Offshore


TGS' Elephant $CO_2$ storage project is an offshore carbon storage development in the Norwegian Sea off mid-Norway.

GEOSCIENCES

# Seismic data de-risk Elephant CO2 storage site offshore Norway

Seismic-driven subsurface understanding and risk-based monitoring planning are shaping a Norwegian Sea CO2 storage hub.

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## Key highlights:

- The Elephant site is located on a stable geological platform with thick Jurassic saline aquifers capable of gigaton-scale $CO_2$ storage.
- High-fidelity seismic imaging reduces uncertainties in reservoir connectivity, capacity and containment, supporting robust modeling and injection planning.
- Ongoing risk management focuses on potential leakage pathways, reservoir heterogeneity and pressure variations, with continuous surveillance to validate containment.
- Time-lapse seismic monitoring, ocean-bottom sensing and well integrity surveillance form the core of the project's MMV strategy, ensuring real-time plume tracking.

*By Kristian B. Brandsegg, Sougata Halder, Allan McKay and Gunhild Myhr, TGS*

As industry and governments intensify efforts to meet net-zero targets, carbon capture and storage (CCS) is becoming a cornerstone of long-term emissions management. The maturation of secure, high-capacity carbon storage sites that are demonstrably monitorable has become a defining requirement. Yet, fewer than 50 Mtpa of $CO_2$ are currently captured worldwide, far short of the multi-gigaton scale needed to curb atmospheric emissions. Therefore, developing robust geological storage at an industrial scale is no longer optional; it is an essential enabler of decarbonization.

Against this backdrop, TGS' Elephant $CO_2$ storage project emerges as a strategically significant offshore carbon storage development in the Norwegian

Sea off mid-Norway. This project site is developed on modern 3D broadband seismic data and strengthened by a comprehensive, risk-based monitoring measurement and verification (MMV) philosophy. The project demonstrates how integrated geoscience and optimized monitoring planning can accelerate CCS deployment across Northern Scandinavia.

**What is CCS?**

CCS involves three main stages: capturing CO2 at industrial sites, transporting it via pipelines or ships, and securely storing it underground.

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## A stable geological foundation

The Elephant storage complex lies on the Trøndelag Platform, a region characterized by long-term structural stability with relatively limited faulting compared with adjacent offshore provinces. Thick, laterally extensive Jurassic saline aquifers have potential of gigaton-scale storage, offering capacity sufficient to support multiple industrial $CO_2$ value chains over decades of operation. The primary reservoirs, the Garn and Ile formations, are overlain by laterally extensive seals of the Melke and Spekk formations. This reservoir-seal configuration, validated by oil and gas accumulations in the region, provides several trapping mechanisms, including structural, residual and solubility trapping, supporting permanent containment of $CO_2$ within mapped reservoir zones.

Further, proximity of the Elephant $CO_2$ storage site to emerging ship-based $CO_2$ transport hub, provides a cost-effective $CO_2$ transport model for dispersed northern European emitters or combined with a pipeline solution from an intermediate onshore terminal.

## Seismic data driving subsurface certainty

More than 10,000 sq km of modern 3D broadband seismic data underpin characterization of the Elephant $CO_2$ storage site (Figure 1a). High fidelity imaging enables detailed mapping of reservoir connectivity, depositional architecture and seal continuity. These insights reduce uncertainty related to injectivity, storage capacity and containment performance, forming the basis for robust static and dynamic modeling.

Norwegian Sea
Sweden
Gulf of Bothnia
Norway
Oslo
Stockholm
Skagerrak
North Sea
Denmark
Copenhagen

Figure 1a. The mid-Norway Elephant carbon storage site is named after the seismic survey outline mimicking an elephant (grey polygon). The red polygon indicates the likely extent of the main storage site.

Static and dynamic reservoir models were developed to test industrial-scale injection scenarios involving multiple wells and sustained injection rates. Simulation results showed low-pressure buildup and predictable plume migration, largely confined to the Ile Formation (Figure 1b). Vertical migration into overlying units was limited and transient, with long-term immobilization achieved through multiple trapping processes.

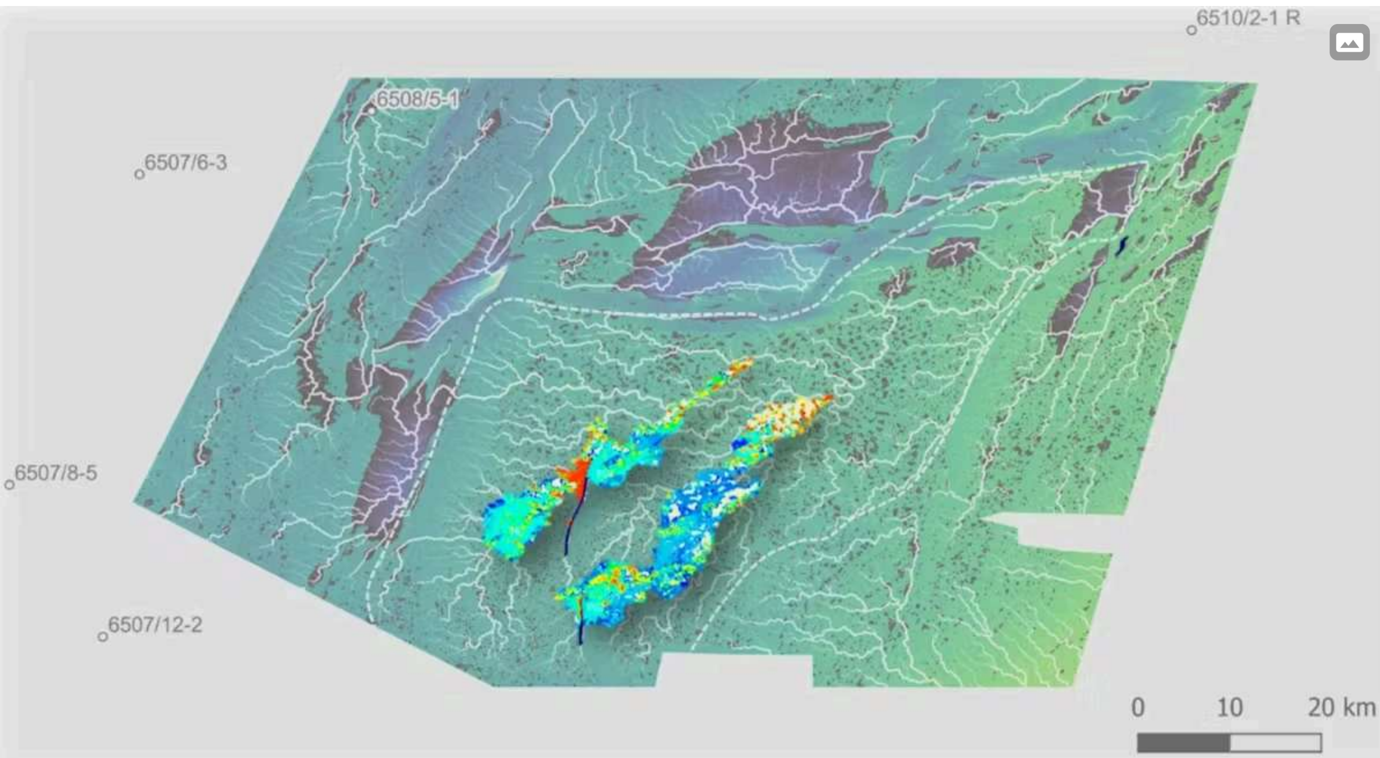


Figure 1b. The initial dynamic modeling results (total 250 Mt $CO_2$ injection from five injector wells over five years) show that the Elephant $CO_2$ storage site should not see critical pressure increases from the injection of 1 Gt. The $CO_2$ injected appears to stop migrating about 2,000 years after injection. The risk of $CO_2$ migrating out of the aquifer interval appears to be very low. Still, the main lateral leakage point is NE corner of the white-dotted polygon.

## Subsurface risks: Designing for the unexpected

Even with thick regional seals and some of the highest quality seismic imaging available offshore Norway, the subsurface beneath Elephant $CO_2$ storage site does not come with guarantees. A detailed understanding of subsurface risks will play a central role in shaping the site's monitoring and risk management strategy as the project moves toward Phase 1 development.

Despite the presence of regionally extensive seals and a high-capacity storage system, project assessments indicate that several geological and operational uncertainties must be actively managed to ensure long-term $CO_2$ containment (Table 1).

| Major subsurface risk of the Elephant $CO_2$ storage site | Rare | Unlikely | Possible | Likely | Almost Certain |
| --- | --- | --- | --- | --- | --- |
| | 1 | 2 | 3 | 4 | 5 |
| 5 - Severe | **1** Top seal failure<br>**2** $CO_2$ leakage via subcrop | **4** Require brine production<br>**5** Elephant capacity is underestimated (phase1)<br>**6** License extension approval (non-delivery on work program)<br>**7** Reputational damage from brine flux | **11** Insufficient Monitoring Program<br>**12** NGO opposition towards CCS | | |
| 4 - Major | **3** Joule-Thomson effect equipment qualification | **8** Injectivity impairment due to phase behavior of $CO_2$<br>**9** Well damage due to dispatchability<br>**10** Reservoir compartmentalization | | | |
| 3- Medium | | | | | |
| 2 - Low | | | | | |
| 1 - Insignificant | | | | | |

Table 1 summarizes the impact and likelihood of the major technical and operational subsurface risks associated with the Elephant $CO_2$ storage site.

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There are three ways of carbon leakage from the storage site influencing the environment:

1. $CO_2$ leaves the storage site vertically;
2. $CO_2$ leaves the storage site horizontally; and
3. Brine discharge via subcrop in the northeast part of the structure.

One of the primary considerations is the potential for unexpected plume migration driven by small-scale reservoir heterogeneity or previously unrecognized connectivity that could alter $CO_2$ flow paths from those predicted by models, underscoring the need for continuous subsurface surveillance once injection begins. Potentially reservoir pressure buildup and/or salinity variations may impact $CO_2$ solubility, plume migration and injectivity, necessitating ongoing calibration within dynamic models.

While the likelihood of leakage is considered low, the project team emphasized that containment must be demonstrated over time, not assumed. After first injection is initiated, the ongoing MMV will be used to validate plume behavior and provide early detection of any deviations from expected performance.

Further monitorability challenges could arise as multiple injection wells are phased in, requiring optimized well placement and seismic acquisition strategies to maintain full field visibility.

## MMV: The cornerstone of storage confidence

In offshore CCS, monitorability is inseparable from storage viability. At the Elephant $CO_2$ storage site, MMV planning (and execution) is treated as an engineering control system rather than solely a regulatory requirement.

Designing a risk-based MMV program emphasizes requirements of a high-resolution baseline 3D seismic survey for identification and mapping of containment risks to define a scalable, fit-for-purpose monitoring program. Time-lapse (4D) seismic monitoring forms the backbone of the MMV strategy, supported by ocean-bottom sensing, well integrity surveillance and seabed monitoring. Together, these tools provide continuous feedback on plume behavior and pressure response throughout the injection lifecycle (Figure 2).

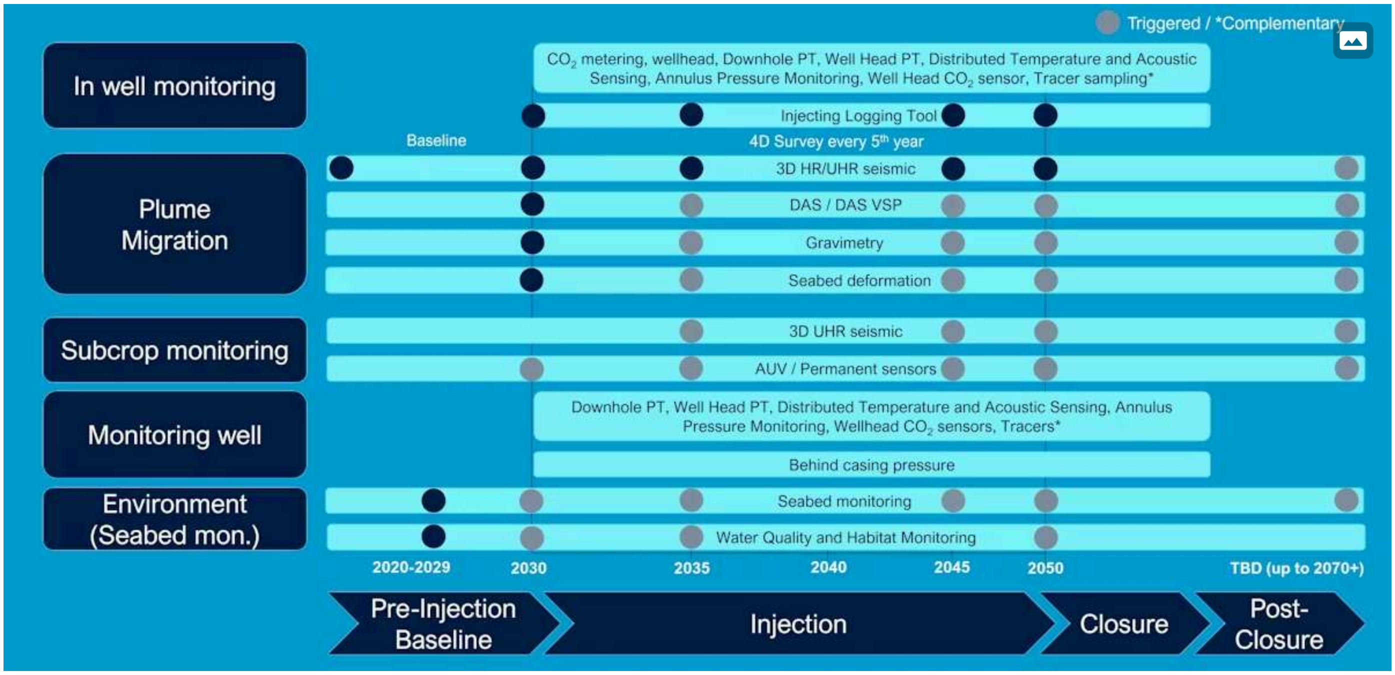


Figure 2. The MMV plan for the Elephant $CO_2$ storage site includes multiple tools to gain optimal insight of the life-span of the carbon storage site. These can be used as a value-creation tool for reducing uncertainty and cost through confidence building and operational efficiency.

## A blueprint for regional CCS deployment

With offshore CCS moving from pilot projects toward large-scale deployment, the Elephant $CO_2$ storage site is positioned as a regional storage hub linking offshore infrastructure with onshore industrial capture projects across Norway, Sweden and Finland. Its scale, geological robustness and monitoring framework support its role as a foundational asset within a broader Northern European CCS network.

The Elephant $CO_2$ storage site demonstrates how broadband seismic acquisition, advanced seismic imaging and risk-based monitoring can be integrated into a storage system that can transform a subsurface concept into a mature, investment-ready storage solution.

As offshore CCS becomes a material component of the energy transition, projects like the Elephant $CO_2$ storage site provide a practical blueprint for building confidence in the subsurface evaluation and modeling for developing an optimized monitoring strategy for secure, long-term permanent $CO_2$ storage.

Given the multi-decade lifecycle of offshore storage assets, the Elephant $CO_2$ storage site needs to rely on a digital integration platform designed to harmonize real-time operational data across the $CO_2$ injection infrastructure to ensure data continuity, unification, traceability and real-time monitoring of the operational workflows for performance tracking and efficient regulatory reporting. These digital workflows reduce handover risk between project phases and help support long-term stewardship and liability management.

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