., Meirles, L.T.P., Schovsbo, N.H., Stenby, E.H., Yan, W. 2023. Long tube flooding tests for investigating salt precipitation induced by CO2 injection. Carbon Capture Science & Technology. https://doi.org/10.1016/j.ccst.2023.100143

Petersen, H.I., Al-Masri, W.F., Rudra, A., Mohammadkhani, S., Sanei, H., 2023. Movable and non-movable hydrocarbon fractions in an oil-depleted sandstone reservoir considered for CO_2 storage, Nini West Field, Danish North Sea. International Journal of Coal Geology. https://doi.org/10.1016/j.coal.2023.104399

Khosravi, M., Stenby, E.H., Yan, W., submitted. Unveiling near-wellbore Salt Deposition Patterns in Large-Scale CO_2 Storage Simulations. Submitted to International Journal of Greenhouse Gas Control.

Weibel, R., Keulen, N., Hillier, S., Friis, H., Petersen, H.I., Olivarius, M., Malkki, S.N., Stokkendal, J., Schovsbo, N.H. 2023. Reactivity of glauconitic clasts during burial diagenesis. Sedimentary Geology. https://doi.org/10.1016/j.sedgeo.2023.106519

Reports (non-peer reviewed)

Burmester, C., 2023. CO_2/brine steady-state flooding experiment; Low flow rate imbibition and drainage. Experiments conducted as part of work package 3 task 1 within the Greensand Phase 2 project. Internal report prepared by Wintershall Dea TSC for EUDP reporting. 11 pages

Cassiede, M., Yang, Y., Smith, S., Stenby, E.H., Yan, W., 2023. Experimental PVT report for CO_2-Nini brine. DTU Final report

Kazmierczak, J., Holmslykke, H.D., Kim, H., Ai, J., Weibel, R., Dideriksen, K., 2023. Impact of injection of CO_2 with NO_2, SO_2, and O_2 impurities on the near well environment: Part 1 based on theoretical understanding of impurity reaction. Deliverable 3.3 in Project Greensand Phase 2. 44 pp.

Khosravi, M., Stenby, E.H., Yan, W., 2023. Simulation study of the salt precipitation risk in the near wellbore region during cyclic CO_2 injection in the Nini field. DTU Final report.

Khosravi, M., Xu, Y., Mirazimi, S., Stenby, E.H., Yan, W., 2023. Challenges in simulation of salt clogging. Paper SPE-214350-MS presented at SPE EuropEC, June 5-8, 2023, Vienna, Austria.

Mohammadkhani, S., Al-Masri, A.F., Olsen, D., 2023. Results of CO_2 flooding experiments Exp-1, Exp-2, Exp-3, and Exp-4. Greensand Phase 2 WP3.1. Danmarks og Grønlands Geologiske Undersøgelse Rapport 2023/28

Narayanan, P., Stenby, E.H., Yan, W., 2023. Long-tube flooding tests for investigating salt pre-capitation induced by CO_2 injection. DTU Final Report.

Petersen, H.I., Al-Masri, W.F., Rudra, A., Mohammadkhani, S., Sanei, H., 2023. Compositional characterisation of Nini dead oil and remaining oil in preserved, cleaned, restored, and CO_2-flooded core plugs from the Nini-4 well, Nini West reservoir. Project Greensand Phase 2, WP 3.3. Danmarks og Grønlands Geologiske Undersøgelse Rapport 2023/11, 46 pp.

Schovsbo, N.H., Petersen, H.I., Weibel, R., Springer, N., 2022. Upper seal characterization and capacity evaluation based on cuttings analysis of the Nini-4 well. Project Greensand Phase 2 WP3.7 report. Danmarks og Grønlands Geologiske Undersøgelse Rapport 2022/31, 68 pp.

Shamsolhodaei, A., 2023. Changes in rock mechanical properties of the Greensand due to CO_2 injection. Greensand Phase II, GEO Job No 206169. Report 1 2023-08-07. Prepared for GEUS. 107 pages including enclosures.

Weibel, R., Olivarius, M., Keulen, N., Fogden, A., Mohammadkhani, S., Holmslykke, H.D., Al-Masri, W.F., Narayanan, P., Yan, W., Malkki, S.N., Schovsbo, N.H., 2023. Mineral reactions in glauconitic sandstones induced by CO_2 experiments. Project Greensand Phase 2 WP3. Danmarks og Grønlands Geologiske Undersøgelse Rapport 2023/24. 117 pp.

Yan, W., Khosravi, M., 2023. PVT modeling of the Nini-4 fluid. DTU Final report.

Presented or submitted abstracts

Andrianov, N., Mohammadkhani, S., Olsen, D., Schovsbo, N.H., 2022. An Integrated Approach to Characterize Fluid-Rock Interactions During CO_2 Injection. 83rd EAGE Annual Conference & Exhibition, Jun 2022, Volume 2022, p.1 - 5 https://doi.org/10.3997/2214-4609.202210587

Cassiede, M., Smith, S.A.M., Stenby, E.H., Yan, W., 2023. Measurement and modelling of thermophysical properties of CO_2-brine mixtures. The 22nd European Conference on Thermophysical Properties, September 10-13, 2023, Venice, Italy.

Dideriksen, K., Molander, J., & Kjøller, C., 2023. Python applications for performing parametric studies and simulations with sequentially adjusted parameters. TOUGH symposium 2023, Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

Fogden et al. 2023. Application of Digital Rocks Technology to Carbon Storage: Greensand Project Case Study. 84th EAGE Annual Conference & Exhibition, Jun 2023, Volume 2023, p.1 - 5 https://doi.org/10.3997/2214-4609.202310367

Kazmierczak, J., Kim, H., Dideriksen, K., 2023. Effects of co-injection of impurities (O_2, SO_2 and NO_x) with CO_2 into reservoirs – reactive-transport modeling. TOUGH symposium 2023, Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

Khosravi, M., Stenby, E.H., Yan, W., 2023. A simulation study of salt precipitation during CO_2 storge in a depleted oil reservoir. The 2023 IEA EOR TCP conference, Sep 26-28, Calgary, AB, Canada.

Kim, H., Kazmierczak, J., Dideriksen, K., 2023. A parametric study of aqueous kinetic reactions of NO_2, O_2 and SO_2 impurities of the CO_2 stream. TOUGH symposium 2023, Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

Larsen, M., Dominek, K., Burachok, O., Stokkendal, J., 2023. Pre- and post-injection dynamic modelling of CO_2 injection in a depleted oil field - the Greensand CO_2 storage project, Danish North Sea. Conference abstract: EGC1, Aberdeen, UK.

Mohammadkhani et al. 2022. Effect of Residual Oil Saturation on CO_2 Injectivity-A Case Study from Nini West Depleted Oil Field. EAGE GET 2022, Nov 2022, Volume 2022, p.1 - 5. https://doi.org/10.3997/2214-4609.202221061

Narayanan, P., Khosravi, M., Stenby, E.H., Yan, W., 2023. Long-tube flooding tests for investigating salt precipitation induced by CO_2 injection. The 12th Trondheim Conference on CO_2 Capture, Transport and Storage, June 19-21, 2023, Trondheim, Norway.

Petersen, H.I., Smit, F.W.H., 2023. Seal integrity evaluation of potential CO_2 storage sites in depleted oil fields using mud gas logs and leakage phenomena. EGC 1, Energy Geoscience Conference, May 16-18, 2023, Aberdeen, UK. Abstract Book, 56–57.

Petersen, H.I., Rudra, A., Sanei, H., 2022. Residual oil in a depleted oilfield considered for CO_2storage, Danish North Sea. 38thAnnual Meeting of The Society of Organic Petrology (TSOP), September 14–16, virtual conference. Programme and abstracts vol. 38, p. 52.

Schovsbo, N.H., Weibel, R., Springer, N., Fodgen, A., Sheldon, E., Petersen, H.I., 2023. Workflow for characterization of the Nini West storage site seal, Danish North Sea. EAGE GET conference November 2023. 1-5. https://doi.org/10.3997/2214-4609.202321010

Smith, S.A.M., Cassiede, M., Stenby, E.H., Yan, W., 2023. Modelling of CO_2 solubility in brines using a generalised Søreide-Whitson model. The 12th Trondheim Conference on CO_2 Capture, Transport and Storage, June 19-21, 2023, Trondheim, Norway.

Szabados et al. 2022. Greensand Focused Seismic Monitoring for Offshore CO_2 Pilot Injection. EAGE GET 2022 conference. DOI: https://doi.org/10.3997/2214-4609.202221081

Weibel, R., Keulen, N.T., Hillier, S., Friis, H., Petersen, H.I., Olivarius, M., Stokkendal, J., Schovsbo, N.H., 2023. Reactivity of glauconitic clasts during burial diagenesis. 36th IAS Meeting of Sedimentology, Dubrovnik (Abstract).

WP4 Well Integrity

Project Greensand phase 2 work package 4 (hereinafter referred to as WP4) was initiated to evaluate well construction materials for providing long-term well integrity according to the relevant ISO and DNV standards for new CO_2 injection wells and for P&A activities on legacy wells. WP4 comprises of eleven different tasks T4.1-T4.11 with seven deliverables related to these tasks. The tasks themselves are highly interlinked within WP4, i.e. some building the foundation for others, but they also interact with other work packages like WP3.

Overall, it can be stated clearly that the objectives of WP4 have been achieved successfully. Minor adjustments in project details have been made to some of the original targets during project execution to cater for the learnings obtained. A list of the different tasks is given below with brief summaries comprising of the intended objectives and the results gained. Deviations from initial tasks are discussed.

Thermodynamic description of transported medium. Based on the expected compositions of the CO_2 streams which will be injected (as per Ineos document number C081-INEO-Z-KN-0002), an evaluation was conducted to understand the phase behavior and the phase properties of the transported streams within the operational and compositional envelope in Greensand CO_2 injector wells. Deliverable D4.1 [1] describes the processes relevant to material selection and thus to ascertain well integrity under downhole conditions. The assessment given in [1] has limitations as it covers only the operational period of the project, not the storage period upon P&A of the wells. For the operational phase it discriminates between the two boundary cases, injection phase and shut-in period in equilibrium conditions. Transient analyses, i.e. analyses describing other operational condition e.g. start of injection and the situation after shut-in, are not discussed in detail as well as flow assurance topics like hydrate formation. A set of proposed test conditions for laboratory testing is derived from the evaluation, however, some adoptions have been made to the actual test setups in discussion with the laboratories executing the test program.

Corrosion resistivity assessment of metallic materials. Task 4.2 comprised of the development of a reasonable proposal for qualification of materials in general and for project Greensand specifically. It has to be noted that a similar work package exists in EUDP project COLLATE work package 6 and that both documents overlap significantly with the one for project Greensand phase 2 being more project specific and less generic. The proposal is oriented along the established standards in the European chemical and oil and gas industry. It covers the reservoir filling period up to plug and abandonment of the well. It is shown in deliverable D4.2 [2].

Operational window for metallic materials. Task 4.3 was to gain understanding of the phase behavior of the injected CO_2 stream under different operational conditions in order to define service condition in the CO_2 injector wells and to subsequently conclude on operating/storage conditions which can be expected. This ensures that the materials used as well barriers are sufficiently resistant against corrosion and other forms of degradation. This task is strongly interlinked with T4.1 and was thus not discussed in an individual document or deliverable. T4.3 is covered in deliverable D4.1 [1] together with T4.1.

Metallic materials lab testing. Task 4.4 is comprised of planning and conducting material testing in the laboratory and reviewing the results with the aim of identifying suitable materials for the Greensand project. Based on literature review, a pre-selection of materials was conducted, and these materials were sent to two different laboratories to be subjected to corrosion tests, Welltec (Denmark) for flow loop testing and Vallourec (France) for autoclave testing, respectively.

Corrosion testing at the flow loop facility from Welltec had the aim to address the corrosion risks associated with subsequent operational phases of Greensand project and the impact of different CO_2/fluid environment on candidate materials. In total three tests were carried out at the Flow Loop facility:

1. Baseline assessment, i.e. in pure CO_2 and Nini formation fluid to test the equipment and establish the baseline corrosion rates.

2. Simulation of conditions below the downhole valve in the injector well, exposed during some periods to CO_2 with impurities and Nini formation fluid; the latter was saturated with NaCl to simulate downhole conditions. The salt concentration is expected to increase in the reservoir fluid as cause of the periodic CO_2 injection and intermittently drying of the formation by CO_2 pushing the water deeper into the reservoir. This leaves the salt behind and with the salt being dissolved when the reservoir fluid is flowing back, the concentration increases. Some test specimens have been placed in the aqueous phase and some in the supercritical CO_2 phase.
3. Representation of worst-case conditions inducing severely corrosive conditions using CO_2 with impurities (and refreshing the CO_2 during the test) together with low amounts of Nini formation fluid. This way, the fluid corrosivity is increased as the ratio between CO_2 and impurities is increased relative to the water amount.

The type and concentration of impurities in the CO_2 stream was based on CO_2 compositions published for other CCS projects and from potential emitters and comprised of O_2, NO_2, SO_2 and H_2S. This combination of acidic and oxidizing impurities is expected to result in severely corrosive conditions.

Test 1 and test 2 evaluated the same materials (Cr13, Cr15, Cr17, Cr22 and Cr25). For test 3, Cr17 was replaced by S2550, a Ni-based alloy with supposedly high corrosion resistance in the test environment. More details about the test protocols are given in deliverable 4.3 [3].

The assessment of the test specimen based on a thorough visual inspection, a calculation of mass losses and SEM/EDX analyses of corrosion products and localized corrosion on the specimen to assess occurring corrosion mechanisms qualitatively and quantitatively.

The results from the test program can be briefly summarized into following main conclusions:

- Test 1 and Test 2: 13Cr showed substantially higher corrosion rates than the other materials. 22Cr and 25Cr outperformed the other materials and showed comparable corrosion trends. Addition of the acidic and oxidizing impurities increased the corrosion rates significantly. No cracks were observed. The samples placed in the supercritical CO_2 phase primarily revealed localized corrosion (likely caused by the oxidizing impurities) whereas the samples placed in the salt-enriched aqueous phase indicated general corrosion and higher overall mass losses.
- Test 3: All samples showed superficial localized corrosion in the parts of the sample which remained wet throughout the test. For the lower grade materials, the relatively small amount of aqueous phase showed a significant increase of pH value during the test, indicating corrosion occurring (consumption of corrosive species and subsequent production of corrosion products). The increased pH value resulted in the corrosion subsiding, i.e. it stops itself in the test set-up. Bigger fluid volumes as they are expected in the field, however, would have less impact on the pH values which would result in corrosion rates remaining high. Lower grade materials showed pitting corrosion. Crevice corrosion was found on several samples but was considered to be a test artifact related to the geometry of the test setup. Against expectations, S2550 showed higher impact of corrosion than 22Cr and 25Cr. This is explained by variations in the test setup which potentially enhanced crevice corrosion.

Corrosion testing at Vallourec was conducted in autoclaves in which some test specimens were submerged in the aqueous phase, and some were exposed to the supercritical CO_2 phase. The test setup considered a relatively high ratio of supercritical CO_2 phase to aqueous phase. The impurities in the CO_2 phase were based on a study by Pace CCS [4] and ISO 27913. The test protocol assessed general corrosivity including different corrosion mechanisms as well as stress corrosion cracking (SCC) with a four-point-bend-test (FPB). Testing was performed with 4 different materials, 15Cr and 17Cr stainless steels, super duplex 25CrS and duplex 28Cr steel. The test revealed a positive for all materials in the mass loss test as well as in the FPB tests according to the acceptance criteria agreed on. Crevice corrosion tests gave different results though. 15Cr and 17Cr did not pass the test while the higher alloys achieved the acceptance criteria.

Metallic materials selection. The actual selection of metallic materials is not depending on the corrosion tests alone, but it requires consideration of the well design, barrier philosophy and CO_2 injection scheme. Suitable material selection is intrinsically tied to the context of well design options.

Cement material acquisition. This task comprised of activities related to the production of cement samples and the definition of a brine recipe representative for Nini reservoir fluid. Completion of this task is prerequisite for the following cement experiments and cement degradation testing

Cement experiments. Laboratory experiments were conducted to understand the impact of supercritical CO_2 and/or Nini formation fluids on the prepared cement samples. These tests were conducted at PT conditions prevailing in the downhole environment. Changes in the water composition by interaction with the cement were monitored additionally. The focus of the experiments was on two types of cement, Class G Portland cements (as used in the legacy well NA-3 Nini West 9 5/8 tail intermediate casing) and a Class G cement amended with latex.

Laboratory cement degradation characterization. Both reacted and unreacted cement samples were characterized with multiple analytical technologies (CT scan, SEM EDX, XRD) which give spatial resolution to detect and understand changes to the material inside the cement plugs. Porosity and diffusivity measurements have been conducted to supplement the evaluation

Initial literature research on the impact of CO_2 on the durability of Class G cements showed contrary conclusions which could relate to specifics in cement type, presence of additives and method of sample preparation. All cement plugs were prepared with typical additives and produced according to API Recommended Practices and Specifications, and then they were cured at reservoir pressure and temperature (200 bar and 60 °C). Subsequently, the plugs were aged in synthetic Nini brine at 200 bar and 60 °C for 28 days to provide additional time for the cement to harden. The prepared plugs were then used in experiments with CO_2 at 150-200 bar and 60 °C to mimic downhole conditions. During the tests, the cement plugs were placed in the supercritical CO_2 phase and/or submerged in the Nini brine in equilibrium with the CO_2.

The experiments indicate that the legacy Class G cements react with CO_2 in a way that slows further penetration of CO_2 into its matrix. Penetration depths were found to be in the order of 1-3 mm after 4 months exposure, with carbonation occurring to a depth of 0.5 - 1.5 mm. The reactions did not result in fractures of a size visible with the techniques used. No evidence was found that chemical alteration resulted in loss of function. The latex amended Class G cement showed less chemical alteration and is thus expected to perform better. However, carbon density measurements revealed that the latex compound got enriched at the outer surface of the cements plug. A potential degradation of latex into soluble compounds throughout the storage period might result in an increased porosity of these near-surface regions and allow for CO_2 penetration. In summary, the conducted experiments indicate that the legacy Class G is durable and most likely able to withstand interaction with CO_2 for extended timespans without substantial loss of its sealing capabilities.

Geochemical and geomechanical modelling. To enhance the knowledge about the integrity of the storage side and the durability of the barriers (metal/cement/rock layers), a coupled model was developed considering fluids flows, geochemical reactions and geomechanical responses.

The simulations for the cement samples predict a full passivation of the cement caused by the formation of a carbonated layer which inhibits diffusion of CO_2. Similarly, the geomechanical studies suggest that geomechanical failure of the Legacy class G cement will not occur at the studied conditions. Reactive transport modelling predicts, however, that the cement could degrade if in contact with a clay rock that contains little or no CaCO3, such as the lower portion of the Nini West caprock. The simulation indicates that the degradation with time generates a porous, leached layer of ~0.5 mm thickness which may potentially act as pathway for supercritical CO_2. The estimated speed of CO_2 migration is very slow though and thus it is unlikely that the integrity of the barrier is compromised.

In summary, the experiments and the reactive transport modelling of the legacy Class G cement alteration upon interaction with CO_2 indicate that it will provide adequate sealing capabilities for at least 100 years under in the expected downhole conditions.

Conceptual P&A design for legacy wells. Conceptual designs for P&A activities planned for legacy wells and design for conversion of well CO_2 injector wells/new CO_2 injector wells are highly interlinked and therefore reported below.

Conceptual CO_2 injector design. Conceptual designs for both P&A activities as well as for CO_2 injector wells require a detailed assessment of the existing infrastructure in the vicinity. Any well penetrating the cap rock in the storage site poses a significant risk for the long-term containment of CO_2, thus their actual conditions need to be understood thoroughly. Additionally, it needs to be considered that the service condition in CCS vary from the original purpose. In-depth risk assessments have been performed and are building the foundation for this task. Reducing the impact of corrosive water flowing back to the well by customized well design and other options have been discussed in detail.

Well status reports were prepared for four Nini West wells (Nini Wells (Nini 4/4A, NA-3B, NA-5 and NA-7D) forming the basis of conceptual design studies specifically designed for their further designation. P&A requirements for NA-05 and NA-07 Nini West wells and Nini West Exploration well N4/4 together with a study for the conversion of Nini West NA-3B well into a CO_2 injector well which outlines technical and regulatory requirements as well as conceptual options.

WP5-9 CO_2 Offshore injection

Objectives

The Greensand Phase 2 project included in-situ batch injection of liquified CO_2 offshore in the Nini field offshore Denmark, Greensand Pilot project. The key objectives of the Greensand Pilot project were to:

- Demonstrate the suitability (from a subsurface standpoint) of the Nini West reservoir as a storage site for CO_2 injection. It was recognised that the Greensand Pilot project, given its limited timeframe, would not be able to assess any possible long-term reservoir behaviour but may address any immediate deterioration of the reservoir properties (and injectivity).
- Confirm safe handling and injection of CO_2 in an offshore environment. The offshore operations of fluid transfer between units and injection in a well through coiled tubing unit (as planned for the pilot project) are common operations for an oil and gas field. However, the fluid in itself (CO_2) together with the conditions at which the fluid is handled are very different. It was therefore of outmost importance for the Greensand project to demonstrate that such offshore operations can be handled safely and successfully.

The Nini Joint Venture (JV) is the owner of the Nini field and INEOS Energy DK, as operator of the Nini field, was the overall responsible for the delivery of the Greensand Pilot project. The Nini JV has teamed up with a consortium selected for their expertise and interest in the Greensand Pilot project. The Work has been divided in Work Packages as illustrated in Figure 5 *5:* below.

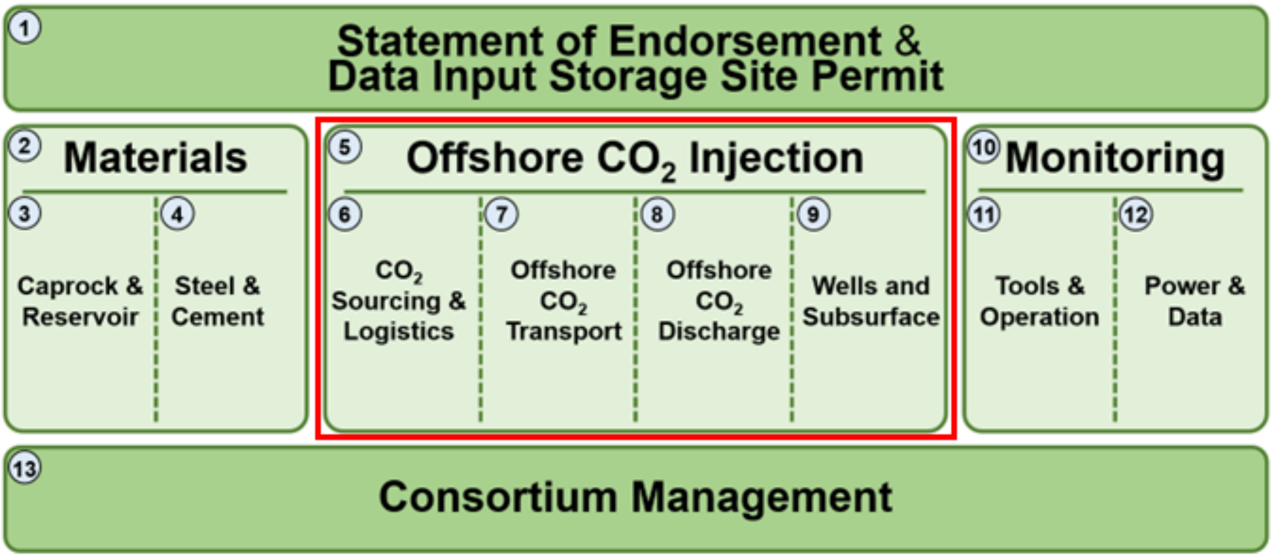

Figure 5 5: Greensand Phase 2 Work Package overview

Work Programme:

Work Package 5 Offshore CO_2 Injection

This work package served a coordinating function for all activities in relation to CO_2 storage pilot test, ensuring that activities and deliverables in WP6-9 were coordinated and carried out in accordance with applicable regulations and the ISO standard 27914:2017. It included:

- Independent verification by DNV
- Preparation and input for the various authority applications such as Environmental Impact Assessment screening, Combined Operations

- Flow assurance and technical safety studies executed by Rambøll as a support to the CO_2 injection system and above applications
- Preparation of the operations and maintenance philosophies
- General review and assurance processes

Work Package 6 CO_2 Sourcing and Logistics

This work package consisted of:

- Sourcing of liquified CO_2 for the planned injection operations
- Onshore logistic services for temporary storing liquefied CO_2 and transporting it between the capture plant and the loading port
- Provision of ISO containers to store and transport liquified CO_2

Work Package 7 CO_2 Offshore Transportation

This work package consisted of:

- Provision of a vessel (platform supply vessel with dynamic position class 2) capable of transporting CO_2 in ISO containers between the port of Antwerp and the Nini A platform
- Preparations of the platform supply vessel to support installation of the ISO tanks and CO_2 detection system
- Port operations and logistic services to secure berthing and loading / unloading of the ISO tanks at the port of Antwerp

Work Package 8 CO_2 Offshore Discharge

This work package corresponded to:

- Supply of a jack-up rig to accommodate CO_2 Offshore Discharge equipment and the Coiled Tubing Unit
- Engineering, procurement and delivery of the offshore CO_2 discharge unit from the ISO tanks to the Coil Tubing Unit, equipment located on both the PSV and jack-up rig
- Preparations for the offshore injection operations with provision of personnel to operate the equipment, development of the operating procedures to safely operate the equipment and provision of services to support the offshore operations

Work Package 9 Wells & Subsurface

This work package consisted of:

- Pre-Injection well logging to understand the mechanical condition of the well and serve as input to the engineering of the Coiled Tubing Unit
- Engineering and supply of Coiled Tubing services
- Subsurface evaluation pre-injection to characterize the Nini West reservoir and develop the injection plan
- Subsurface evaluation post injection to calibrate the subsurface Pilot injection model and incorporate learnings from the injection operations including the spot seismic monitoring (WP12)
- Implement learnings into the subsurface full field dynamic modelling
- Development of the Monitoring and Verification Plan

Project Description

The Greensand Pilot project consisted of:

- Sourcing substantial batches of liquified CO_2 and handling them between the CO_2 capture plant and the port of Antwerp
- Transporting liquified CO_2 between the port of Antwerp and the Nini A platform using a Platform Supply Vessel (PSV)
- Injecting liquified CO_2 in several batches into the Nini West reservoir using discharge equipment placed on both the PSV and a jack-up rig with a coiled tubing unit installed in NA-05 well
- Monitoring reservoir performance before, during and after these cyclic injections

An illustration of the Greensand Pilot project is presented in Figure 6:*6*.

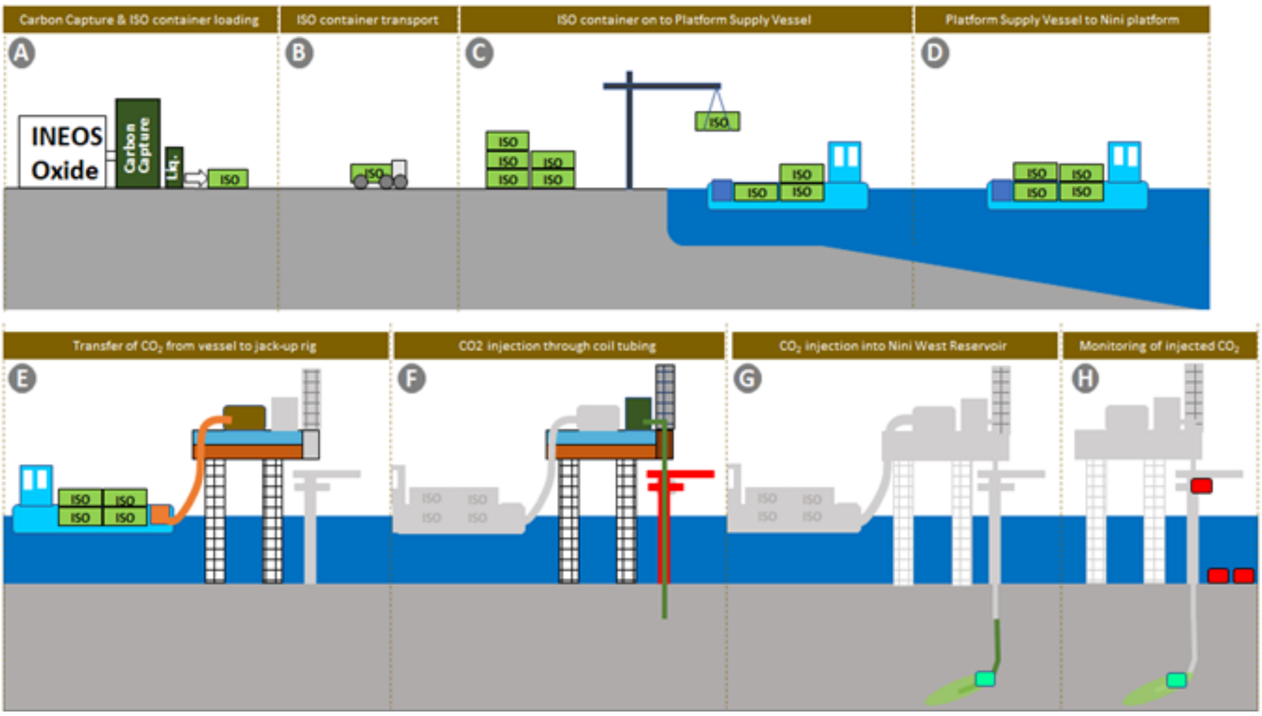

Figure 6:6 Greensand Pilot project illustration

The CO_2 for the Greensand Pilot project originated from INEOS Oxide capture site in Antwerp, Belgium.

The CO_2 was temporarily stored and transported as a liquid in 20' cryogenic ISO tank containers. Each CO_2 ISO tank container had a capacity of 20 tonnes and 80 containers were rented during the Greensand Pilot project duration (2 sets of 40 containers: 1 set onboard the PSV and 1 set at the capture plant for filling). The ISO tank containers filled with CO_2 were then loaded onto the PSV at the Europort terminal in Antwerp, close to the INEOS Oxide capture site. From Antwerp, the CO_2 was transported to the Nini field for injection.

To facilitate the injection, the PSV was outfitted with equipment to transfer in an environmentally safe manner the liquified CO_2 from the ISO tanks onboard of the PSV to the Jack-up rig. On the Jack-up rig, the liquified CO_2 stream was pressurized and heated to meet the required conditions for injection in the NA-05 well.

The Jack-up rig supported the coiled tubing unit installed in NA-05. Injection was performed through coiled tubing to protect the existing water injection well NA-05 from any degradation during CO_2 injection.

Results

CO_2 injection system

Process Flow Diagrams (PFDs) were developed to depict the flow path and the main equipment necessary to transfer and inject the liquefied CO_2 from the ISO tanks to the Coil Tubing Unit in NA-05, see Figure 7 below.

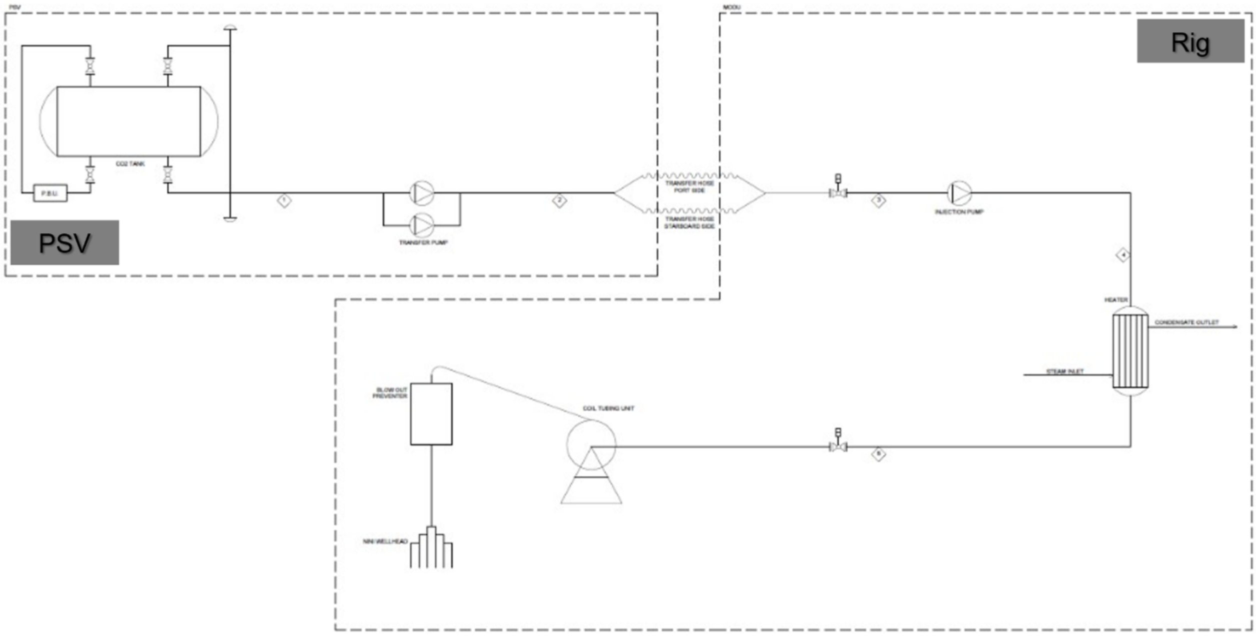

Figure 7: CO2 injection system Process Flow Diagram

The supply vessel was equipped with 40 ISO tanks loaded with liquid CO_2 at approx. -30°C and 15 bara. Each ISO tank contained 22 m^3 CO_2. Each ISO tank was equipped with a pressure build-up unit (PBU), which is a simple finned heat exchanger evaporating a small part of the liquid CO_2 using ambient air as heating medium. This way, the pressure decrease during emptying of the ISO tank can be counter balanced. Each ISO tank was connected to common outlet manifolds, from which the CO_2 is routed to transfer pumps (2x50% centrifugal type). The transfer pumps were located in a brine tank below deck on the PSV to ensure adequate suction head. From the transfer pumps, the CO_2 was pumped to the jack-up rig loading station via hose reel / flexible hoses. From the loading station, the CO_2 was routed to the high-pressure injection pump (fixed displacement type). From the high-pressure pump, the CO_2 was heated to approx. 10 / 20°C before being injected into the reservoir via a coiled tubing located in the NA-05 well tubing. The discharge pressure of the high-pressure injection pump was approx. 275-300 bara at a flow of 40 m3/h. The pressure upstream the injection pump was governed by the transfer pumps and needs to be above the saturation pressure of the CO_2 when accounting for both frictional pressure loss as well as static head loss in order to avoid boiling of the CO_2 upstream the HP injection pumps.

The following equipment were designed, procured, installed and commissioned to support the injection operations:

- Flexible hoses between the ISO tanks and CO_2 piping
- Transfer pumps
- Flexible transfer hoses between the PSV and jack-up rig
- High pressure injection pump (leased)
- Heater package (leased)
- Piping and valves, including piping supports

- Pressure relief valves
- Electrical switchboards
- Instruments

The injection system and associated equipment were spread across the PSV and jack-up rig as illustrated in the below 8 and 9.

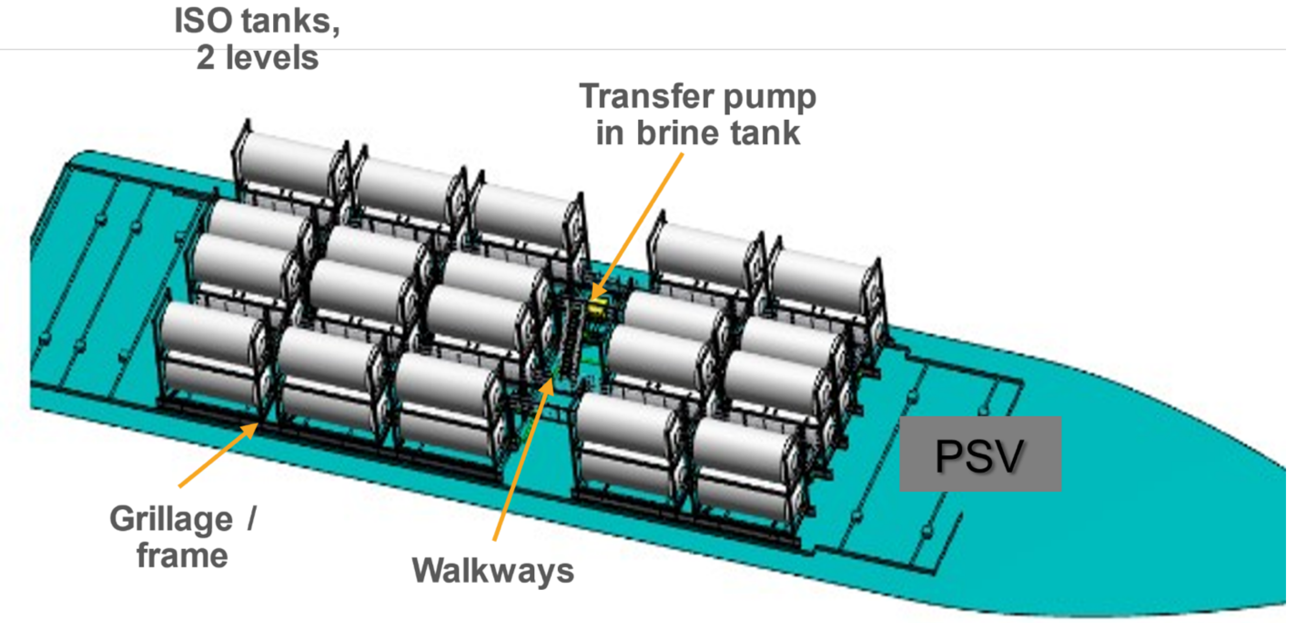

Figure 8 Illustration of the injection equipment on the PSV

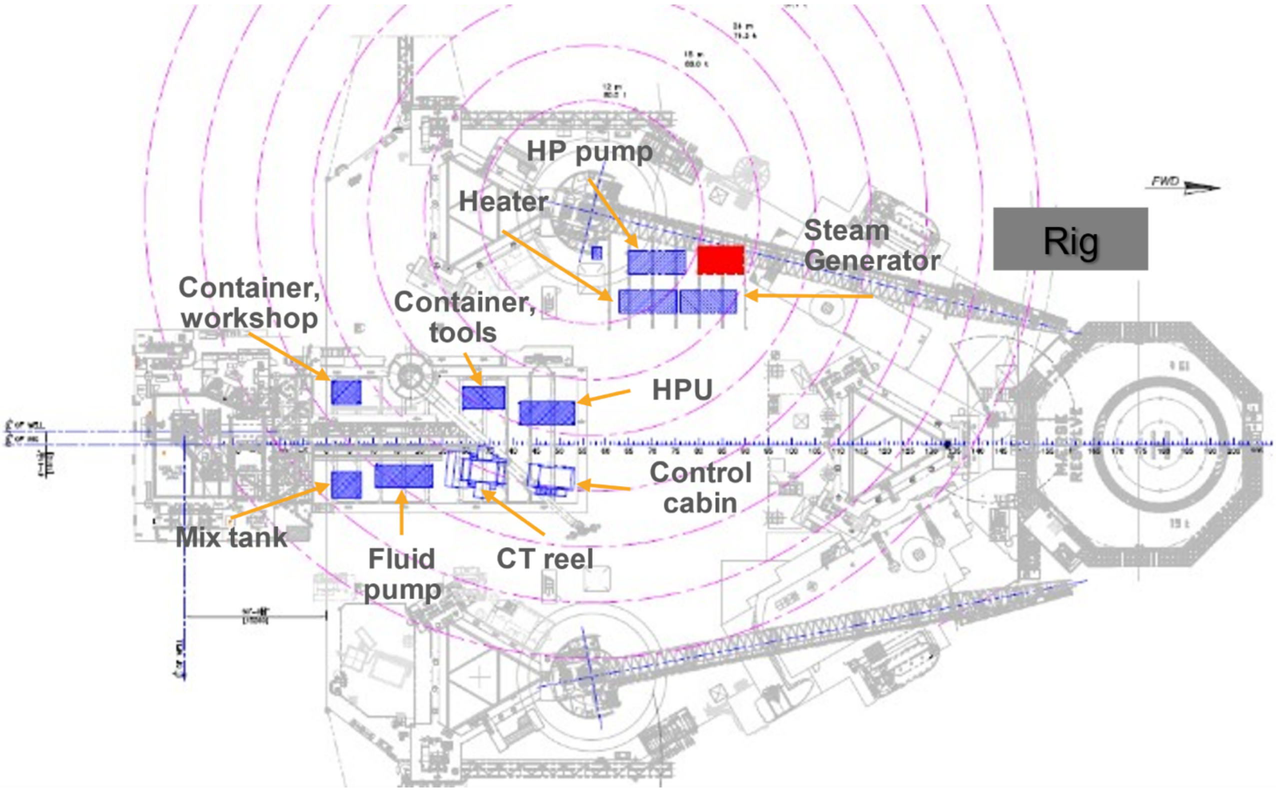

Figure 9: Illustration of the injection equipment on the jack-up rig

The CO_2 injection system has been verified by DNV as part of the independent verification required by the Danish Offshore Safety Act. The verification was done to ensure compliance with applicable laws, regulations and recognized standards relevant to safety, health and environment, before the equipment used for the pilot injection was put into operation.

ISO tanks

The Greensand pilot project secured the lease of 80 ISO tank containers, rented over the injection period (including mobilization and demobilization periods). The ISO tanks were approved and suitable for carrying liquid CO_2 under 15 bar pressure and -30°C. An ISO tank is illustrated in 10 below.

Figure 10: Typical ISO tank used for the Greensand pilot project

Filling and withdrawal of the CO_2 are done under pressure. The container is filled using an external pressurized source. Withdrawal is done by applying pressure to the vapour space above the liquid. The built-in pressure build-up system was used for doing so. By circulating liquid through the build-up fins, liquid is vaporized and the gas fed back into the vapour space of the inner vessel. A pressure gauge was fitted on the ISO tank to indicate the tank gas phase pressure. A differential pressure gauge was also fitted to indicate the liquid content in the tank. A Piping and Instruments Diagram of the ISO tank is shown in Figure below to illustrate the ISO tank make-up.

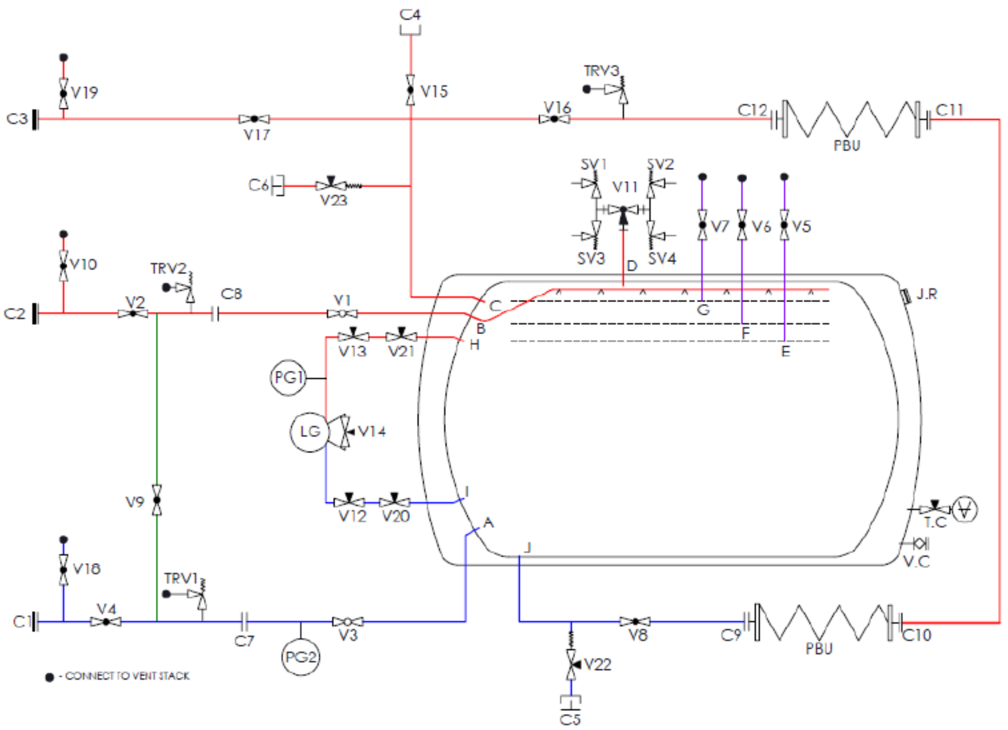

Figure 11: Piping & Instrument Diagram of an ISO tank

Platform Supply Vessel

The Greensand Pilot project secured the lease of dedicated Platform Supply Vessel (Aurora Storm) able to accommodate 40 ISO tanks in 2 layers, grillage to fasten the ISO tanks in place, transfer pumps, all piping and manifolds between the ISO tanks and the transfer hose. Such arrangement required a deck size of minimum 50 x 15,9 m.
A stowage plan was developed to illustrate the installation of all the above equipment as shown in Figure *12*2 and Figure 3.

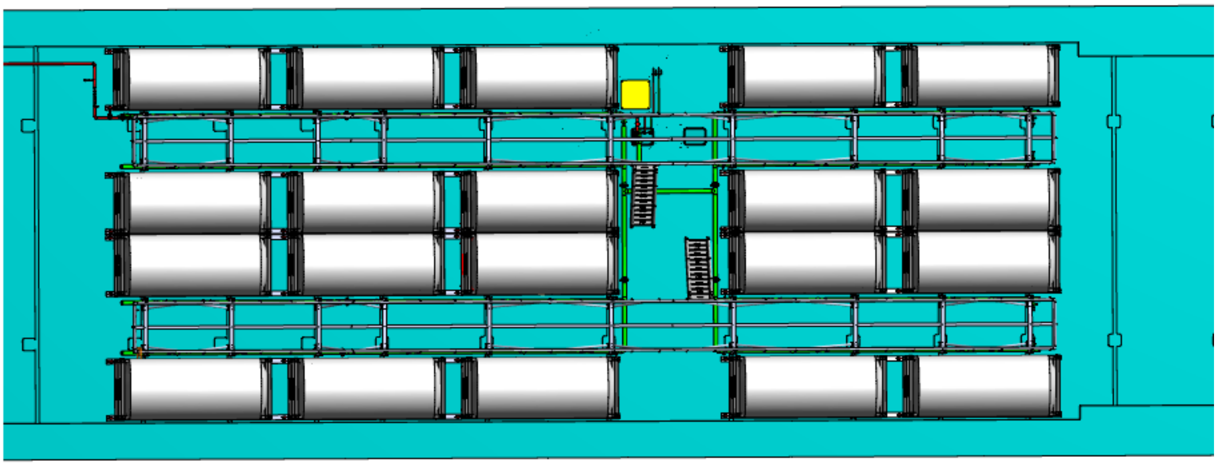

Figure 12: PSV Stowage plan

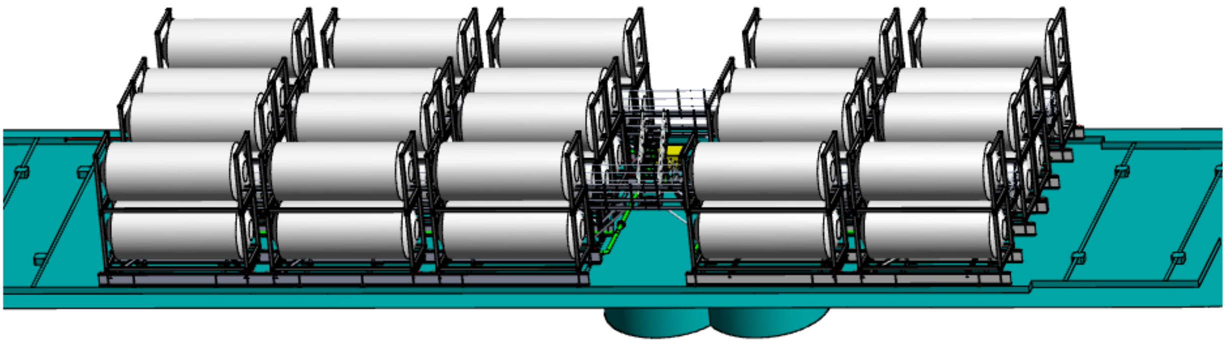

Figure 13: 3D model PSV

The Guidelines for Offshore Marine Operations (GOMO) were used as best practice standards. The vessel was required to have Dynamic Positioning Class 2, i.e. automatically maintains its position exclusively by means of thruster force, to operate in the vicinity of the Nini A platform. Engine power capacity was able to keep station at 33 knots at power utilization of 45% maximum.

Jack-up rig

The Greensand Pilot project secured a dedicated jack-up rig, Noble Resolve, for the injection operation. Most of the rig capabilities were not used since no drilling activities took place. Instead, the main functions of the rig for the project were to:

- Accommodate the installation and operations of the injection equipment (transfer hose, HP injection pump and heater package)
- Accommodate the installation and operations of the coil tubing unit into NA-05
- Accommodate the offshore personnel to supervise and operate the injection operations

Bridging document was prepared, as required by Danish law, to demonstrate and provide means to verify the integration of INEOS SHE Management Systems (operator of the Nini A platform) with Noble HSE Management Systems (operator of Noble Resolve jack-up rig) for the duration of the Greensand pilot project. It included the definition of the document 'primacy' and served as a working tool to assist the identification of the procedures to use in given situations. The project developed a Resolve / Nini combined emergency response procedure identifying the course of actions in case of emergency and a Simultaneous Operations matrix specifying which activities are allowed to be conducted simultaneously and which activities are restricted.

Operating philosophy

The CO_2 pumping operations involved many parties located at different locations. It was therefore of prime importance to define the roles of each party and break down the operations into smaller steps [see appendix 2]. The following key roles and their main responsibilities were outlined:

- PSV crew
  - Confirm weather window
  - Position PSV
  - Hose handling to rig crane (deck crew)
- Tank Supervisor (on PSV)
  - Operate valves on ISO tanks/manifolds
  - Monitor tank level
  - Operate/monitor transfer pumps
- Injection pump operator (on jack-up rig)
  - Control and monitor main injection pump
- Heater Operator (on jack-up rig)
  - Operate steam generator
  - Monitor/control heater
- Process Operator (on jack-up rig)
  - Valve/process operations (CO_2 system)
- Well service (INEOS)
  - Well monitoring/control
  - CT crew
- Rig crew
  - Crane operations for hose (crane operator and deck crew)
  - Operation of utility systems required to support injection operations and equipment
  - PTW system for rig activities outside the CO_2 injection activities
- Injection supervisor
  - Overall coordinator of the above operations

The physical phase behavior of CO_2 required that the correct steps were taken to introduce CO_2 to the piping system transferring CO_2 from the ISO tanks on the PSV to the coiled tubing at the rig and into the Nini West reservoir. Failure to follow the correct steps may result in CO_2 solidification, blockage and damage equipment as well as risk for the personnel onboard.

- Purging

Purging operations displaced the air in the injection system with CO_2 and was done by pressurizing with gas phase CO_2 followed by depressurizing, repeated a number of times until all atmospheric air/contaminants in the system has been displaced and vented off. When the system was considered adequately purged, the system remained pressurized for the following steps.

- Priming

Priming (displacement of gas phase by liquid phase) of pumps must take place at pressurized conditions. Liquid is either flowing by gravity into the manifold/piping system below or pumped to the system above. All gas in the piping system must be displaced with liquid before the system is considered fully primed and pumps can function. At this stage, the injection operations could take place.

- Injection operations

With the transfer and injection pumps primed, the CO_2 pumping operations were started, together with the heating of the CO_2. Flow was increased to the target injection rate for the particular batch.

- Draining

Upon completion of the batch and before depressurizing and disconnecting, the system should be drained out of liquids to the extent possible.

- Depressurization

When systems were drained, depressurization could safely take place. During depressurization the expansion of CO_2 in the pipe will cause JT cooling and the pipe will cool

The operations were repeated for each batch injection.

Well

NA-05 was the preferred well to be used as conduit into the Nini West reservoir in the Greensand pilot project. However, the well was not originally designed to meet the requirements of a CO_2 injection well. To mitigate risks of potential corrosion, chemical incompatibilities and potential leak paths in the existing NA-05 well tubing and accessories, the well concept was to inject the liquefied CO2 via a temporary Coil Tubing string.

Pre CO_2 injection survey

NA-05 is an active water injection well used for water disposal in the Siri Area and the current mechanical condition of the well (tubing) was not known in detail as there had been no well intervention since its completion in 2004. To confirm the well condition and its fitness for use, a downhole measurement (logging) of the well was deemed necessary. A multi-finger caliper survey was carried out well ahead of the actual injections to measure the inner diameter of the tubing. The survey took place in April 2022 [see Appendix 3] and the well was confirmed to be clean and in very good condition all the way from the surface down to the top of the perforated interval. A summary of the survey is shown in Figure 14 illustrating the metal loss across the well joints. NA-05 was then confirmed suitable for the Greensand pilot injection, able to accommodate installation of a coil tubing.

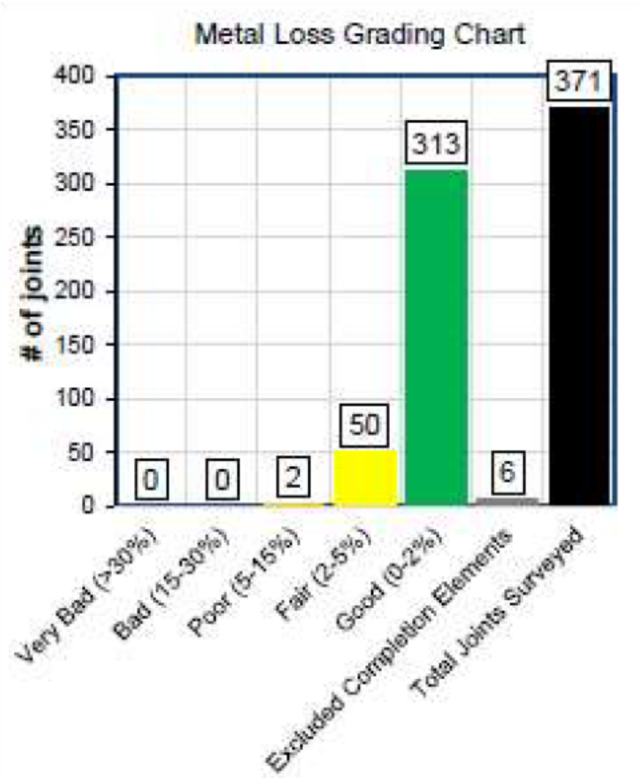

Figure 14: NA-05 caliper survey results (pre-injection) – Metal loss

Well intervention programme

A detailed well intervention programme was developed to define the requirements to the coil tubing unit (well control, chemicals, interfaces with the rig and injection equipment) and to depict the operational steps to prepare the well for CO_2 injection, support the CO_2 injection operations and handover the well back to its original duty as water injector .

The following operational steps were performed:

- Clean the packer setting area with a jet blaster.
- Install peak packer with memory gauges and check valve. The installation of memory gauges was essential to be able to record pressure and temperature downhole before, during and after CO_2 injection.
- Circulate the Coiled Tubing / Well Tubing annulus to MEG and latch the coiled tubing into the packer. The coil was then installed and stayed in this configuration stationary for the duration of the injection.
- Perform a step rate test with injection water. The purpose was to inject treated seawater into the coil at different pump rates and obtain pressure at the top of the coil to validate the expected friction though the coil and later compare them with the pressure values while pumping CO_2.
- CO_2 injection.
- Recover the coil by releasing the stinger from the packer and pull the coil out of the hole.
- Retrieve the peak retainer, memory gauges and check valve from the well.

The final configuration of the coil in NA-05 is illustrated in Figure 75.

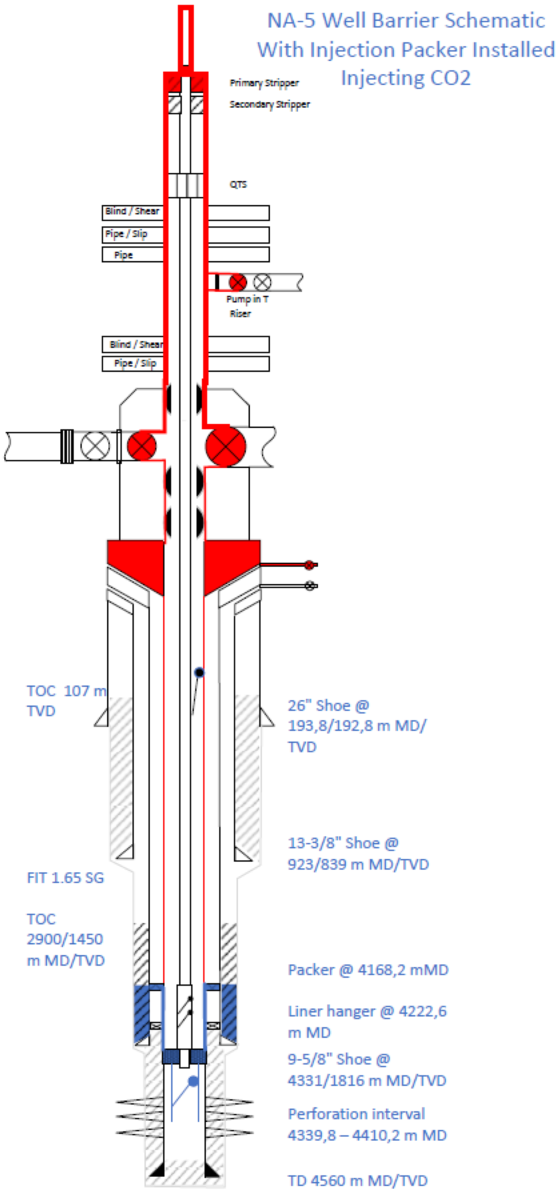

Figure 75: NA-05 Well barrier schematic with coil tubing installed.

Post CO_2 injection survey

Upon completion of the above operational steps, water injection was resumed in the well to displace the CO_2 from the near well bore. A post injection survey (similar to the one performed prior to the CO_2 injection) was performed to assess the potential corrosion caused by the CO_2 injection in the area between the well perforations and the packer location. The survey concluded that the well was in very good condition after the CO_2 injection where the zone exposed to the CO_2 did not present any notable anomaly, as shown in 6 comparing the 2022 (pre-injection) and 2023 (post-injection) surveys.

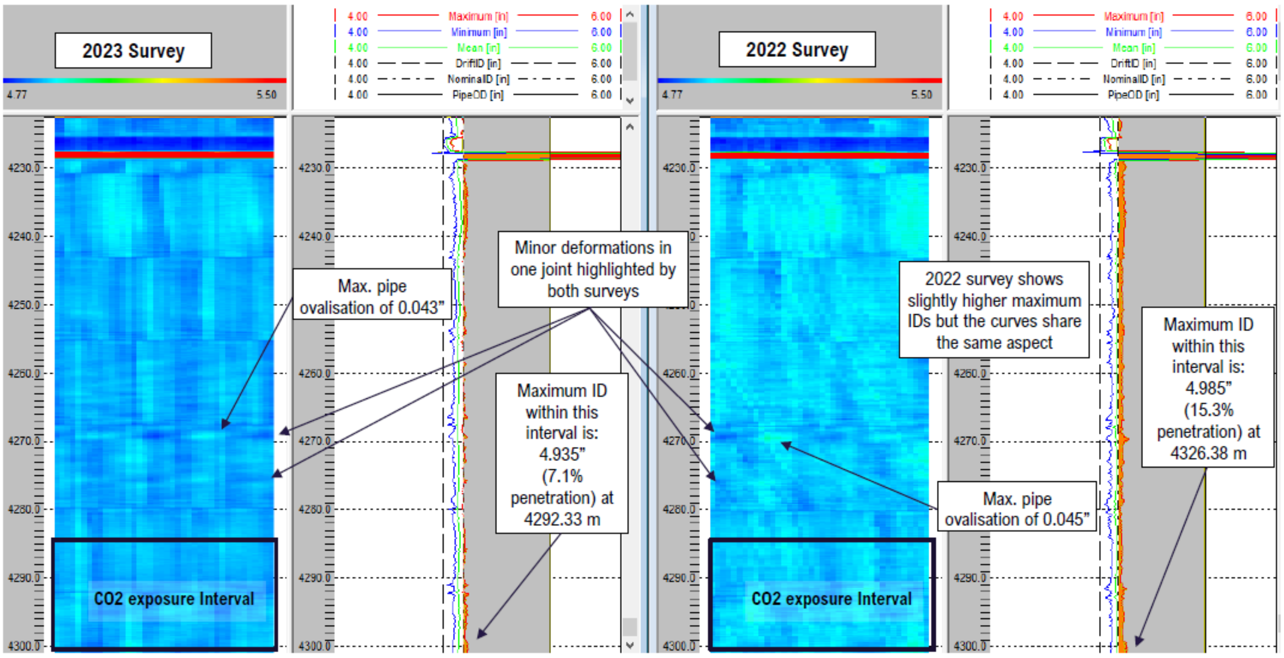

Figure 16: Comparison results from caliper surveys (pre and post CO_2 injection) in NA-05

Subsurface Modelling

The pilot injection design and the associated CO_2 plume migration in the reservoir has been studied through a numerical model (ECLIPSE 300). The model covers the Nini West oil accumulation and has served as reference for the Nini West reservoir management over the production period 2003-2018.
The model, being matched to the historic pressure and production/injection data, formed basis for the storage capacity assessment for the Nini West in the feasibility assessment (Site Feasibility Certificate, 2020).
For modelling of CO_2 injection in the NA-05, and in order to capture the injection pressures at the well/reservoir interface and the saturation changes at the injection site, a local finer resolution grid was prepared (Figure 17).
The model was used as a predictive tool for the plume migration in the reservoir and to define a safe operational window for the injection rate, temperature and injection pressure. The predicted downhole injection pressures were compared to results from the geomechanical model evaluating caprock integrity and fault stability in Nini West area.
The geomechanical evaluation showed low risk of caprock failure and no risk of fault reactivation in the overburden for the planned Pilot injection.
In summary, the most critical mode of failure identified was the possible tensile failure of the Horda caprock which suggested a safe operational limit of 280 Bar for the Frigg Sand reservoir.

Table 3 summarizes the main design parameters for the NA-05 pilot injection test and the expected impact of the pilot injection on the reservoir pressure and temperature. No injectivity change was assumed in the NA-05 injector, due to the injection phase change nor any injectivity impairment in time over the duration of the pilot injection was built into the pre-injection modelling. The injection design rates, and durations of the injection periods were estimates and represented best case assumptions adopted in the pre-injection modelling.

Table 3 Main design parameters for the NA-05 pilot injection adopted for the pre-injection modelling and the expected pressure and temperature conditions over the pilot duration

Max no. of cycles	Injection rate/cycle *tonnes/day*	Injection time	Shut-in time	Initial reservoir pressure *bara*	End pilot injection reservoir pressure	Initial reservoir temperature, *deg.C*	End pilot reservoir temperature *deg.C*
14	750	15 hrs	6-7 days	204-218	211-218	60	40

The pre-injection modelling results are shown in Figure 17 illustrating the CO_2 saturation changes in the top layer of the Frigg sandstones reservoir at the injection site of NA-05 over the duration of the pilot, ie. a total of 14 injection cycles . The modelled saturation of the CO_2 in the top reservoir reaches up to approximately 55% at the end of the injection period. Due to homogenous reservoir flow properties (porosity/permeability) in the simulation model the CO_2 plume spreads out radially from the injection wellbore (CO_2 plume along the reservoir top reaches ca.150m radius after the last injection cycle).

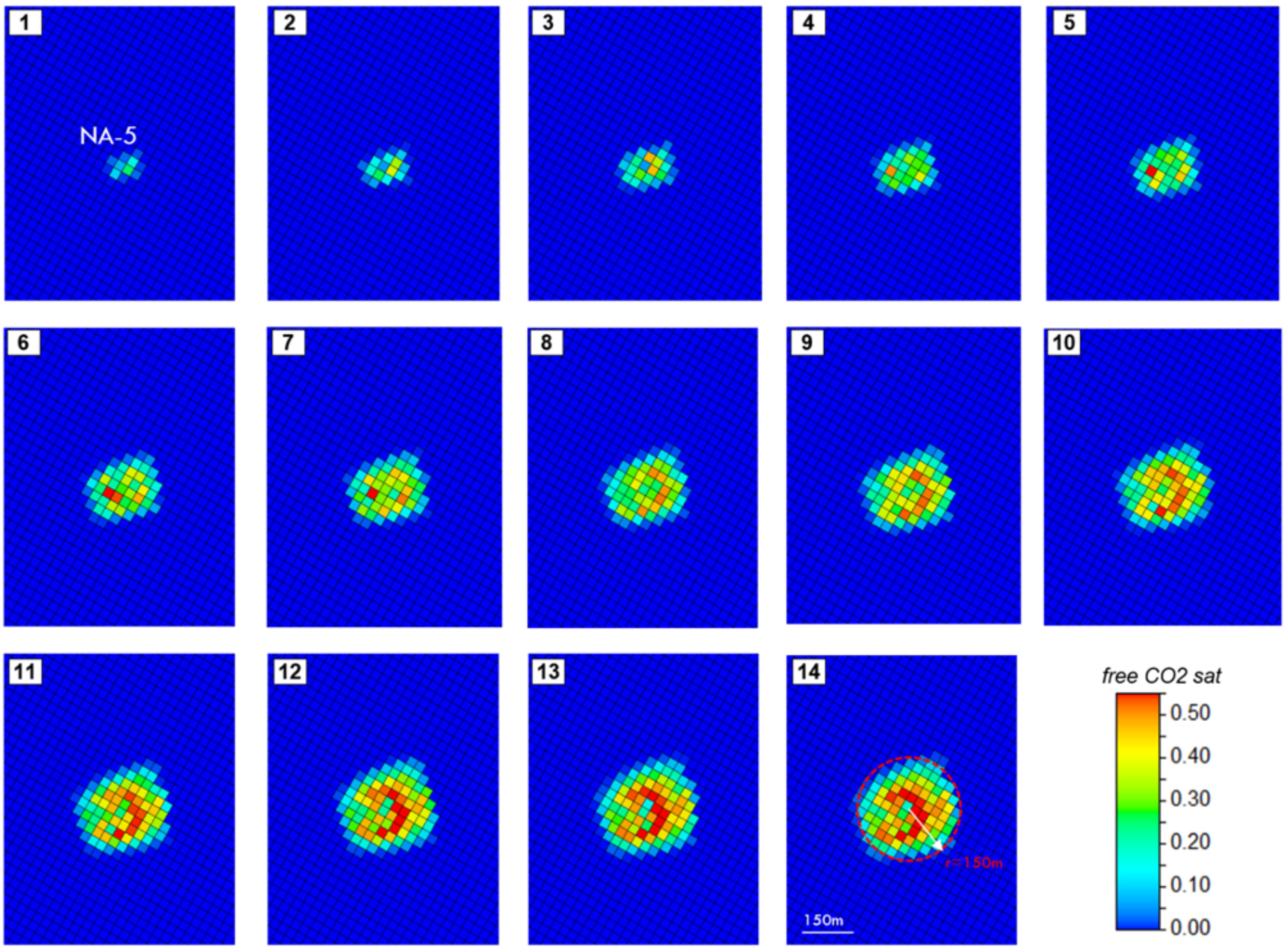

Figure 17: CO2 saturation changes over the pilot injection shown in a top map view the Frigg sand. 14 cycles of injection, each of 750 tonnes over 15 hrs were modelled. CO_2 saturations up to ca.55% are expected within 150m radius away from the well at the end of the pilot.

Figure 18 shows a cross section of the model corresponding to the end of the injection period. The free CO_2 will form into an inverted cone geometry at the end of the injection, which is a result of the interplay between the gravity and viscous forces during the CO_2 migration into the reservoir.

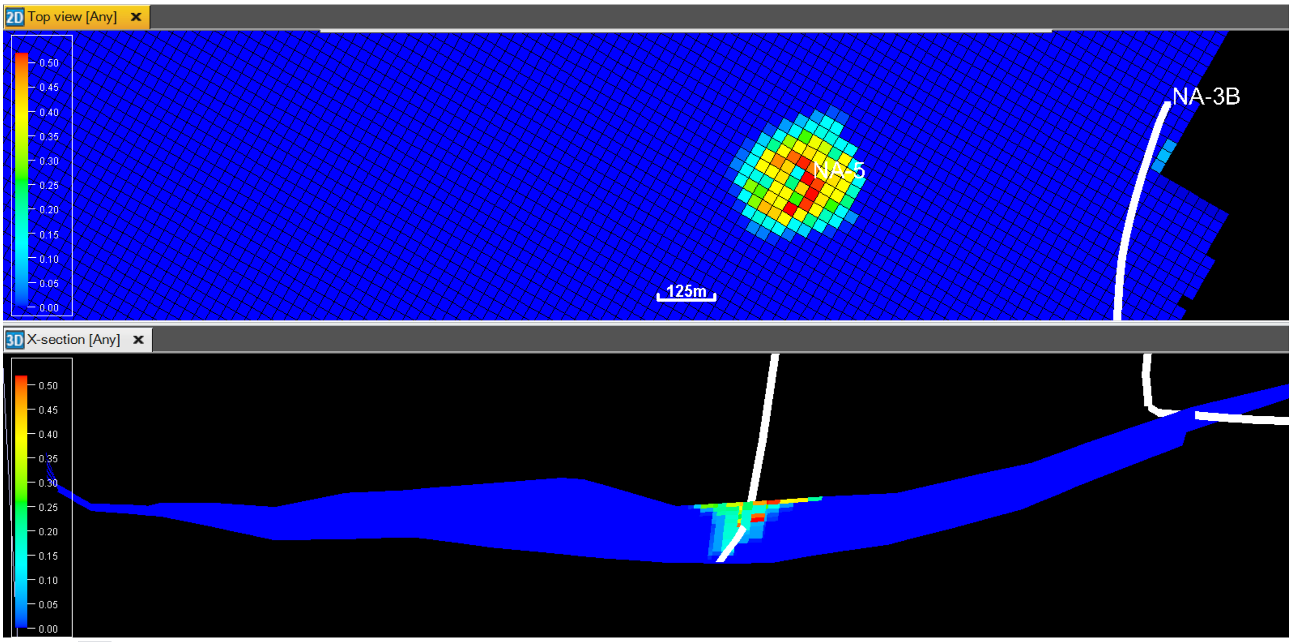

Figure 18: Free CO_2 concentration at end of pilot injection at NA-05 in a top and x-section view

Long term dynamic modelling has been performed to show the migration of the injected CO_2 after the end of pilot injection and the impact of a progressive dissolution of the CO_2 in brine. With time, the free CO_2 saturations at the injection site decrease even further, due to the progressive CO_2 dissolution in water. After 500 years post pilot injection, free CO_2 saturations of 1-3% are expected at the injection site, with the plume extent of ca. triple the size as compared to the one immediately after the pilot end.

Injection programme

An injection programme was developed to prepare for the injection operations offshore and agree on the injection sequence and purpose of each batch injection. The injection programme designed for the Greensand pilot project is reminded in Figure 19.

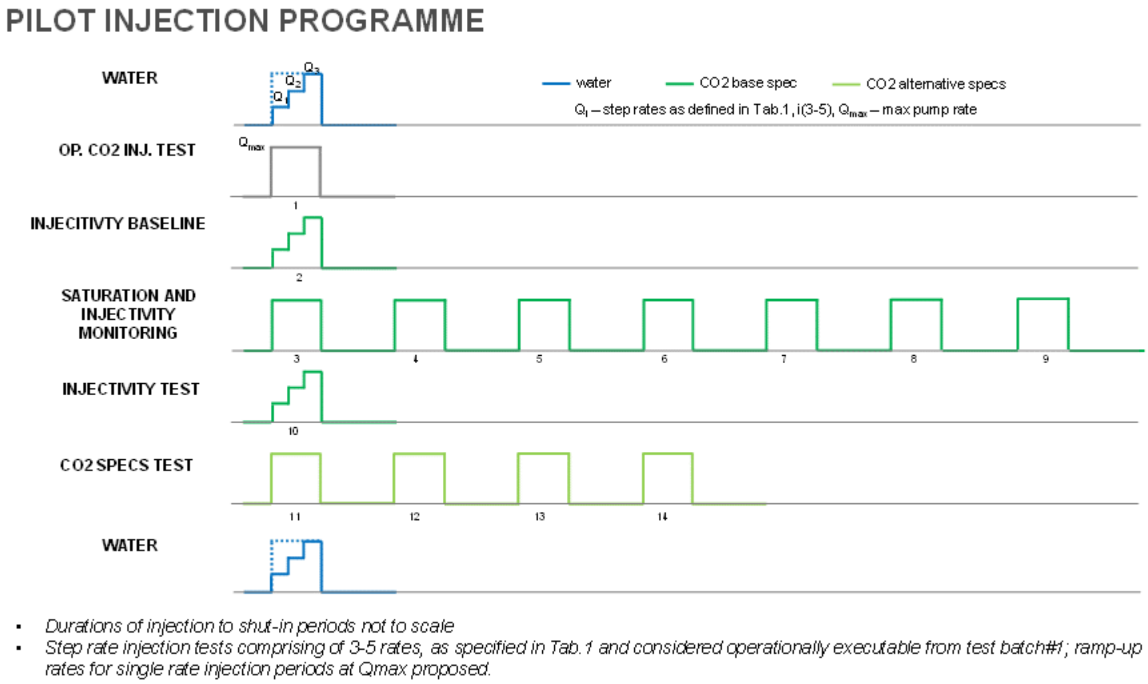

Figure 19: Illustration of the injection programme proposed for the Greensand Pilot injection

A total of 14 cycles were planned for the Greensand pilot injection, following the below sequence:

- Calibration period (batch #0)

Water injection through a coil tubing (CT) to constitute an injectivity baseline for water and calibration point for injectivity changes throughout the test (batch#0). Injection to be followed by the rest period for 12-24 hrs to record the fall off pressures.

- Operational baseline (batch#1)

This first batch injection was meant to achieve familiarization of the injection equipment and establish an operational control of injection rate and temperatures of CO_2 phase.

- Main injection programme (batches#2-10)
  - Baseline injectivity test (batch#2): step rate test serving as a baseline and repeated at the end of the pilot injection
  - Single rate injection sequence at a maximum injection rate Qmax (batches#3-9)
  - Final injectivity test (batch#10): step rate test as per the initial one (batch#2) to assess any changes in injectivity due to CO_2 injection
- CO_2 specification tests (batches#11-14)

Initially, it was considered to introduce alternative CO_2 specification. These were considered optional, and the project did not manage to source alternative CO_2 sources.

- Final injectivity test

Water injection to displace CO_2 in CT, for injectivity analysis comparison with pre-injection test (batch#0)

The injection programme is also summarized in Table 4 below.

Table 4 Design specification - Injection Programme

	Design specification	
Cycle	**Test type**	**Injection rate**
1	CO_2 test injection	N/A
2	CO_2 step rate	20t/hr / 30t/hr / 40t/hr
3	CO_2 single rate test	40t/hr
4	CO_2 single rate test	40t/hr
5	CO_2 single rate test	40t/hr
6	CO_2 single rate test	40t/hr
7	CO_2 single rate test	40t/hr
8	CO_2 single rate test	40t/hr
9	CO_2 single rate test	40t/hr
10	CO_2 step rate	20t/hr / 30t/hr / 40t/hr
11	Optional - Alternate CO_2 composition	40t/hr
12	Optional - Alternate CO_2 composition	40t/hr
13	Optional - Alternate CO_2 composition	40t/hr
14	Optional - Alternate CO_2 composition	40t/hr

Injection operations

The Greensand Pilot injection operations were performed between 11th February and 23rd March 2023. In total, seven injection cycles were executed with a total of approx. 4,100 tonnes of CO_2 injected. This is to be compared with ten injection cycles (fourteen when including the optional cycles) and a total of 7,500 tonnes of CO_2 injected (or 10,500 tonnes when including the optional cycles).
The main objectives of the injection programme were achieved with each cycle's purpose met, despite a disappointing total amount of CO_2 injected.
The Noble Resolve rig move was concluded on 22nd January 2023, more than one month later than planned. Delays were experienced in the start of the injection operations due to adverse weather conditions and inability to move the jack-up rig from Esbjerg to Nini A. Following successful rig move, establishment of the interfaces between Noble Resolve and Nini A and coiled tubing rig up operations, the NA-05 well was ready for receiving CO_2 on 9th February 2023. A step-rate water injection test was executed through the coil prior to the CO_2 injection, as per injection programme.

The first CO_2 injection took place on 11th and 12th February 2023. Due to the initial delays, the first cycle combined the operational control of the injection equipment together with the CO_2 step rate test. As a consequence of friction loss in the coil, lower injection rate was achieved to ensure stable operations and prevent the injection pump from tripping. The first injection cycle also showed that emptying the ISO tanks was more complicated than anticipated. Indeed, the CO_2 was loaded into the ISO tanks early resulting in different pressures in the tanks and gas break out when mixing liquid from tanks with different conditions. The injection pump had to be stopped and manually re-primed.

The second CO_2 injection took place on 16th and 17th February 2023. The second cycle aimed at injecting at a single rate. Similar issues than the ones in the first cycle were experienced with the introduction of CO_2 gas in the injection system since CO_2 was loaded in the ISO tanks too early. The injection operations were also aborted before the ISO tanks were emptied due to adverse weather.
The third CO_2 injection took place on 21st and 22nd February 2023. The third cycle aimed at injecting at a single rate. Despite some operational issues, the injection operations were conducted successfully achieving the maximum achievable injection rate.

The fourth CO_2 injection took place on 26th and 27th February 2023. The fourth cycle aimed at injecting at a single rate. This was achieved with stable injection operations at the maximum achievable injection rate.
The fifth CO_2 injection took place on 2nd and 3rd March 2023. The fifth cycle aimed at injecting at a single rate. This was achieved with stable injection operations at the maximum achievable injection rate. The injection operations were aborted earlier than anticipated due to adverse weather. On the way back to Antwerp for loading the new batch of ISO tanks, the PSV experienced a breakdown on one of its engines, preventing it from using its DP2 capabilities. The repair took place between 6th and 14th March.
The sixth CO_2 injection took place on 17th and 18th March 2023. The sixth cycle aimed at injecting at a single rate. This was achieved with stable injection operations at the maximum achievable injection rate.
The seventh and last CO_2 injection took place on 22nd and 23rd March 2023. The last injection cycle combined the single rate test and the step rate test, aiming at reproducing the same rates as per the first injection cycle.
Following the completion of the last injection cycle, the demobilisation process took place. The well intervention programme, including step-rate water injectivity test through the coil, retrieval of the coiled tubing and downhole equipment (including downhole memory gauge), survey of the well and rig down of the coiled tubing equipment was completed on 01st April 2023. The CO_2 injection equipment was decommissioned and removed from Noble Resolve on 28th March 2023. Noble Resolve move out of the Nini A 500 m zone on 03rd April 2023. Aurora Storm went back to Antwerp to unload the last batch of ISO tanks on 24th March 2023. The ISO tanks were then returned to the owner on 3rd April 2023. Aurora Storm headed to Esbjerg on 27th March for decommissioning and removal of the CO_2 injection equipment, completed on 5th April 2023.
Surface pressure, temperature and injection rates were recorded and monitored during injection cycles whereas reservoir pressure and temperature were recorded continuously by downhole memory gauges throughout the duration of the Pilot. The downhole memory gauges were retrieved upon completion of the injection operations and demobilisation of the injection equipment.

Comparison of Injection Operations Objectives and Timeline

Table 5 below compares the intended design specification against the actual operations.
It has been identified that the theoretical maximum injection rate of 40 t/hr would not be reached and a lower injection rate would be achieved to provide an operational margin and prevent from operating too close to the set point for the injection pump. The optional scope (alternate CO_2 specification) has not been carried out due to the lack of alternate CO_2 sources.

Table 5 Comparison between initial design specification and actual operational parameters

	Design specification		**Actual operations**	
Cycle	**Test type**	**Injection rate**	**Comments**	**Injection rate**
1	CO_2 test injection	N/A	Operational control and step rate test combined Lower injection rate achieved	20t/hr / 25t/hr / 30t/hr
2	CO_2 step rate	20t/hr / 30t/hr / 40t/hr		
3	CO_2 single rate test	40t/hr	Lower injection rate achieved	25 t/hr
4	CO_2 single rate test	40t/hr	Lower injection rate achieved	25 t/hr
5	CO_2 single rate test	40t/hr	Lower injection rate achieved	30t/hr
6	CO_2 single rate test	40t/hr	Lower injection rate achieved	30t/hr
7	CO_2 single rate test	40t/hr	Injection not performed due to initial delays and PSV engine breakdown	N/A
8	CO_2 single rate test	40t/hr	Lower injection rate achieved	30t/hr
9	CO_2 single rate test	40t/hr	Single rate test and step rate test combined Lower injection rate achieved	20t/hr / 25t/hr / 30t/hr
10	CO_2 step rate	20t/hr / 30t/hr / 40t/hr		
11	Optional - Alternate CO_2 composition	40t/hr	Not performed – No alternate CO_2 composition	N/A
12	Optional - Alternate CO_2 composition	40t/hr	Not performed – No alternate CO_2 composition	N/A
13	Optional - Alternate CO_2 composition	40t/hr	Not performed – No alternate CO_2 composition	N/A
14	Optional - Alternate CO_2 composition	40t/hr	Not performed – No alternate CO_2 composition	N/A

Figure 20 below illustrates the original timeline used for the planning of the project against the actual operations. As indicated, the project was unable to move Noble Resolve to Nini A location mid December 2022 due to adverse weather and only completed the rig move late January 2023. The project has been able to accelerate and optimise the operations by increasing the transit speed of the PSV (ie reducing the period between each injection cycle). A number of injection cycles were also impacted by weather, either aborting the operations or pausing of those. Following the completion of cycle #5, the PSV experienced an engine breakdown preventing the execution of injection operations for approx. 13 days. Following the completion of the repair of the PSV engine, two injection cycles were then carried out before the project had to demobilise, in line with the storage permit approval.

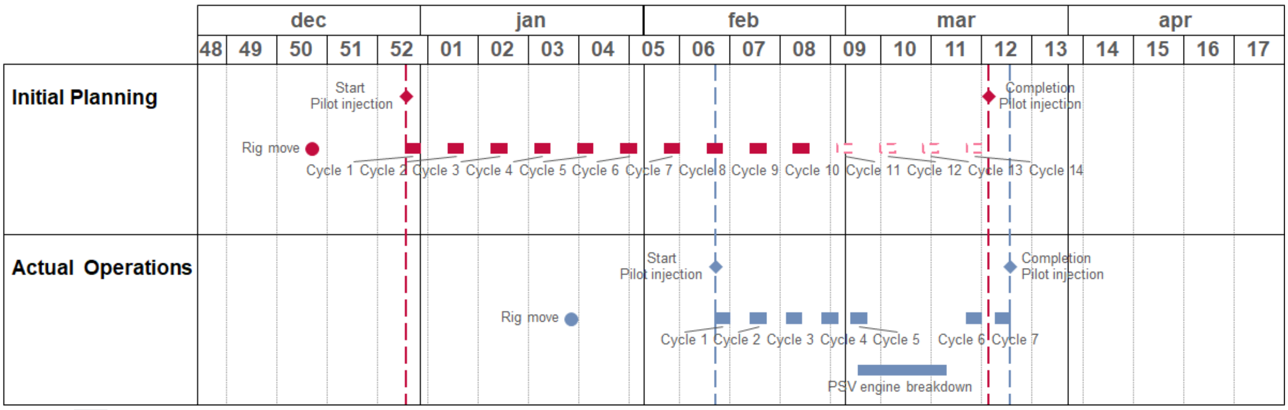

Figure 20: Pilot injection timeline, Planned vs actual operations

Injected CO_2 quantities

Table 6 below summarises the volumes of CO_2 transported for each cycle, together with the actual injected volumes.

Table 6 CO2 volumes transported to and injected into Nini West

	CO_2 Quality	**CO_2 Cargo volume**	**CO_2 Injected quantities**	**Comments**
Cycle 1	Carbon dioxide refrigerated; Gourmet C; Plantline C99	791	523	Injection start delayed due to weather
Cycle 2	Carbon dioxide refrigerated; Gourmet C; Plantline C99	794	413	Injection aborted due to weather
Cycle 3	Carbon dioxide refrigerated; Gourmet C; Plantline C99	800	553	
Cycle 4	Carbon dioxide refrigerated; Gourmet C; Plantline C99	799	655	
Cycle 5	Carbon dioxide refrigerated; Gourmet C; Plantline C99	805	483	Injection aborted due to weather
Cycle 6	Carbon dioxide refrigerated; Gourmet C; Plantline C99	815	717	
Cycle 7	Carbon dioxide refrigerated; Gourmet C; Plantline C99	813	721	Injection paused due to weather
Total		**5,617**	**4,065**	

The above table can also be visualized in Figure 21:

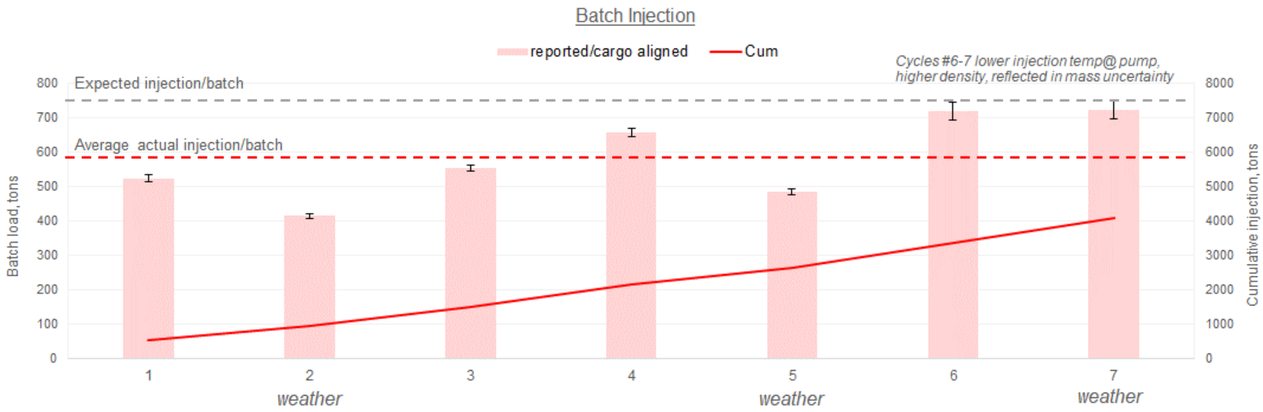

Figure 21 CO2 volumes injected into Nini West

Surface Injection rates, pressure and temperature

Table 7 gives an overview of the CO_2 injection rates, maximum surface injection pressures and the average injection temperatures achieved over the duration of the Pilot test. Figure 22, Figure 23 and Figure 24 illustrate the injection rates, pressures and temperatures for the pilot injection cycles.

Table 7 CO_2 injection rates, maximum surface injection pressures and the average injection temperatures

CO_2 injection cycles	**Injection rates (average)**	**Max surface injection pressure, bar**	**Surface injection temperature (average), deg.C**	**Comments**
Cycle 1	20t/hr / 25t/hr / 30t/hr	277	22	Fluctuations in injection pressure and temperature – injection optimisation test; step-rate test
Cycle 2	25 t/hr	268	25	Injection temperature fluctuations – leak in the steam heater
Cycle 3	25 t/hr	209	27	Leak in injection pump and a trip due to gas in system, otherwise stable injection
Cycle 4	30t/hr	295	23	Stable continuous injection
Cycle 5	30t/hr	283	23	Stable injection, short duration due to weather disruption
Cycle 6	30t/hr	288	20	Stable continuous injection
Cycle 7	20t/hr / 25t/hr / 30t/hr	273	20	Stable continuous injection terminated with step-rate test

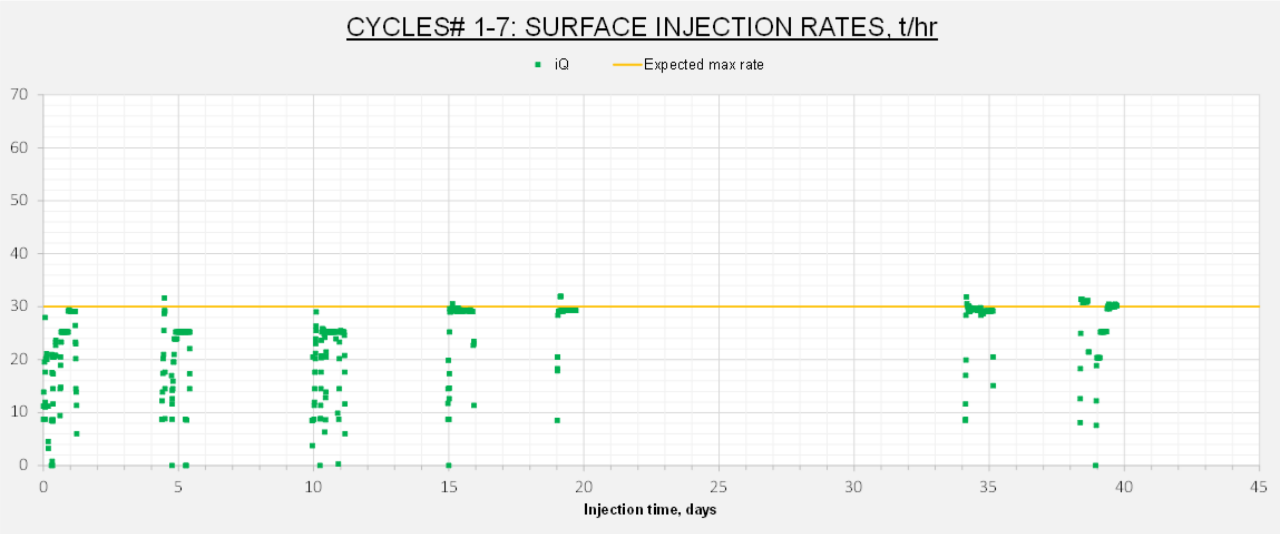

Figure 22: Actual vs expected injection rates. Note that the expected injection rate shown in the figure (30t/h) was adjusted from an pre-injection estimate of 42t/h after the water injection test and the initial CO_2 injection cycle.

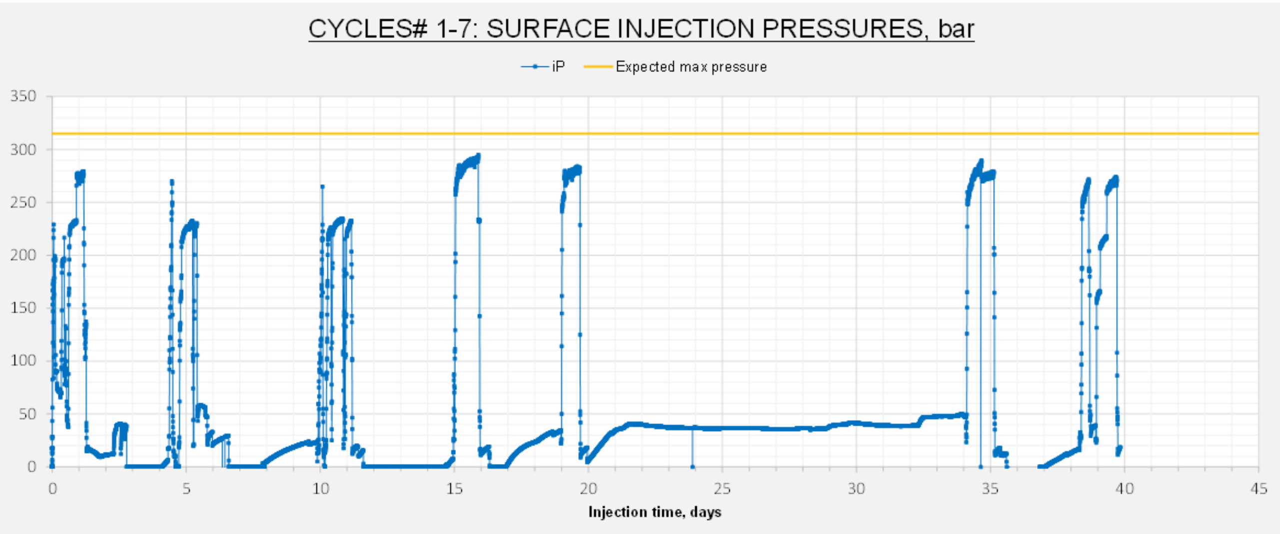

Figure 23: Recorded surface injection pressures and defined maximum injection pressure

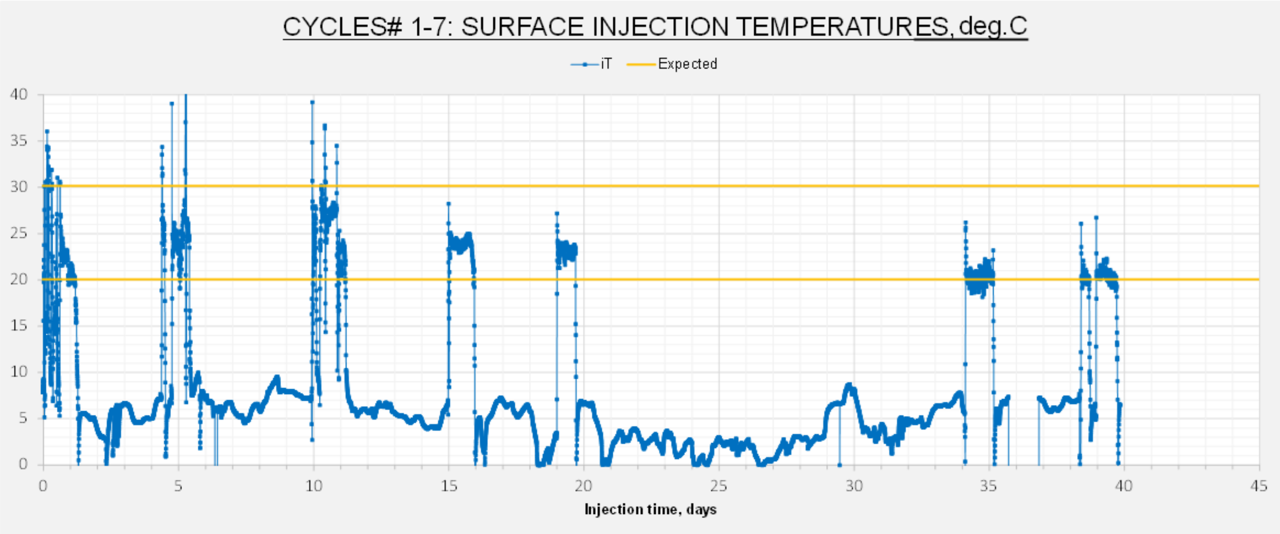

Figure 24: Recorded surface injection temperature. The expected injection temperature window was adjusted to 20-30 deg C after the initial the initial CO_2 injection cycles. Pre injection estimated temperature was 10-20 deg. C which showed difficult to control. Note that higher injection temperatures resulted in less cooling of the near well bore hence reducing the risk of thermal stress in the reservoir.

Downhole injection pressure monitoring

The injection pump for the pilot test displaced a fixed volume of liquid CO_2 against the anticipated reservoir pressure and the friction loss through the coil. The flow performance modelling performed before the pilot injection had shown that for the expected initial reservoir pressure (220 bar) the maximum discharge pressure of the pump of 315 bars would allow for the injection of 40 m3/h of the CO_2 downhole.
Based on the water injection test prior to the CO_2 injection the injection performance of the coil was recalibrated. For the calibrated friction loss of the coil the injection pressure-rate operating envelope (Figure 25) was used as a means of monitoring the bottom hole injection pressure in the reservoir.
The coil pressure-rate curve with the injection pressure constraints defining the safe pressure envelope of the pilot injection operation. With the pump pressure limit of 315 bar and limiting injection bottomhole pressure of 300 bar, the maximum injection rates of 32 t/hr were achieved.

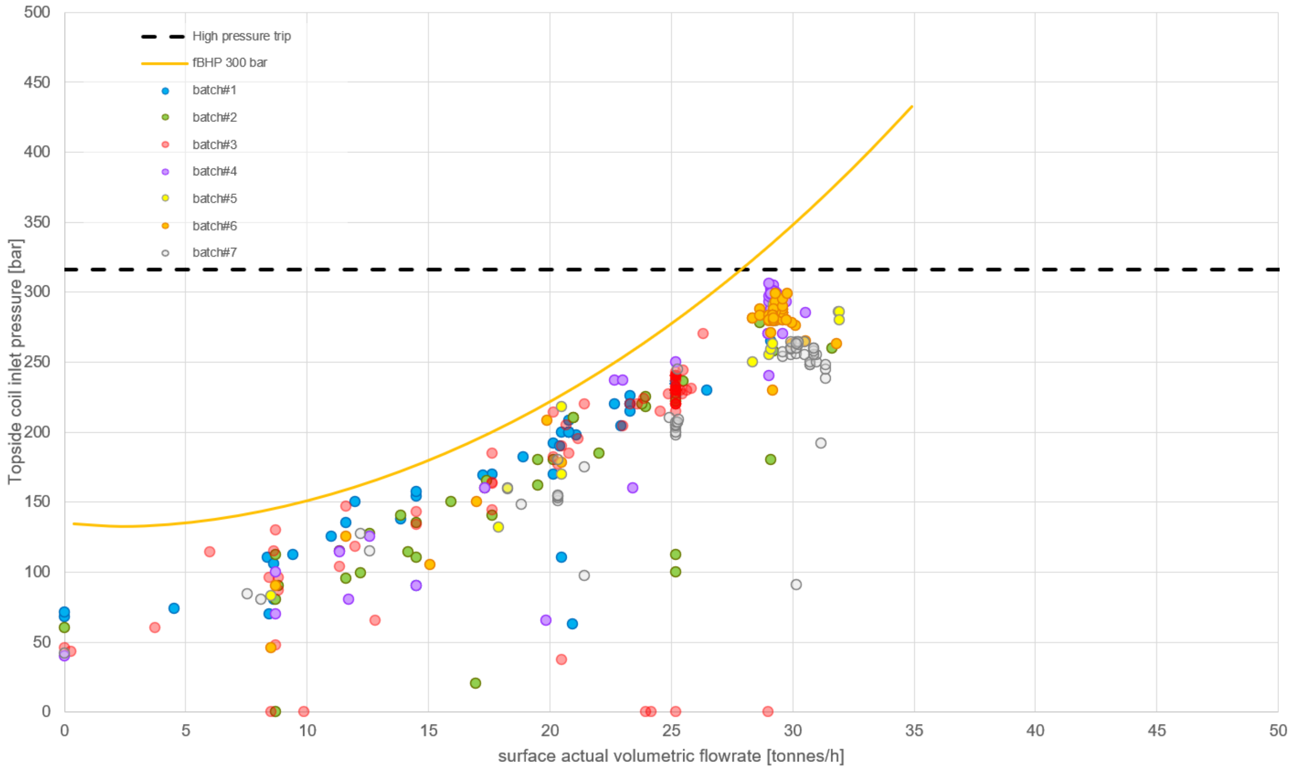

Figure 25: Coil pressure-rate operating envelope with the injection pressure constraints defining the safe pressure envelope of the pilot injection operation. Injection data (flow rate and corresponding surface pressure) for each batch shown by colored dots.

Table 8 summarizes the maximum injection pressures expected through pre-injection modelling prior to the pilot with the actual maximum injection pressures recorded in the test.

Table 8 Surface and reservoir pressures, expected vs actual

	Max well head pressure	**Initial reservoir pressure**	**End pilot reservoir pressure**	**Max pilot injection reservoir pressure**
Expected	315 bar	220 bar	210 bar	<280bar
Actual	294 bar	216 bar	214 bar	282

No deviation of the observed inlet injection pressure build-up was observed during the pilot injection which would indicate reservoir injection pressure approaching the leak-off equivalent pressure (or the fracture re-opening pressure).

Downhole Injection data: Injection pressure and temperature

Table 9 gives an overview of the CO_2 injection rates, maximum downhole injection pressures and the injection temperatures achieved towards the end of each injection cycle. Figure 26 and Figure 27 illustrate the downhole gauge injection pressures and temperatures for all of the pilot injection cycles, including the water injection tests prior and after the CO_2 injection sequence. It is noted that the recorded max reservoir injection pressure is higher than predicted from the pre-injection modelling at a given injection rate, this either reflects resistance in the operation set-up (coil friction) or a lower permeability for CO_2 than water. The measured reservoir pressures, however, show an excellent match to the coil modelling prediction performed after the initial water injection test.

Table 9 Measured downhole injection pressure and temperature

CO_2 injection cycles	Injection rates (average)	Max downhole injection pressure, bar	Downhole injection temperature (at cycle end) deg.C	Comments
Cycle 1	20t/hr / 25t/hr / 30t/hr	282	39	Stable pressure build-up
Cycle 2	25 t/hr	272	42	Stable pressure build-up
Cycle 3	25 t/hr	272	42	Stable pressure build-up
Cycle 4	30t/hr	280	40	Stable pressure build-up
Cycle 5	30t/hr	277	39	Stable pressure build-up
Cycle 6	30t/hr	274	38	Stable pressure build-up
Cycle 7	20t/hr / 25t/hr / 30t/hr	269	38	Stable pressure build-up

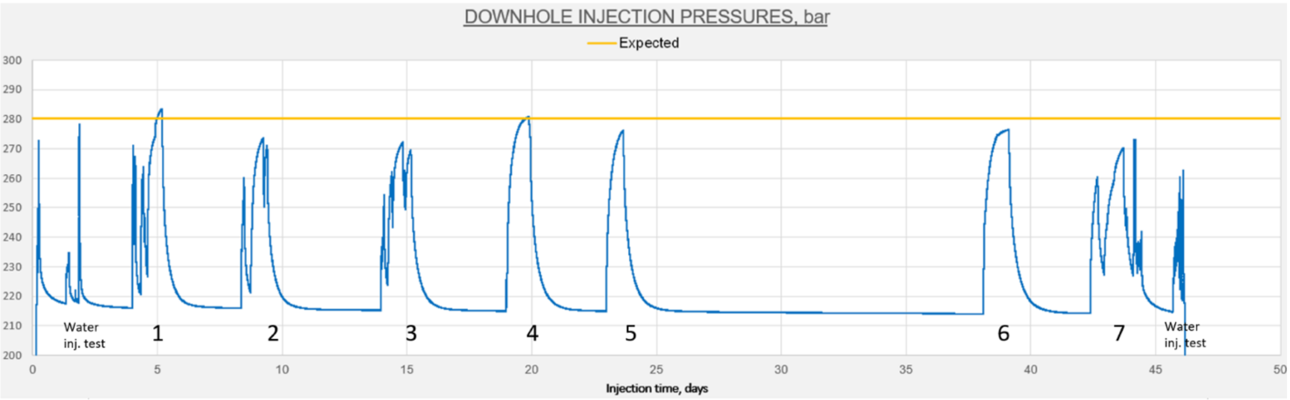

Figure 26 Actual vs expected maximum injection pressure recorded by the downhole memory gauge

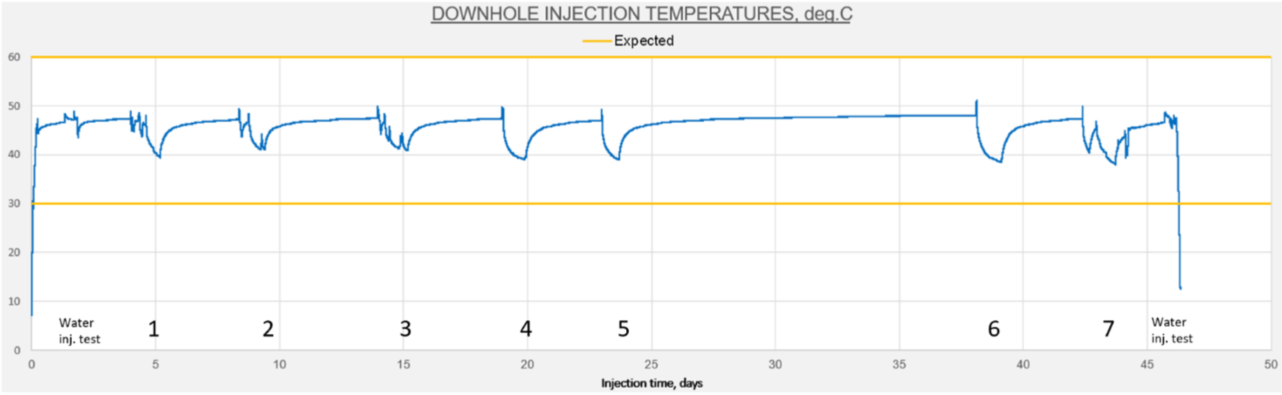

Figure 27: Actual vs expected downhole temperatures recorded by the downhole memory gauge. The expected temperature range as specified from 30 to 60 deg.C

Lessons Learned

Following the completion of the pilot injection, decommissioning of the injection equipment both onboard the PSV and jack-up rig and demobilization from the site, a lessons learned session was organized at the end of April 2023 with the involved partners.
The aim of the session was to try and record the learnings from the planning and execution phases of the project. The learnings are available in Appendix 8 and some of the key CO_2 related learnings are extracted below:

- CO_2 holding time in ISO tanks

Some ISO tanks were filled many weeks ahead of use / injection. This led to pressure build up in the ISO tanks due to the temperature rise and complexity in operating these tanks with different conditions (pressure / temperature). The consequence was the inability to empty the ISO tanks for the initial batches. Learnings were made and the operators onboard the PSV were required to read the temperature / pressure of each ISO tank to allow the supervisor to define the operating sequence of the ISO tanks.

- CO_2 flow metering

Ultrasonic flowmeters were installed on both the PSV and jack-up rig to log and monitor the injection rates. They proved to be unreliable and the project had to implement and rely solely on manual reading and recording of the data from the injection pump. The selection of the right technology is considered fundamental for the next phase of the project.

Dissemination

The Greensand pilot injection operations were officially kicked off through the organisation of the Greensand Injection Event ('First Carbon Storage') on the 8th March 2023. The event allowed the project to be showcased as the first European cross border offshore carbon storage project to reduce CO_2 emissions. The project was honored by our guest of honour, the Crown Prince of Denmark, who gave the order to start the injection. The event was very well relayed by the national and international press, with coverage from Reuters, Bloomberg, BBC News, The Times, De Tijd, L'Echo, Le Soir, AP News, Washington Post, Le Figaro, Le Monde, Welt, Blick. This equates to approximately 550 written articles and 14 million views. The live stream from the injection event is available on YouTube: https://www.youtube.com/watch?v=8boNkULlHKg.

Following the completion of the injection operations, the project presented its preliminary results and learnings to the Danish Energy Agency and the Ministry of Energy on the 26th June 2023. The presentation and its results were well received and left no comments.

WP10 Monitoring

WP10 Monitoring had an overarching role to coordinate and integrate activities between WP11 and WP12 and to contribute to activities in the other WPs. The overall scope of WP10 Monitoring was to develop cost efficient monitoring tools and solutions, and to integrate the learnings into an MMV (Measurement, Monitoring and Verification) Plan for the Nini West storage site development, ready for submission to the authorities. This included a review process of an independent third-party verifier (DNV).
WP10 coordinated and developed the operational requirements for the focused marine seismic acquisition in WP11 as part of the CO_2 injection pilot operation in the winter of 2022/2023. Despite very challenging weather conditions, the seismic operation was successfully completed with a baseline and 2 monitor surveys. The results of the seismic monitoring operation are conclusive and exceeded expectations despite less CO_2 injected than planned (4.100 tons vs 15.000 tons). This spot seismic method is capable of detecting CO_2 in very low saturations in the aquifer of the Nini West reservoir, which was disseminated in various technical papers and presentations.
Recent work conducted by Spotlight Earth after termination of the EUDP work program end of 2023, analyzed additional source-receiver pairs with the ray path travelling through the reservoir near the injection location. In total, 6 more spots are signaling the CO2 presence in the expected locations and 5 more spots slightly outside the CO2 plume with no CO2 signal received. This is a significant improvement of the spot seismic approach, now also statistically and spacially relevant, despite very low amounts of CO2 injected and without adding more source and receiver locations.
It is planned to publish these results in a peer reviewed geophysical journal to facilitate the establishment of the spot seismic methodology for CCS plume monitoring as a proven technology with highest technological readiness level for European projects.

Part of the scope was to develop power generating and data communication buoys that are connected to water column sensors (lander) for detection of CO_2 in the sea water and ocean bottom nodes (OBN) for continuous seismicity monitoring. Initially, it was planned to test these buoy-sensor systems in conjunction with the pilot injection in the winter 2022/2023. However, the post pandemic supply chain crisis significantly affected the lead times of the electronical components for the buoys. As a mitigation measure it was decided early in the project to untangle the buoy-sensor development from the pilot operation. That allowed to develop separate laboratory testing, integration, and demonstration procedures for the buoy-sensor systems later in the project as well as longer procurement times. However, that plan was also abandoned due to significant further delays and cost increases. In the early summer of 2023, it became evident that the required components of the power and data communication buoy could not be delivered, integrated, and tested before project end.
Notwithstanding, the lander was successfully developed and tested in a CO_2 release experiment in sheltered water in Southampton. The lander plays a role in the MMV plan and is planned to be placed at the legacy plugged and abandoned Nini-04 well head location.
Furthermore, WP10 supported the bowtie risk assessment, Environmental Impact Assessment (EIA) study (both WP1) and provided advise on other relevant aspects of the storage site development (e.g., Fast Track Nini West and Nini Full Scale) in conjunction with the plume migration modelling (WP3) and well integrity assessment (WP4).

Coordination of tasks in WP11 and 12

The main activity of this task was to prepare the operational activities and to coordinate the various stakeholders. The seismic operation was permitted and approved as a research seismic acquisition within the Nini production license (4/95), a Joint Venture with INEOS as operator (04/95, INEOS, Wintershall Dea). Spotlight Earth was client to TGS (Magseis Fairfield), using a vessel under contract of INEOS (ESVAGT Innovator) and other subcontractors of INEOS (ROV, logistics etc.). The operation was conducted by TGS according to their project management principles ensuring highest HSE standards. Further, client representatives from Wintershall Dea (on behalf of Spotlight Earth) ensured flexible decision making and communication. A project governance (HSE bridging docs, safety manuals, HAZID, communications org charts) was prepared and implemented prior to mobilization, endorsed by the INEOS internal "Operational Readiness Review" process. It is worth mentioning that this novel operation was very successful, on time, on budget and safe based on the ONE TEAM approach fostering the collaborative spirit of all research partners and contractors in the project.
Any discussion and interaction between WP11 and WP12 was coordinated and documented in a bi-weekly Jour Fix, which especially was important in the risk management and re-scoping discussions following the encountered delays in the buoy manufacturing process. The jour fix was supplemented with physical meetings and online meetings with all monitoring partners or groups of partners as well as meetings between the WP leaders of WP10, 11 and 12.
Furthermore, the dissemination and communication strategy in WP11 and WP12 was coordinated and aligned with all stakeholders encouraging to publish all scientifically relevant content developed in WP11 and WP12.
The list of publications and presentations on the scopes and results in WP10, WP11, and WP12 entail all dissemination activities, published as well as unpublished:

- Szabados, A., Al Khatib, H., Ahmad, N., Dominek, K., Burachok, O., Roth, T., Schovsbo, N.H. [2022]. Greensand Focused Seismic Monitoring for Offshore CO_2 Pilot Injection. 3rd EAGE GET Conference, The Hague 2022.
- Press release: "Teknologisk Institut inspicerer teststeder" 02.05.2022.
- Press release: " Project Greensand udvikler ny metode til måling af CO_2-lager i Nordsøen", 20.12.2022.
- Al Khatib, H., and Mari J. [2023]. Reflected wave enhancement using a single trace and a projection model: application to focused monitoring. 84th EAGE Annual Conference & Exhibition, Vienna 2023.
- Ollivier, L., Roth, T., Al Khatib, H., Morgan, E., Tang, C., Szabados, A., Ahmad, N., Schovsbo, N. [2023]. Breakthrough in operational model: testing offshore focused seismic for CS monitoring in Denmark. 84th EAGE Annual Conference & Exhibition, Vienna 2023 – unpublished poster presentation.
- Press release «Nyudviklet overvågningsteknologi viser sit værd for Project Greensand på Nordsøen», May 2023.
- DTU CCUS summit 06.06.2023, undisclosed presentations by INEOS and Wintershall Dea Greensand pilot injection monitoring and MMV philosophy.
- SEG online workshop on CCS Monitoring 13.06.2023: Presentations by Spotlight Earth and Wintershall Dea on spot seismic pilot operation – recorded.
- IEAGHG CCS workshop Edinburgh: Unpublished poster presentation of NOC and University of Southampton on Lander development 28.06.2023.
- SEG Image 2023 in Houston 28.08.2023: Unpublished presentation by Spotlight Earth and Wintershall Dea about Greensand spot seismic operation.
- IEAGHG workshop on CCS Monitoring 14.09.2023: Unpublished presentation about Greensand spot seismic operation.
- Roth, T., J. L. Mari, L. Ollivier, H. Al Khatib, A. Szabados, J. Grobys, N. Ahmad: Focused seismic monitoring in the Greensand project. EAGEGET 2023 Paris.

- B. Roche, A. Schaap, A. Morris, J. M. Bull, P. R. White, A.Z. Eikeland, M. Frederiksen: Long-term Monitoring of Relict Wells: The development of a real-time acoustic-chemical lander for Project Greensand. EAGEGET 2023 Paris.
- A. Szabados, S. Poulsen: The CCS Greensand Project: CO_2 Pilot Injection and Monitoring. Abstract and unpublished presentation– Baltic Carbon Forum 2023 Riga.
- A. Szabados: The CCS Greensand Project: CO_2 Pilot Injection and Monitoring. Unpublished key note presentation. EAGEGET 2023 Paris.

Technical support and verification of results

The seismic data acquisition, processing, and interpretation workflows of the spot seismic concept were reviewed and verified by an independent technical expert (Prof. Dr. Dirk Gajewski), a senior researcher and retired professor, in the field of applied seismics at the University of Hamburg. Prof. Dr. Gajewski's review confirmed the validity and correctness of the spot seismic concept, and his expert opinion was documented for the project.
The recorded data of the 22 OBNs deployed during the seismic campaign (80 days) were verified by BakerHughes. The main aim of this study was to analyse the full data record in terms of seismicity events and background levels. The CO_2 injection and other operational activities are visible in the data set, but no seismic event was observed. A preliminary interpretation of this fact is that the reservoir was already exposed to long-term water disposal in the NA-05 injector well exceeding the initial reservoir pressure. As a result, the injected CO_2 did not change the stress field in the near well bore area. Some abnormal data readings were observed in some OBNs, and they coincide with the unexpected movement of the OBNs of up to 6 meters during stormy conditions. In addition, it is recommended to collect seismicity baseline information for a minimum of 6 months prior to the first injection.
The sensor data of the lander recorded from the wet test in the harbour of Southampton was published (Roche et al. 2023) and builds on the peer reviewed and published sensor assembly of the STEMM experiment. Hence, the sensors work accurately and are capable of detecting CO_2 in low quantities.

Monitoring Plans

Based on the assessment of the EU Directive, DNV comments, ISO standards, market surveys, vendor meetings, and other activities a set of monitoring techniques have been assessed.. The documents developed have been issued to the authorities in conjunction with the Nini West Storage Permit Application of the Iris License and are subject to authority approval.

In total, 5 monitoring related documents were developed and have been verified and endorsed by DNV:

1. The Monitoring Plan for the Pilot Injection. It contains spot seismic monitoring, plume migration simulation, P/T gauges in NA-05 injector well and NA-03a observer well, P/T gauges at the well head, other sensors along the flow line and manifolds, as well as environmental seabed sampling pre and post injection.
2. The MMV Plan for Storage Site Endorsement includes the newly developed monitoring concepts and solutions such as spot seismic and lander, subject to authority approval.
3. The Predictive Maintenance Plan (PMP) for Storage Site Endorsement is a supplemental document to the MMV Plan. It describes the workflows of the yearly recurring activities regarding monitoring and verification such as the fluid flow simulation and seismic acquisitions.
4. The Corrective Measures Plan outlines the corrective measures to be taken in case of significant irregularities occur, as per threshold definition of the MMV Plan.

5. The Monitoring Governance includes a proposal to a reporting scheme, description of roles and responsibilities of the operating units related to monitoring and elaborates on expected monitoring parameters and defined thresholds for triggered actions.

WP11 Monitoring tools and operation

The objective of the work package was to develop cost efficient monitoring tools for CO_2 subsurface plume migration and leaks to the seabed and waterbody and demonstrate these during the pilot injection.
The original objective was to ensure that the sensors in the monitoring tools became autonomous systems powered by smart power buoys. However, the post pandemic supply chain crisis significantly affected the lead times of the electronical components of the buoys and ultimately made it impossible to produce the smart power buoys within the project lifetime (for more information please see WP12). Therefore, the scope of work package 11 was adjusted to focus on:

- Focused seismic baseline and two surveys were performed in connection with the pilot injection, but without the connected nodes.
- Development, testing, and deployment in sheltered waters of the lander including water column monitoring sensors and laboratory testing of transfer of data using 4G.
- Development of nodes for wired connection with the aim of transferring data to the surface and onwards to onshore.

For dissemination activities performed as part of the monitoring programme, please see the list in the section "Results of WP10: Monitoring".

Focused seismic

One of the most critical aspects of a CCS MMV (Monitoring, Measurement, and Verification) plan is to determine the frequency of monitoring a CCS field with active seismic methods. Combining the predicted extension of CO_2 plumes (i.e., a dynamic model) and focused monitoring can provide a nimble and efficient response to this question. By analysing the output of the dynamic model, we can identify where and when to focus seismic monitoring, thereby validating the primary reservoir hypothesis while excluding worst-case scenarios and assessing identified risks. Focused seismic monitoring aims to monitor the CO_2 conformance in these selected areas of the reservoir. It is a light monitoring solution that (compared with conventional 4D monitoring) reduces environmental and financial costs by allowing surveys to be performed more frequently with fewer constraints in time (short surveys can, e.g., be carried out during winter in the North Sea) and space (not impacted by maritime traffic or windfarms). In this project, the objective was to design and conduct a focused seismic survey program for the pilot injection and to demonstrate the value of the concept offshore.
A survey design was made for the pilot injection of up to 15.000 tons of CO_2 into the NA-05 well. The CO_2 plume was assumed to mainly evolve around the mid-point of the perforation length of approximately 50 m along hole. Five spots were designed to monitor this injection: one at the injection point and four 150 m away from the injection point. These four spots were for monitoring the vicinity of the injection spot. Additionally, two control spots were placed away from the injection point to serve as reference spots.

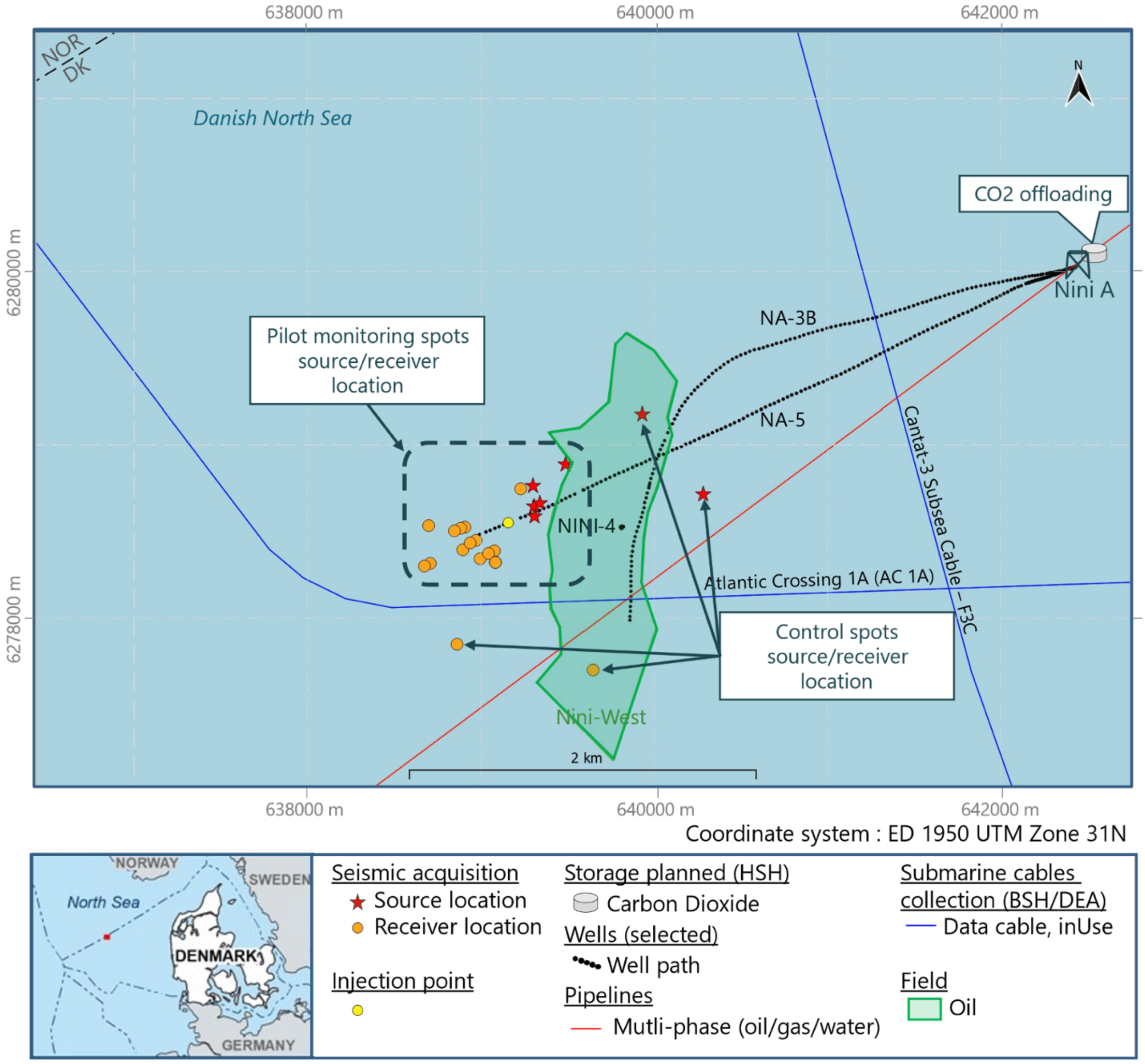

Figure 28:: Final survey design for the seismic monitoring of CO_2 injection during Greensand pilot monitoring, from December 2022 to March 2023.

One seismic baseline and two monitors were acquired in the North Sea between January and March 2023 by TGS (Magseis Fairfield), using the platform supply vessel INNOVATOR of ESVAGT. The survey design makes use of one source and one receiver location (with the receivers being ocean bottom nodes, OBNs, placed on the seabed) to monitor each spot in the subsurface. The seismic source consisted of three 200 cui airguns, shooting up to 80 times at each of the 7 stationary source locations. A total of 1208 shots out of the 7 source locations and one shot line were acquired during the baseline. 22 Mass III nodes (OBNs) were deployed by an ROV at 20 different positions. One node was retrieved after the first shooting sequence for quality control and to test the node and airgun set-up. The other nodes remained at seabed level until completion of monitor 2. The baseline survey and monitor 2 were each performed in approximatively 2 days due to ROV operations involved for node deployment and retrieval, whereas monitor 1 needed 12h operational shooting time only. Altogether, 2265 airgun shots were fired, including the required ramp-up procedures.
The HSE standards of the survey were very high. A HAZID risk assessment was conducted prior to the operation. There were no LTIs during the period. Personnel were diligent in following the procedures. Toolbox

meetings were held before any personnel movement on deck. Equipment handling was tested in sheltered water (harbour of Esbjerg) before offshore work commenced, and procedures were reviewed and adopted when necessary.

The precision of the positioning of the vessel and in-sea equipment (airgun and nodes) was around 1 m, much less than originally required (5 m). The technical standards of the crew were outstanding, no equipment failures occurred during the survey. Overall, it was a safe operation and yielded a quality seismic data set that is fit for the purpose.

In addition to the high quality of the seismic data, the success of this monitoring is also due to the processing sequence that has been set in place. As the expected 4D effect is very small, the usual processing sequence wasn't enough to increase the signal-to-noise ratio. The new sequence, based on de-migration and available data from the 3D survey (NODAB97 migrated stack and velocity model) was a way to increase the denoising of the newly acquired data.

It was then possible to detect the arrival of the CO_2 plume around the injection point inside the reservoir. As expected, CO_2 was detected at spot 1 and not detected in spots 2, 4, 5, 6 and 7. Contrary to the model's predictions, CO_2 was detected at spot 3. An update of the fluid flow model explained this difference, the CO2 apparently entered the reservoir mostly in the upper part of the perforation and flowed slightly updip. The processing sequence established for the spot seismic data is efficient and robust as several antennas in the same spot gave the same results.

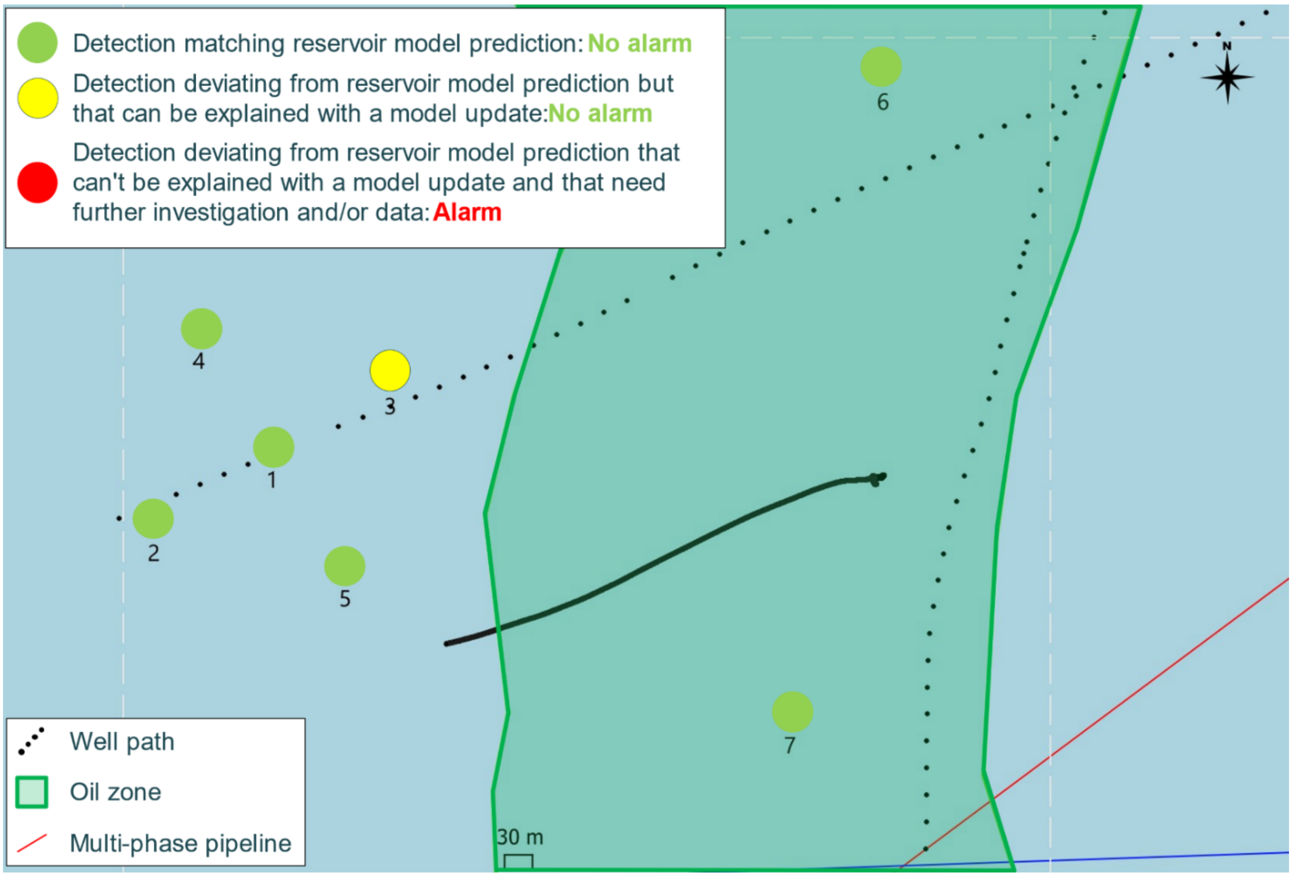

Figure 29: Map of the detection results compared with the model predictions between baseline and monitors. Injection was carried out at spot 1 location. As expected, CO_2 was detected at spot 1 and not at spot 2, 4, 5, 6, and 7. Contrary to the model's predictions, CO_2 was detected at spot 3. An update of the model explained this difference.

Connected ocean bottom nodes

The task was to develop a system, where three ZXPLR nodes would be deployed permanently on the seabed, and it should be possible to charge and download data from them without retrieval. Charging and data download would take place via a wave buoy. The wave buoy would have a 4G modem for data communication, a GPS receiver to be able to get a 1PPS signal for clock tuning, and a generator for charging a set of batteries for internal use and for charging the nodes. Communication would utilise fibre-optics due to the possible length of the cables as the system was to be specified for an operating depth of up to 500 m.

An interface box was designed that would connect to the three nodes by using a waterproof connector developed specifically for this purpose. The interface box would also be directly connected to the wave buoy by an integrated cable that would manage the transfer of data signals and charge the current for the contained node batteries. The interface box would be deployed along with the nodes, maintaining specific distances between them, by using a frame lifted down from the operational vessel. Once on the seabed, an acoustic signal would trigger a mechanism on the deployment frame, releasing the nodes and interface box. The deployment frame would then be recovered to the operational vessel, leaving the node system in place on the seabed. The frame is then ready to be used at the next node drop location.

The developed interface box contained a Z-system Node Board for communication and a Charger Board for charging the nodes. In addition, it contained a custom-designed board for adapting the optical 1PPS signal to the electrical signal for the Node Board, as well as charging a couple of internal batteries.

A custom-designed board was developed by and received from Resen Waves. It i.a. had an electrical-to-optical converter for getting the 1PPS signal from a GPS receiver to the interface box via fibre-optic. In addition, a GPS receiver and a 4G Modem was supplied. Unfortunately, the electronical components were delayed, and therefore, the ongoing integration, programming, and testing of the connected OBNs in the TGS laboratory in Stavanger was aborted in mid-October 2023 prior to completion of the task.

Sensor system for monitoring the water column

The purpose of the Greensand water column monitoring lander is to continuously monitor a given area on the seabed for signs of leakage from the underlying reservoir. The lander will be deployed at higher risk locations such as relict wells, and it is able to detect both gaseous and dissolved CO_2 seeps in a timely manner. The lander was designed to incorporate two complementary systems, acoustic and chemical, working in tandem to identify, verify, and quantify any potential leak.
The lander's acoustic system uses an onboard multibeam echo sounder (a type of sonar) to regularly survey the area in front of the lander, sending out a high frequency (500 kHz) acoustic signal and measuring the strength of the returning echo as it bounces off objects in the water column. Gas bubbles produce very strong acoustic reflections making them easy to identify up to 150 m from the lander. However, acoustically it is not possible to detect dissolved CO_2.
The lander's chemical monitoring system can detect changes in the marine carbonate system caused by dissolved CO_2. Therefore, it perfectly complements the acoustic system. This is enabled through a series of sensors monitoring pH, total alkalinity (TA), nitrate, local currents, oxygen, temperature, salinity, and pressure. Of particular interest are the pH, TA and nitrate sensors which run as part of "lab-on-chip" (LOC) devices that perform complex chemical analyses on the seabed with low power and reagent consumption. The complete alkalinity system underwent targeted development within the project, resulting in enhanced future versions of the technology for CO_2 monitoring.
In late 2022, the capabilities of the Greensand Lander were demonstrated during a 2-week deployment in Empress Dock, Southampton (UK). The lander was placed on the seabed, with power and communication

cables running to a nearby test facility. Once baseline measurements had been established, a controlled amount of CO_2 was released from a sintered pipe on the seabed. The rate of gas release and the distance from the lander varied throughout the experiment to encompass a range of situations the lander could encounter in the field. This work was presented at EAGE GET 2023 in Paris, and a peer reviewed publication to follow.

The lander demonstrated its ability to detect even the smallest scale leaks. The acoustic system can detect release rates as low as 1 L/min (1000 Kg/year) at over a 100 m range. Furthermore, the lander's chemical systems were able to detect minute changes in the composition of the seawater brought about by tidal changes altering the current flow to and from the lander.

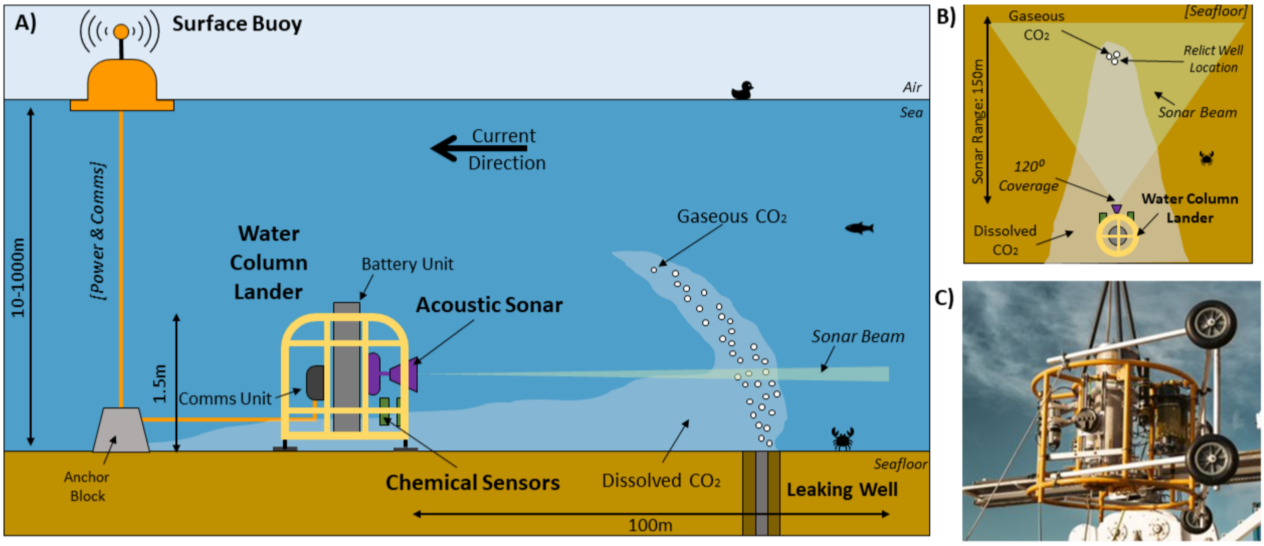

Figure 30: A) conceptual diagram of the deployment of the Greensand water column monitoring lander. The lander consists of an array of chemical sensors that detect dissolved CO_2 in the water column. An acoustic sonar surveys the area in front of the lander for CO_2 bubbles. Together, the two systems allow for the continuous monitoring and verification of higher risk sites such as relict wells. The lander will communicate with researchers on land via a surface buoy, and an anchor block will ensure that it is in place. B) conceptual diagram of the lander in the field as viewed from above. C) the Greensand water column monitoring lander being lowered into the water as part of the controlled release wet test.

The team considers the lander ready for deployment in the Nini-West site in 2024. However, the team notes that a communication buoy must be acquired for near-real time communication - either from the commercial sector or developed with future partnerships and integrated. All deliverables for this section of the project have been completed (please see the appendix Water Column Monitoring Results for full details).

WP12 Power and Data

The purpose of the Power and Data work package was to develop an autonomous power supply system for sensors and nodes deployed offshore at the seabed, including a solution for transmission of monitoring data to the shore and a user interface for data management. In addition, strategies for obtaining monitoring data onshore during later phases of Project Greensand, e.g., full-scale operation and post-injection were to be developed.
A data management tool along with a tool for visualisation of relevant parameters from the water column monitoring sensors from WP11 were successfully developed, and different strategies for obtaining data onshore were described.
The buoy production, testing, and integration processes were challenged by delays due to the global supply chain crisis. Mitigation measures were taken, but ultimately, the production of the buoys had to be aborted.

The delays and cost increases incurred made it impossible to finish the production and demonstration within the project lifetime. A project change request applying for the discontinuation of the buoy production, integration, testing, and deployment was submitted and granted. The objectives of the updated work package description have been obtained.
For dissemination activities performed as part of the monitoring programme, please see the list in the section "Results for WP10: Monitoring".

Smart power buoy development

The initial scope was to produce two smart power buoys and test and optimize the power and data handling system on the buoys. The buoys were to be integrated with the sensor systems and tested along with the sensor systems in sheltered waters and offshore as part of WP11. However, the original plan, which required the production, testing, and deployment of the buoys to be finalised in time for the offshore pilot operation in winter 2022/23 had to be abandoned to provide more time for the production and testing of the buoy-sensor systems. Due to further delays and cost increases in the buoy production, it became evident in the summer of 2023 that the buoys could not be produced, integrated, and tested within the project lifetime.
That is why the main results of the work on the buoys primarily are the designs of two different buoys and elements or parts of the buoys. The control electronics and software are the most important parts.
The two buoy systems that were designed are:

- A buoy producing power from wave energy for the Lander.
- A simplified battery powered buoy for the connected nodes, where the batteries replace the power generating mechanism in the buoy.

Both systems were designed with cabled connection to the sensors on the seabed and wireless connection for communication and data transfer to onshore. The battery powered buoy was introduced to circumvent the long lead times for components essential for the power generating buoy, in the hope that the buoy would be ready for integration and demonstration along with the ocean bottom nodes in time for the seismic acquisition during pilot operations in the winter 2022/2023. The procurement of elements to produce the battery powered buoy also faced delays making it impossible to finalise the production of this buoy in time for test and demonstration.
New electronics for intelligent power control were developed and tested. The system was designed to secure stable power supply and distribution to all connected sensors, electronics, and instruments, and – in case of a power shortage – prioritize power to the most essential functions and sensors. The electronics also allowed the systems to be controlled remotely and provided reports on the status of the connected sensors and components of the buoys. An initial version of a Scada system was developed to provide an overview of the status of the connected systems.

Data management tool

Objective: The objective of this work is to develop a data management tool tailored to handle data gathered by underwater sensors. These sensors collect various information, which is then transmitted from the seabed to the surface through cables to a buoy. Subsequently, the data is relayed to the shore. The data transmission to the shore can occur either through a 4G/5G connection on the Nini platform or via a direct satellite link. During the development process of the buoy and data transmission interface, unexpected issues emerged, resulting in lack of data acquisition within the project. However, a similar dataset was provided to facilitate the construction of a web platform and the development of algorithms designed to analyze the data and identify instances of CO_2 leaks.

Data collection: The data collected within the project can be categorized into three types: Seismic, Sonar, and Chemical data. Seismic and Sonar data necessitate expert assessment to interpret their significance. For the Chemical sensor data, algorithms have been created to identify thresholds for measurements that can be classified as “unusual” or a potential CO_2 leakage.
The chemical sensor data employed in the project included a controlled CO_2 leak with an increasing flow rate over time. This information was leveraged to devise an algorithm capable of detecting whether a CO_2 leak was transpiring. Subsequently, seismic and sonar data is used to enhance the understanding of CO_2 leaks.

Data handling: The outcome of the algorithm's assessment regarding the presence of a CO_2 leak is presented through a web application. This web app is designed as a scalable containerized application, meaning it can adjust its resource usage according to demand, minimizing costs during periods of low activity but swiftly accommodating increased usage, such as during a CO_2 leak event when numerous users seek to understand the situation.

Visualization: The web platform is thoughtfully designed to provide a user-friendly interface that efficiently offers a comprehensive overview of the various chemical sensor outputs and their corresponding threshold values. The system adeptly flags any values that fall outside the acceptable range, indicating deviations from the normal range. Furthermore, the platform furnishes essential information regarding the operational status of all sensors, ensuring real-time data transmission to the shore. Once the sensors are deployed on-site and project data consistently falls within acceptable parameters, it is crucial to optimize the system to suit the site's specific conditions. This optimization ensures that the appropriate alerts are triggered in the event of a CO_2 leakage.
If no sensor data is received or transmitted, an automatic alarm mechanism is activated. This alarm system is specifically designed to promptly alert administrative users, enabling them to investigate and rectify any potential issues that may arise. This proactive approach ensures the continuous and seamless operation of the sensor network, maintaining its integrity and data flow consistency.
The web platform is designed in a user-friendly manner, providing a convenient interface to comprehensively display various chemical sensor outputs and associated threshold values. It efficiently identifies deviations from normal values. Additionally, the platform allows for data segmentation, enabling users to focus on specific time intervals for in-depth analysis.

Data access: All chemical sensor data is stored in a relational database, organized into database tables. The application is designed to facilitate the inclusion of additional sensors at specific locations or for new areas, such as Siri, Cecilie, Stine, Tyra, or Nini West. The seismic and sonar data is organized so it quickly can retrieve data from a specific period in case of a potential CO_2 leakage.

Perspectives: A very interesting topic pertains to the commercial evolution of the web application, transitioning from a pilot project to a fully-fledged commercial solution. A noteworthy discussion arose, prompting further investigation into the liability associated with the insights generated by the system. Key questions include identifying responsibility in cases where the system fails to detect a leak and conversely, determining accountability when the system triggers a comprehensive site investigation.

Strategy for data harvesting

The overall objective of the work on the data harvesting strategy was to analyze possible system architectures, communication methods below and above the sea surface, data frequency and amount, and power supply options that could be used in the future. Below, a summary of the results is presented. More information can be found in the appendix *Analysis of Data Harvest Strategies*.

The analysis of system architectures presents the different options for establishing a communication link from the seabed to onshore and describes the pros and cons of the architectures. The presented system architectures span period pickup by autonomous vehicles as well as multi-hop systems, where buoys and nearby platforms are used to relay the data messages onshore.

The primary underwater communication methods were identified as acoustic and optical. Underwater acoustic communication works at low frequencies and small bandwidth, resulting in low data rates. Its main advantage is the operating range, which can reach several kilometers. This range can provide good flexibility for long-term operation where multiple units can communicate with a central hub. In general, contrary underwater optical communication can achieve higher data rates at lower power consumption but at a much shorter range.
For communication above the sea surface the possibilities are all based on electromagnetic waves. The analyzed options include the high frequency (HF) technologies commonly used for radio communication and the automatic identification system (AIS), cellular, and satellite. HF can provide long range and low data rate communication on both licensed and unlicensed frequency bands. The LoRa technology could also be an option where the hardware is low cost and low power. Cellular options include the high data rate 4G, but also NB-IoT that is designed for low data rate and power consumption. However, cellular requires connection to an existing network operated by a service provider. Satellite is an obvious option where the distances in the system can be ignored, but its main drawback is the very high cost of data plans.

Part of achieving an efficient data collection system is minimizing the transferred data, while maintaining a satisfactory information level. Therefore, the analysis also suggests methods of minimizing payload and strategy for which data to send and when. Both have heavy focus on enabling a low-cost, long-term monitoring operation, with an appropriate fallback solution in case of CO_2 leaks.
The last part of the analysis suggests powering methods for both the lander and auxiliary systems required for the monitoring system. With low power communication technologies and minimal data transfer the power system can be reduced in size and complexity, further enabling a low cost and maintenance monitoring system in the short and long term.

WP13 Consortium Management
The management of the Greensand Phase 2 was under the responsibility of the WP13 and consisted of INEOS, Wintershall Dea as the Greensand lead partners together with Energy Cluster Denmark (ECD). Monthly reports, monthly project WP lead meetings and Steering Group meetings was handled by the ECD Project Management Office (PMO). Other key activities included handling the project finances, guiding the consortium partners to ensure compliance, external dissemination, general bridging between the consortium partners but also between the key partners INEOS Energy and Wintershall Dea and the EUDP. The list is long stressing the need for 3rd party PMO office in such large state/EU funded projects. In other words, without the very important contribution from the ECD, the Greensand Phase 2 would have suffered significantly.

Other activities managed through WP13 was continuous dissemination of the project progress, results and outlook at mainly European CCUS related conferences but also in the US and the East Asia region. Public meetings attendance and CCS event arrangement includes Folkemødet on Allinge,Bornholm and Energi Folkemødet in the City of Esbjerg. A website (www.projectgreensand.com) was also prepared and launched through the WP13.

The final before task of the WP 13 is deliver this Final Close-out report of Greensand Phase 2 to the EUDP and other important stakeholders.

6. Utilisation of project results

Project Greensand Phase 2 is not the final step of the CO_2 storage project, and the innovation height of the project should be evaluated based upon the successful offshore pilot, and from here leading to a subsequent full-scale project. Although the full-scale development of Project Greensand, with direct offshore CO_2-transferal, will be the first of its kind in the world, it utilizes multiple technologies and operational procedures commonly used worldwide and in this part of the North Sea. The innovation of Project Greensand Phase 2 was therefore the combination of the technologies rather than the technologies themselves.

Since the Project Greensand operational concept has been proved, it will lead to substantial impact on the future of CO_2 Transport and Storage, as the implementation of CCS will be accelerated. The main areas where Project Greensand has been moving the technologies are:

- Utilization of existing oil & gas infrastructure
- Transport of large quantities of CO_2 by ship
- Next generation monitoring technologies

Utilizing the project results

Results from Project Greensand will be utilized in several research, innovation, demonstration projects, in Denmark and abroad. Ultimately it will most likely pave the way for commercial CCS value chains in Denmark and in the EU through collaboration on regulatory, technical and commercially levels in Denmark and cross-border where it makes sense. Below is mentioned further projects standing on the should of the EUDP supported Greensand Phase 2 project, the offshore monitoring and CO_2 injection pilot itself but equally important all the additional results from the work packages established within the Greensand Phase 2 Scope of Work.

As direct continuation and standing on the results and learnings from Greensand Phase 2, the Key Partners INEOS Energy and Wintershall Dea (now Harbour Energy), maturation of the first commercial Greensand CCS project, Project Future, is underway. Provided the necessary and timely approvals are obtained, then this project will be in operation late 2025/early 2026 and be the first commercial BECCS project operational in the EU. The customers will primarily be several of the Danish Biogas producers that through addition of liquification facilities on their plants of the today already captured CO_2 can deliver significant amounts of biogenic CO_2 to sustain a commercial BECCS Project Future. This will lead to reducing the Danish GHG footprint as represents negative emissions but also having Project Future as a proof case it will accelerate the CCS industry in Denmark and the EU, motivate the CCUS academia even further and the technology providers. Finally, it should be mentioned that part of the customer base for the Project Future originates for EU based biogenic CO_2 sources. The below figure 31 provides a general overview of the Project Future value chain and Figure 32 provides a provides a general map overview.

Three projects which has been promoted on the back of the Greensand Phase 2 outcome is listed:

Greenport Scandinavia establishes commercial CCUS value chains across geography and industrial sectors by development of a Danish CO_2 hub in Northern Jutland centered around Port of Hirtshals. Ineos and Wintershall Dea, asset owners in the Nini field, has joined a consortium whose members have signed an agreement to jointly mature and pursue the Greenport Scandinavia project.

The project aims to establish a CO_2 hub at the premises of Port of Hirtshals on the Danish North Sea coast. Greenport Scandinavia is meant to serve as a collection point for CO_2 generated during the production of biogas in regional plants. It will then be transported by ship to Project Greensand to be permanently and safely stored. Approximately 1.5 million tonnes of CO_2, some of which will come from countries along the Baltic Sea, are to be sequestered each year in this way. Using biogas will result in negative emissions, which can make a significant contribution to achieving Denmark's climate policy goals.

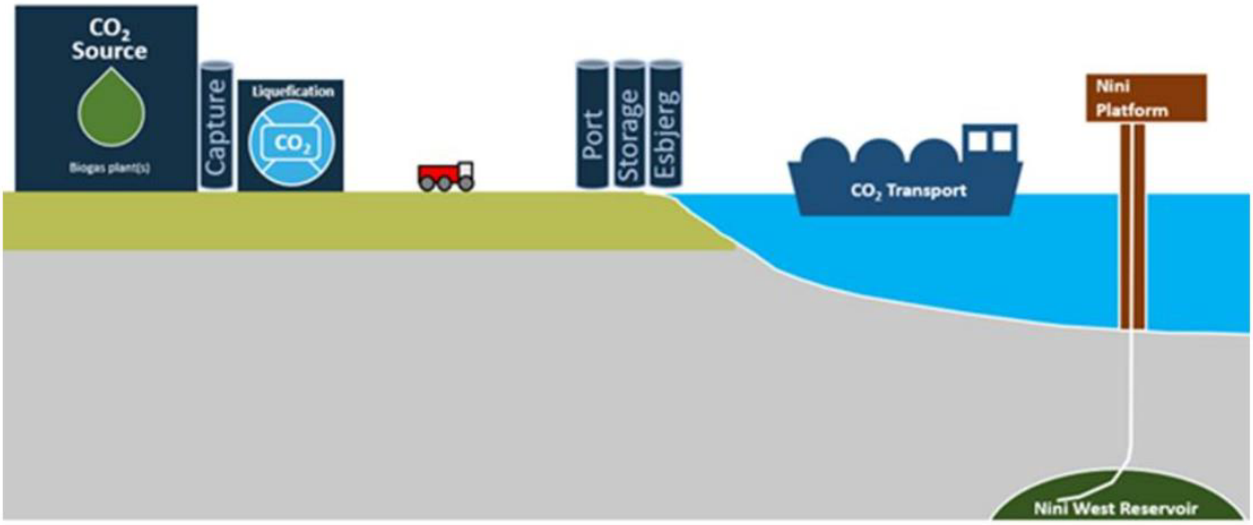

Figure 31: Project Future commercial CO_2 CCS value chain

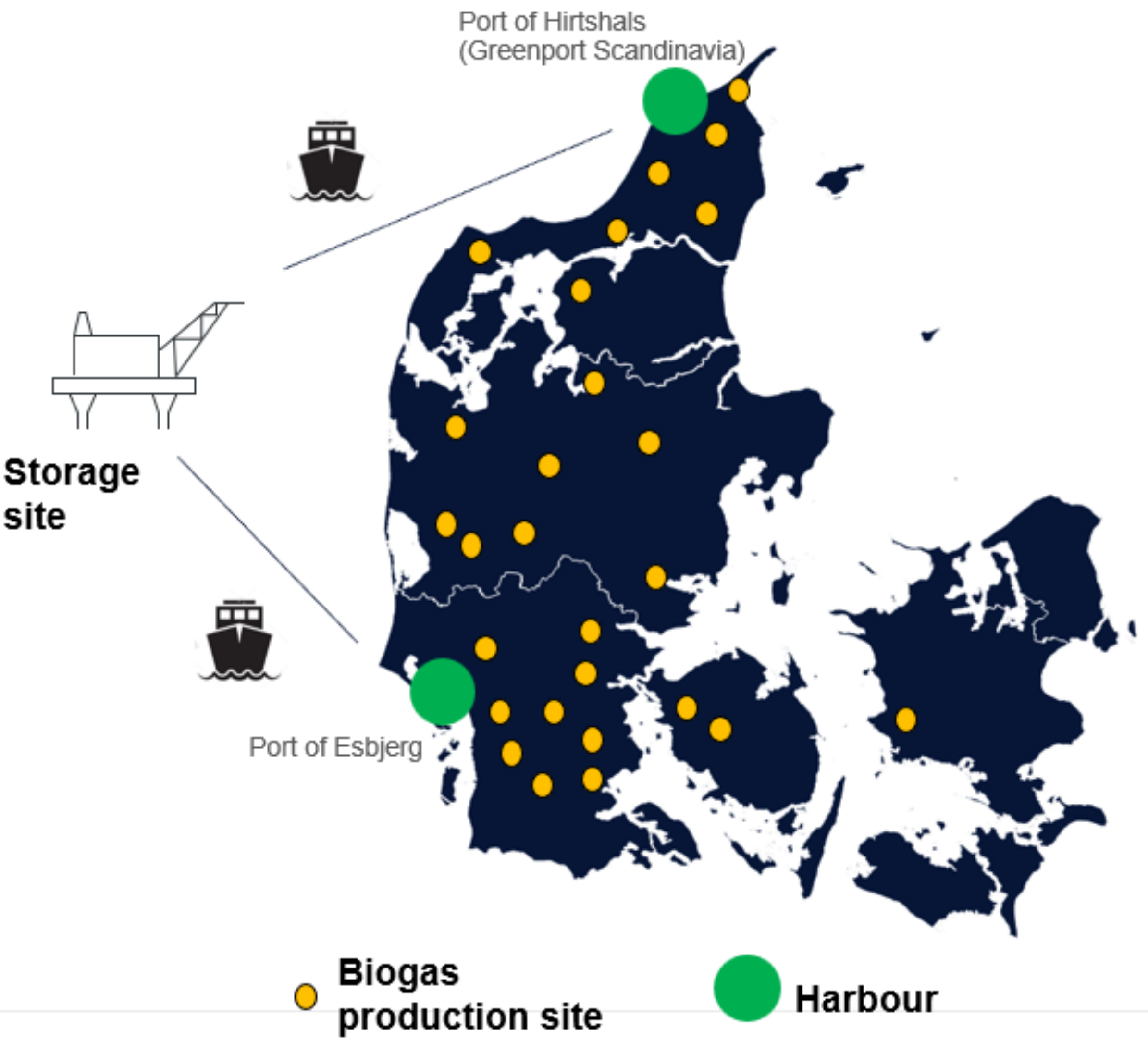

Figure 32: General map overview of the Project Future. Two commercial ports indicated as two suitable sites for interim storage of The CO_2 until loaded on a new build CO_2 carrier ship, sailed to the Greensand area and injected directly from the ship into the Nini West reservoir (tested successfully in the Greensand Phase 2 injection pilot).

CO_2 Hubs at suitable commercial ports throughout Europe receiving and distributing CO_2 for permanent and safe storage is key to facilitate a cost effective and operationally flexible CCS industry in Europe. The Greensand key partners together with other partners in the Greenport Scandinavia project have started the maturation of such following the successful outcome of the Greensand Phase 2. The Port of Hirthals (Figure 32) will be the site for construction and operation of the CO_2 import/export terminal connected to the necessary CO2 transport infrastructure (Ship, Truck, Train and Pipelines) to facilitate safe and permanent storage of CO_2 for the European costumers. Figure 33 illustrates the outlook for the fully developed Greenport Scandinavia Hub (further info can be found on www.greenportscandinavia.com).

Finally, the hub will designed such that, as more and more Danish CO_2 storage sites are being matured in the vicinity it will be connected to these if possible and sensible to these to harvest the economies of scale to the benefit of the emitters.

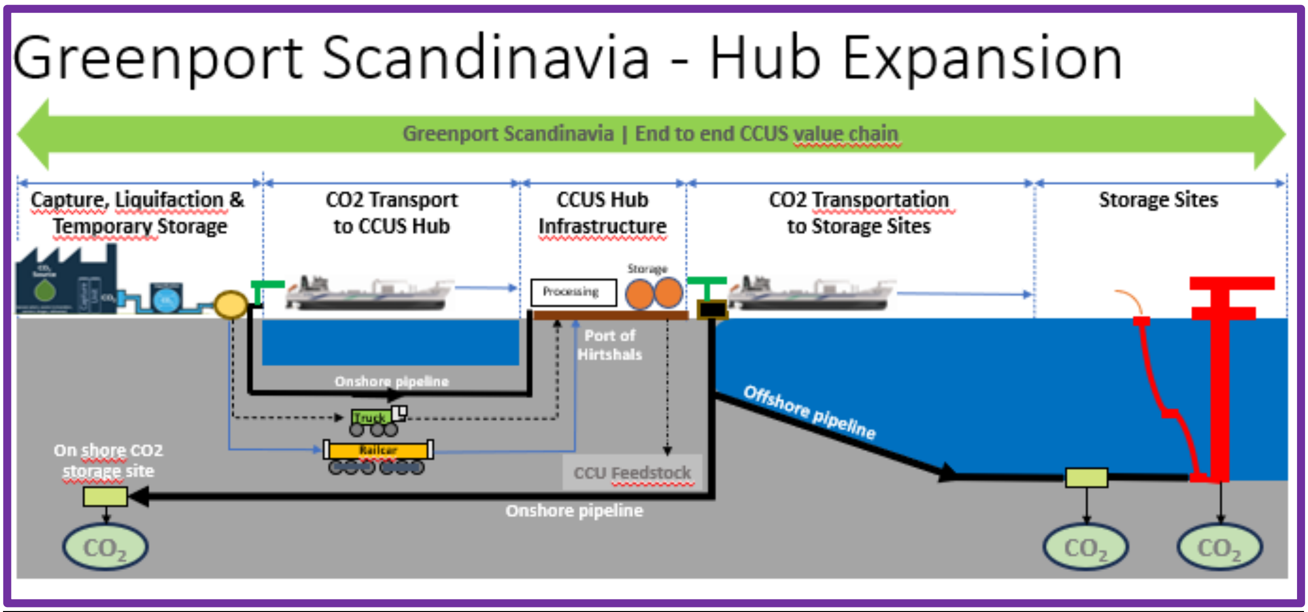

Figure 33: Greenport Scandinavia CO_2 terminal with various means of infrastructure and multiple storage sites connected.

Further in an international perspective, another CCS project Poseidon in the southern UK offshore sector have adopted the Greensand Phase 2 CO_2 pilot injection and monitoring concept to further derisk their storage Poseidon site and harvest the crucial learning necessary to deliver a robust and safe commercial project. See further details CO2 injection test on schedule at license encompassing 'UK's largest depleted gas field' - Offshore Energy (offshore-energy.biz)

Market foresights and commercial impact of CCS in Denmark

Accordingly, to IEA's Annual Energy Outlooks for many years and latest the 2023 Outlook, CCS is one of the technologies which will be vital in ensuring that international climate goals are met. Many emission sources are unable to achieve a sufficient reduction in emissions, which is why it is necessary to capture CO_2. In the long term, global net emissions must be negative, which requires the removal of CO_2 from the atmosphere. Therefore, CCS must play a key role, in conjunction with a number of other important initiatives, in fulfilling global climate ambitions.

There are major differences in the facilities that European countries have available for storing CO_2. Countries with abundant access to underground reservoirs in the North Sea, for instance, such as Denmark, Norway and the UK, can store their own CO_2 emissions for many years. Other countries, such as Germany and Poland, have considerable storage requirements, but have fewer facilities for storing CO_2, while some countries have no capacity at all. This therefore creates a need to establish an international market for trading and transporting CO_2.

International cooperation can also help significantly reduce the cost of CCS. This is down to costs being high when storing small amounts of CO_2, with the potential of costs being halved in the case of larger volumes. In the short term, Denmark and other countries with good storage facilities are unable to capture sufficient CO_2 to achieve the beneficial economy of scale effects. They will only be achieved if the market's size increases, thereby giving rise to a need to establish a common European infrastructure for transporting and trading in CO_2 from several other countries.

An important benefit and side effect of the Greensand research project with its 23 project partners was to further mature the service and supplier´s market by developing requirements, technical solutions and best practices for a long-term storage operation. This did not only involve the project partners but had also a dissemination effect on competitors and the service industry as such and thus allowing for competition and expected cost reduction in the service market. The total amount of CO_2 which potentially may be stored across EU countries by 2030 is calculated at between approx. 360 and 790 million tonnes of CO_2. An annual market potential of this magnitude requires a well-established, reliable transport network and continuous monitoring of storage facilities. Such a system requires international coordination and standardisation, which can obviously be carried out under the auspices of the EU.

European market should be able to attain a total economic value of between DKK 450 and 1,000 billion. The countries participating in a future CCS market can look forward to sharing in the market, but there is uncertainty about the amount which will be assigned to each country. For example, if Denmark's share of the market amounts to 5-10 per cent, this will achieve an economic value estimated at between DKK 23 and 100 billion. If the CCS sector grows to such a size, it is also estimated that the number of jobs which can be created directly and indirectly in the CCS industry will range between 4,000 and 17,000.

As things stand, Denmark's facilities in terms of operating as a recipient country for CO_2 storage are already good. However, this position will only be consolidated in the future as CO_2 emissions decrease and more suitable storage capacity facilities are being continuously mapped. The political goodwill for CO_2 storage already exists in Denmark, which is why Denmark is at the forefront of the effort to create a European market for capturing, transporting and storing CO_2. Large-scale CO_2 storage in Denmark may, at the same time, pave the way for investments in the development and application of capture technologies, which many companies would otherwise be reluctant to get involved in if there were no possibilities to store CO_2.

Contribution to realise energy policy objectives

Development of cost-effective CO2 Storage by 2025, requires the use of full or part of the depleted hydrocarbon fields in the Danish North Sea, as only these can be functional for storage by 2025. It is important to emphasize that the CCS in juvenile areas (nearshore and onshore) cannot meet the timeline laid out in the strategies for 2025 and 2030. Maturing a CO2 storage site in the nearshore and onshore will require ~10 years for the full maturation, to cover for seismic, wells, maturation, and subsequent development, and hence the storage in these areas is first to have impact post 2030.

Project Greensand is to a large extent underpinning all the important climate targets, targets for growth and ambition to make Esbjerg a ‘green Danish capital of the future’ exploiting opportunities given by large-scale CCS in the Danish North Sea. Knowledge from Greensand can be used to increase the maturation pace of the nearshore and onshore storage sites in Denmark and global.

Selected press releases throughout the project period

08.12.2021: Project Greensand modtager 197. mio kr. til lagring af CO2 i Nordsøen

16.03.2022: Aftale om tankcontainere til CO2transport

08.04.2022: Ny hjemmeside i luften

13.04.2022: Nu er transportskib til CO2-lagring sikret

02.05.2022: Teknologisk Institut inspicerer teststeder

20.06.2022: Semco Maritime klar med nyt design til Project Greensand

01.09.2022: Welltec tester materialer til lagring af CO2

30.09.2022: Ny aftale er et vigtigt skridt på vejen mod at lagre 1,5 millioner tons CO2 i Nordsøen i 2025

13.10.2022: DHI og Rambøll tester havbunden

25.10.2022: Dobbelt forsegling over Project Greensands CO2-lager

08.11.2022: Resen Waves udvikler revolutionerende grøn teknologi til offshore monitorering

21.11.2022: Noble Resolve gøres klar i Esbjerg

24.11.2022: Project Greensands skib til CO2-transport gøres klar i Esbjerg

06.12.2022: Energistyrelsen giver tilladelse til Greensands pilotprojekt

20.12.2022: Project Greensand udvikler ny metode til måling af CO2-lager i Nordsøen

18.01.2023: Sikkerheden i Project Greensand er nu verificeret af DNV

19.01.2023: Noble Resolve er på vej til Nordsøen

10.02.2023: Aurora Storm er på vej til Nordsøen

23.02.2023: H.K.H. Kronprins Frederik skal lagre den første CO2 i Nordsøen

07.03.2023:Dansk nøglerolle i europæisk klimakamp skaber tusindvis af jobs

08.03.2023: H.K.H. Kronprins Frederik har nu officielt sat gang i den første lagring af CO2 i DK

12.04.2023: Project Greensand har gennemført den første lagring af CO2 i Danmarks undergrund

25.04.2023: Project Greensand roser nyt samarbejde mellem Danmark og Tyskland

05.04.2023: Nyudviklet overvågningsteknologi viser sit værd for Project Greensand på Nordsøen

14.06.2023: DNV har sikkerhedsverificeret alle aspekter af Project Greensands CO2-lagring i Nordsøen

7. Project conclusion and perspective

WP1 Storage Site Endorsement

WP1 integrated all the cross disciplinary results from the various work packages required to conduct a Third-Party verification and obtain a Storage Site Endorsement on the Nini West storage complex. The verification was completed and confirmed that the work has followed the ISO 27914:2017 standard.

A significant part of WP1 was the conduction of containment and facilities risk assessments ensuring safe operations and a basis for the definition of corrective measures and a complete monitoring program. Environmental data acquisition and subsequent modelling of environmental impact from potential CO2 leakage.

WP2 Materials

WP2 has fulfilled its objective to monitor and coordinate the activities of WP3 and WP4. Both WP3 and WP4 have delivered timely results to de-risk material-related risks identified in Greensand Phase 1 and have provided essential input to WP1.

WP3 Seal and Reservoir

The rigorous and comprehensive investigation of the Nini West storage site has shed valuable light on the intricacies and potential of subsurface CO_2 storage. Evaluating the reservoir and its overlying seal under conditions that closely mirror real-world scenarios has offered insights into a myriad of phenomena related to CO_2 storage. This in-depth exploration has affirmed the storage potential that Nini West holds, emphasizing the capability to store CO_2 under optimal and safe conditions.
The results obtained from the flooding experiments, along with the geostatic and flow models have provided a robust foundation for understanding near to far-wellbore flow dynamics and the impacts of impurities in the CO_2 stream. The improved geostatic models, developed using advanced tools like Petrel and Eclipse, enabled the successful prediction of reservoir pressure and temperature changes. The fact that the history-matched flow model correctly anticipated these changes during the Pilot injection underscores its pivotal role in setting the boundaries for safe and effective injection operations.
Furthermore, the proactive approach in studying optimal operational conditions and establishing a workflow for seal testing exhibits the commitment to not only harness the storage potential but also to ensure the environmental and operational integrity of the CO_2 storage process.
Looking ahead, the predictive modelling of the CO_2 plume's migration within the reservoir will play a decisive role in guiding future monitoring activities. As operations progress, any deviations from the model's forecasts will serve as indicators, possibly prompting increased monitoring or even remedial measures. Such a strategic approach underscores the project's dedication to operational excellence.
In essence, the discoveries and advancements made during these studies underscore the viability of the Nini West storage site as a significant and safe storage site for CO_2.
The risk of formation damage due to salt clogging was also evaluated based on experimental evidence, and the report introduces potential danger and safe regimes in relation to the gas flux, CO_2 temperature, and other factors. It is concluded that the risk of formation damage is low, although there exist many simulation challenges due to the complex nature of salt precipitation. The results obtained pave the way for the endorsement of the Nini West storage site. Using the validated history-matched flow model, the Nini West site's feasibility for large-scale CO_2 storage has been reinforced. To benchmark the Nini reservoir type, a comprehensive database, encompassing all findings from geostatic models to flow dynamics, can be compiled. This will help standardize CO_2 injection, monitoring, and analysis procedures specifically tailored to the Nini reservoir. A

dedicated monitoring system for Nini West will be established, with a feedback loop integrating real-time site data and model predictions. Deviations can refine the models further, evolving the benchmark for the reservoir type. Safety protocols will be developed based on results to ensure site integrity, tracking CO_2 plume movements, and addressing anomalies. To gain site endorsement, engagement with stakeholders is essential, sharing findings, safety protocols, and potential benefits of Nini West. Finally, the benchmarked data on the Nini reservoir will guide the exploration of new sites with similar geological attributes, expediting the validation of new storage sites.

Potential Influence of WP3 Results on Future Developments

The compilation of data, methodologies, and experimental designs established by Project Greensand is seen as a potential cornerstone for guiding future activities in the Carbon Capture and Storage (CCS) domain. The data and methodologies presented could potentially pave the way for more rigorous, data-driven decision-making in sustainable energy solutions in future research.
Seal Evaluation and Characterization: Historically, seal units were uniformly considered as homogenous entities. However, in the findings obtained from WP3, this perspective has been redefined. A multidisciplinary workflow was developed, and it is suggested that this provides an enhanced understanding of the geological properties and seal capacities. Utilization of cutting samples, not just core samples, was emphasized in this workflow. A transformation in the perception of seals was observed. Instead of a singular seal unit, seals were subdivided, their intricacies investigated, and their capacities and risks delineated. From the analyses conducted, confidence in the seal's capacity to offer prolonged and secure CO_2 storage is suggested to have been heightened. The Nini West top seal is now postulated to comprise multiple independent sealing layers, each potentially offering added containment.

Reservoir Evaluation: In the domain of reservoir evaluation, workflows that integrate numerical simulations of unsteady state flows, for determining relative permeability, were formulated. It was found that these methodologies offer valuable insights for informed decision-making. Emphasis was placed on the strategies for managing uncertainties, benchmarking results, and understanding dynamics such as the interaction between CO_2 and residual oil. Significantly, a novel method for characterizing the interaction between $scCO_2$ and residual oil was introduced. Potential risks related to pore throat clogging are postulated based on this characterization.
In additional reservoir reactivity towards impure $scCO_2$, the outcomes from our studies and experiments emphasize the pivotal role of advancements in chemical modelling and theoretical understanding of impurities. This knowledge informs the significance of integrating specific mitigation strategies, especially when dealing with CO_2 streams that contain acidifying impurities like NO_x and SO_x. The aim is to control the pH levels near the well during the injection process to ensure maximum efficiency and safety.
The novel long tube design for testing salt clogging has introduced a new approach to understanding salt precipitation in porous rock. This design can effectively mimic a more extended section of the reservoir, minimizing end-effects and providing a clearer insight into the impact of $scCO_2$ injection on salt behaviour in various conditions. Future evaluations can utilize this design to enhance the accuracy and reliability of predictions regarding salt clogging, ensuring safer and more effective CO_2 storage operations. Considering the complexities associated with salt clogging, it is crucial to pursue more accurate simulations by incorporating complementary experimental evidence and leveraging advanced upscaling techniques.

WP4 Well Integrity

WP4 dealt with well integrity in a wider sense. Main focus was to evaluate well construction materials for providing long-term well integrity and to cover both, P&S activities as well as CO_2 injector wells. In conceptual well designs considerations, barrier management strategies also play a vital role. All work was done in accordance with requirements defined in relevant ISO and DNV standards.

Relevant parts of WP4 are fundamental research activities, either resulting in directly applicable results or building the foundation for further activities in later phases of project Greensand. The outcome of WP4 is paramount for project Greensand, because securing the long-term integrity of the wells which penetrate the caprock is a key factor for the overall success of the project.

Executing WP4 started with gaining an understanding of the service conditions which the materials will be exposed to. A thermodynamic description of the medium was developed and used as input to define test conditions and protocols for material testing. This description could in the further be usefully extended by transient simulations, especially when considering a non-continuous injection scheme.

Lab testing of metallic materials was done under the service conditions anticipated (pressure, temperature, CO_2 with impurities). Suitable materials can be derived from the test results, however, there is not a single solution. The final material selection depends on the well design, because this has mayor impact on the service conditions. The well design itself depends on the different factors, i.e. well purpose (P&A or CO_2 injector) and well origin (re-entry/sidetrack/new drill), but also the injection scheme (continuous/batch). A distinct material selection can only be made when considering the overall context. Different options have been worked out, but the final decision is outstanding.

The impact of supercritical CO_2 on the durability of Portland Class G cements is discussed with contrary conclusions in scientific literature. To prove the suitability of the cement applied in the legacy wells, cement samples have been prepared, exposed to the expected service conditions (reservoir brine, supercritical CO_2) and analyzed for alteration. Additionally, a geochemical and geomechanical model was developed and applied to complement the laboratory experiments. Overall, the model supports the finding of the experiments, however, reactive transport modelling indicated a reaction of cement in contact with clay which contains little or no $CaCO_3$ resulting in a potential pathway for CO_2 to migrate slowly upwards. Analyzing clay samples from the respective zone can help concluding if this mechanism can occur at all, and/or a more sophisticated simulation of the potential pathway could help assessing its impact. WP4 concludes that the legacy cements will provide sufficient sealing capability under the anticipated conditions. Adequate placement of the cement is required to provide the seal, however, even when using tools like centralizers, (micro)annuli can form and provide a pathway for CO_2. A sufficient length of an impermeable cement needs to be assured. Latex amended cements are known for their improved ability to be placed and have therefore been included in the experiments. They outperformed the legacy cement types in various performance aspects, however, the potential impact of the increased latex concentration on the outside of the samples requires investigation prior to recommending this cement type.

Concepts for P&A activities as well as CO_2 injector designs have been derived from risk analyses and well status reports of all wells in the direct vicinity considering also technical and regulatory requirements. To finally select the most suitable concept for the wells (detailed design, material selection, options for minimizing water flowback etc.), project Greensand needs to advance to another project stage.

WP5-9 CO2 Offshore injection

The main objectives of the Greensand pilot injection, namely demonstrating the suitability (from a subsurface standpoint) of the Nini West reservoir as a storage site for CO_2 injection and confirming safe handling and injection of CO_2 in an offshore environment were both achieved.
The Greensand pilot injection managed its operations safely through the entire value chain from the CO_2 capture, transportation and injection into Nini West offshore Denmark. Learnings were made during the planning and execution of the injection operations which are being incorporated in the planning of the next phase of the Greensand project.

From a subsurface perspective, no formation damage was observed during nor following the injection of CO_2 in the Nini West reservoir. The CO_2 injectivity performance was found to be stable throughout the 7 injection cycles, though the CO_2 injectivity was found to be lower than expected but within the uncertainty range of the pre-injection modelling. Bottom hole data, interference data and lab data obtained during the Phase 2 project are being integrated and implemented in the subsurface modelling to plan for the full-scale injection.

WP10 Monitoring

Overall, the monitoring tasks in WP10-12 were very successful and well-acknowledged by international industry partners and stakeholders. Especially the spot seismic concept is very convincing, and it is expected to reduce cost and operational effort whereas the frequency of the measurements can be increased, at least in the aquifer. Over time, this could significantly reduce uncertainties of the fluid flow simulation and also reduce leakage risks as irregularities could be detected very early triggering mitigation or remedial measures.

Based on proceedings of the seismic data analyses conducted by Spotlight Earth post EUDP project, more spots than initially assessed confirm the correct detection near the injection location. It is planned to publish these results in a peer reviewed geophysical journal to facilitate the establishment of the spot seismic methodology for CCS CO2 plume monitoring as a proven technology with highest technological readiness level.

Still, a site closure 3D seismic survey is deemed necessary. For a very small CO_2 storage complex (c. 10 km²) like Nini West, a fully conventional 3D streamer seismic has a very high operational effort, cost, and environmental impact. In the preliminary MMV Plan, a baseline 3D seismic is not foreseen for the same reason and re-processing of the legacy 3D seismic is proposed to be used instead although it was acquired prior to the oil production and therefore does not reflect the depleted oil field situation. The site closure 3D survey will be able to provide a time-laps effect in the aquifer in comparison to the re-processed legacy 3D seismic data. Therefore, it is crucial for Nini West - but also for other CCS projects - to develop lean and flexible 3D seismic technologies (short streamer or sparse node arrays) that also cater for the possibility that a spot seismic trigger a 4D seismic acquisition.

Unfortunately, the buoy manufacturing process failed, due to significantly longer-than-expected lead times for electronic components and cost increases due to the post-pandemic supply chain crisis. One key learning is that such prototype developments may face unexpected problems that perhaps cannot be cured within a defined scope and time frame in a co-funded research project.
Based on market research on marine technologies, other alternative solutions exist to connect the lander to a battery or fuel cell-based power supply and data communication system. However, a long-term test of the lander at the Nini West storage site to collect baseline information and to assess long term durability, maintenance frequency and alteration effects (e.g., biofouling) is still outstanding and is subject to a follow-up activities prior to the first injection of the Nini West CO_2 storage site development. These activities are complemented by a design study on future AUV technology to detect CO_2.

WP11 Monitoring tools and operation

The focused seismic concept demonstrated in the project is very convincing, and it is expected to reduce costs and operational efforts whereas the frequency of the measurements can be increased. Therefore, the concept is expected to detect irregularities earlier than conventional seismic concepts and will allow the operator to act on the irregularities.
During the seismic campaign, a much smaller seismic source (compared with conventional sources) was used, and the environmental footprint of the solution was reduced by far. In the campaign, some of the ocean bottom nodes (OBNs)were co-located (i.e., placed at the same location) to assess whether a transfer function from

one to another OBN in very close proximity could be developed. The seismic repeatability, the trace comparability, and the signal-to-noise ratio are very high. The good OBN – seabed coupling, the very good accuracy of the survey data (airgun and OBN positioning), and the successfully tested drop nodes from TGS have the potential for significantly reducing costs and for simplifying future seismic operations further. For example, ROV operations can be reduced or the development of the connected OBNs to the power and data buoy is less important for seismicity monitoring. The used MASS-III OBNs from TGS have a battery lifetime of 150 days. It would be very beneficial to extend the battery lifetime ideally to one year, the main frequency of the recurring seismic monitoring operations. With this, it would be possible to set out an array of seismicity recording OBNs and replace them year by year or anytime if an event is detected by the geophone in the observer well.

For seismicity monitoring, an array of 3-4 OBNs is required, and they should be accompanied by one geophone or DAS cable that is placed in an observer or injector well. With this set-up, real time detection can be ensured, and a continuous OBN array would deliver the spatial information on demand to triangulate the seismic event once detected by the in-well sensor. Therefore, it is deemed of less importance to connect the OBNs to a smart power and data communication buoy as initially planned. However, depending on the final Nini Full Scale development concept, the in-well sensor requirement for real time detection cannot be guaranteed for the time being. Therefore, the key learning is that a connected node will still be of high importance to monitor seismicity in real time, especially if an in-well geophone solution is discarded. It would ideally be placed near the Nini A platform and directly connect to it via cable.

During the seismic campaign, OBNs have been placed co-located, and the accuracy has also been tested by dropping OBNs to the seabed. The recorded data show that reliable comparisons between co-located OBNs in slightly different positions and seabed couplings can be made. Therefore, it will be possible to obtain a continuous and comparative data record by replacing the OBNs with similar devices before the data and battery limits have been reached. This deployment model for the OBN seismicity array is further simplified by the successful testing of a new retrieval mechanism introduced by TGS. ROV operations can therefore be reduced significantly. Simplification of OBN placement and retrieval processes will also benefit active seismic surveys.

The water column monitoring sensors on the lander were successfully demonstrated in the Empress Dock in Southampton, and they were able to detect low leak levels representative of fractions of proposed injection rates. The next steps for the lander and the related sensors will be to demonstrate the function and durability of the system in the relevant environment – i.e., at the Nini site – for a longer period. In addition, for near-real time monitoring, a communication buoy, or other means of transferring data to onshore must be acquired, either from the commercial sector or developed with future partnerships and integrated. Once this is in place, the consortium believes that a cost-efficient solution for the monitoring of the water column in high-risk areas will have been developed, allowing for timely detection of gaseous and dissolved CO_2 seeps.

WP12 Power and Data

The production of the buoys was challenging, and unfortunately, it was not possible to produce, test or demonstrate the functionalities of the buoys during the project lifetime. The challenges were primarily due to prolonged lead times of several buoy components. However, during the project, two buoy designs were developed, and elements were tested at component or element level. Further work and more time will be needed to demonstrate the buoy technology and the potential and perspectives of the technology.
One key learning is that such prototype developments may face unexpected problems that cannot be cured within a defined scope and time frame in a co-funded research project.

Due to unforeseen issues with the buoys, it was not possible to establish a data feed from the buoys to the cloud for real-time or near-real-time data visualization. However, it was feasible to utilize chemical and acoustic sensor data previously acquired from another project to create a data management tool. This sensor data closely resembled what could be expected from the sensors intended for deployment in the current project. The work package successfully demonstrated the ability to load data from the cloud, analyse the data outputted from the different sensors, and present it visually to end-users. A thresholding algorithm was also developed to inform the users if a potential leakage has occurred.

For a subsequent project, the next step would involve gaining a deeper understanding of the sensor data from Nini and fine-tuning/optimizing the algorithms to inform users if a potential leakage within the Nini area has taken place. To achieve this, the next step would involve fine-tuning the threshold algorithms to enhance the accuracy of estimating potential CO_2 leakage near the sensor. Additionally, a logical progression would be to develop recommendations based on the data. However, this raises a compelling question regarding liability in the event of the system flagging a leak or non-leak.

The data harvest strategy analysis has presented and described the possible system architectures, taking the seabed to surface and surface to onshore transfer of data into account. Furthermore, the differences and consequences of operation and post-operation phases have been outlined. In each domain, the available technologies have been presented with pros, cons, and performance characteristics. Based on the data from the dockside test of the lander performed in WP11, a strategy for reducing data payload size was also proposed, and the impact of sensor sampling rate and data transmission interval was surveyed with regard to the impact on the power supply systems. The last part of the analysis was the powering options for the lander as well as the auxiliary systems. The analysis has presented the viable options for a complete monitoring system from seabed to onshore that can enable informed design decisions for the following phases of the Greensand project.