**Advanced Monitoring for Confident $CO_2$ Containment of the Elephant Carbon Storage site, Norwegian Sea**

## Introduction

A crucial part of development plan for a $CO_2$ storage site is the formulation of the measurement, monitoring, and verification (MMV) plan. As carbon capture and storage (CCS) moves from pilot projects to large scale deployment, MMV has become the cornerstone of trust in the entire $CO_2$ value chain. A risk-based monitoring approach is recommended (IOGP 2022) enabling verification of containment of the $CO_2$ and conformance with the expected behavior at the storage site, whilst ensuring compliance with the regulatory and societal requirements. This means ensuring actual spatio-temporal evolution of the $CO_2$ plume is consistent with model predictions, requiring adjustments in the model and/or MMV plan otherwise. CCS succeeds only when it meets regulatory requirements, earns investor confidence, and demonstrates tangible value to society.

However, to progress efficiently from initial screening to $CO_2$ storage site maturation projects rely on high-quality seismic data for reservoir characterization, storage risking, injection planning and leakage monitoring. Often legacy seismic data is generally sufficient for early-stage storage concept building, but key challenges are ensuring long-term reservoir integrity, optimized injection, and effective monitoring over decades. With access to modern, high-quality 3D seismic data the evaluation and planning process can be accelerated in a cost-effective fashion. As CCS costs currently exceed EU $CO_2$ prices, cost efficiency of the CCS project, especially within 4D monitoring programs, is critical. Integration of geological, geophysical and petrophysical information from subsurface well and seismic data can provide valuable insight for storage suitability for both depleted hydrocarbon and saline reservoirs, onshore and offshore (Halder et al., 2022; Halder et al., 2024).

The Elephant CCS site is introduced as a key storage development in Northern Scandinavia meeting the needs for decarbonization of the industry in the region. Its integrated MMV plan is built on high-quality seismic data and risk-based monitoring principles to show efficient site maturation whilst ensuring safe, verifiable long-term $CO_2$ containment in-line with the likely emitting industries requirements.

## MMV Method

A robust MMV methodology is essential for ensuring that $CO_2$ injected into a CCS site behaves predictably and remains securely contained (Brandsegg, et al., 2026a). Building on a high-quality 3D seismic baseline and a risk-based monitoring philosophy, this approach integrates seismic-led subsurface surveillance with multi-domain monitoring and digital data management to deliver reliable, transparent verification of long-term storage performance.

A properly designed MMV program ensures: (1) Reduction in subsurface uncertainty of $CO_2$ movement and storage, (2) Optimized injection strategies for operational efficiency and safety, (3) Lower long term monitoring costs, (4) Public and stakeholder trust from pre-injection through closure and transfer.

A 7-step methodology (**Table 1**) can be used to assess the optimal MMV plan for a given carbon storage site. The site MMV plan should be aligned with the complete CCS value chain MMV plan to keep operational efficiency along with trackability and stakeholder's accountability of the $CO_2$ flow from capture site to permanent storage.

## The Elephant CCS project

The Elephant CCS project (Brandsegg et al., 2026b) represents a frontier application of high-quality seismic data to large-scale $CO_2$ storage assessment in the Norwegian Sea at approximately 65°N **(Fig. 1**). Based on an extensive (>10,000 km²) broadband dual-sensor 3D seismic dataset, the project targets Lower to Middle Jurassic saline aquifers. It is geographically located in a region with proven favourable reservoir properties, limited hydrocarbon prospectivity, and sparse well control. Only one well is drilled within the seismic volume. Its strategic positioning in Mid Norway offers large-scale storage potential while supporting evolving CCS infrastructure concepts and avoids conflicts with oil and gas activities that likely protects long-term resource value. Of strategic importance to the development of CCS infrastructure in Northern Scandinavia (Skagestad et al., 2026), this site integrates multiple trapping mechanisms, including solubility, residual (capillary), and local structural and stratigraphic trapping, indicating gigaton-scale storage potential. Advanced seismic attribute analysis enables robust aquifer characterization in an area with little well data and provides critical constraints for geological and dynamic models. These results form the basis for detailed cost-effective MMV plan, supporting long-term storage integrity and regulatory confidence to develop this site further. It also gives a strong push to the development of the carbon capture site that is needed to make the CCS value chain operational.

| Steps | Key tasks | Description |
|---|---|---|
| **1. Establish a Robust Baseline** | Baseline 3D Seismic | **Characterize:**<br>- Storage complex architecture<br>- Seal integrity & fault behavior<br>- Legacy well conditions<br>- Structural connectivity & plume migration paths |
| | Data Integration | Integrate seismic with well, geological, and regional data to build a defensible pre-injection understanding |
| **2. Apply a Risk-Based Monitoring Framework** | Identify Risks | Identify credible containment and conformance risks using integrated subsurface data |
| | Map Risks to Monitoring Domains | **Domains:**<br>- Deep geosphere<br>- Overburden / shallow subsurface<br>- Seabed & water column<br>- Active and legacy wells |
| | Tailored Monitoring | Adapt monitoring intensity and technology selection to site-specific risks |
| **3. Use Seismic as the Core Monitoring Tool** | 4D Seismic Objectives | **Track:**<br>- $CO_2$ plume migration<br>- Pressure evolution<br>- Geomechanical responses |
| | Seismic Technology & Optimization | **Utilize:**<br>- Broadband systems<br>- Towed streamers<br>- Ocean bottom nodes (OBN)<br>- Elastic full waveform inversion (FWI)<br>- Distributed Acoustic Sensing (DAS)<br>- Gravimetry |
| | Survey Repeatability | Ensure high repeatability to support reliable time-lapse interpretation |
| **4. Incorporate Multi-Domain Monitoring** | Complementary Monitoring Domains | - **Deep Geosphere:** Fault activation, plume conformance<br>- **Shallow Subsurface:** Anomalous gas or pressure detection<br>- **Seabed & Water Column:** Seepage or environmental impacts<br>- **Wells:** Continuous integrity assessment |
| **5. Enable Digital Integration and Traceability** | Digital Platforms | **Use platforms (e.g., TGS Prediktor) to:**<br>- Integrate monitoring & operations data<br>- Provide near-real-time insights<br>- Enable traceable, auditable $CO_2$ tracking<br>- Streamline reporting |
| | Data Continuity | Maintain continuous, traceable data and interpretation across all $CO_2$ storage phases |
| **6. Implement Lifecycle Monitoring** | Lifecycle Alignment | - **Screening & Appraisal:** Baseline, risk assessment, MMV planning<br>- **Injection:** Track plume, pressure, conformance<br>- **Post-Injection:** Confirm containment & reduce uncertainties<br>- **Closure & Transfer:** Demonstrate long-term stability |
| **7. Use MMV as a Value-Creation Tool** | Reduce Uncertainty | Optimize injection strategy by reducing subsurface uncertainty |
| | Reduce Cost | Lower monitoring costs through adaptive, risk-based planning |
| | Build Confidence | Strengthen public and regulatory trust in permanent $CO_2$ storage |
| | Operational Efficiency | Leverage monitoring tools & digital capabilities for more efficient operations |

***Table 1.*** *The applied methodology for optimal MMV planning for carbon storage sites*

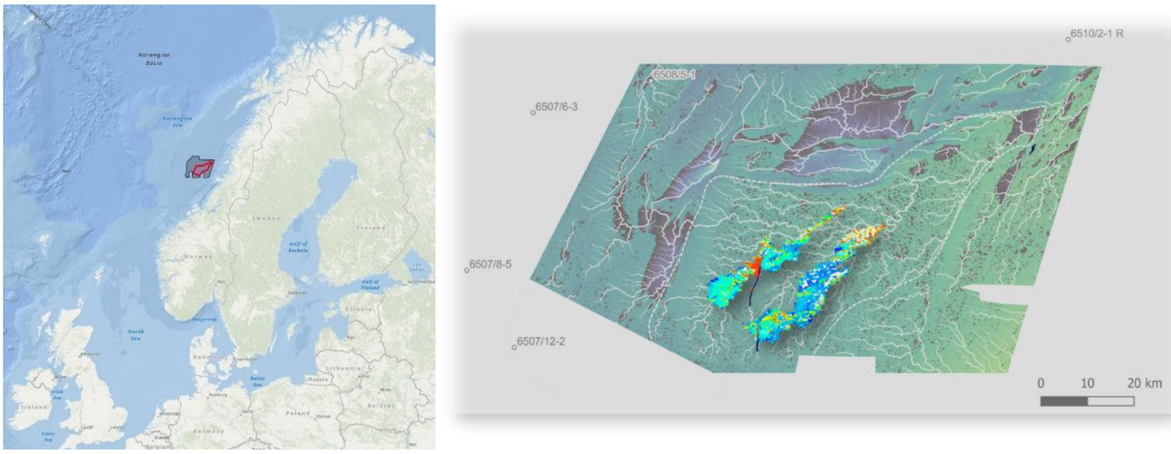


***Figure 1*** *(a) The mid-Norway carbon storage site is named after the seismic survey outline mimicking an elephant (grey polygon). Red polygon indicates the likely main storage site extent. (b) The initial dynamic modelling results (total 250 Mt injection from 5 injector wells over 5 years) show that the Elephant $CO_2$ storage prospect should not see dangerous pressure increase from the injection of 1 Gt. The $CO_2$ injected appears to stop migrating around 2000 years after injection. The risk of $CO_2$ migrating out of the Elephant aquifer site appears to be very low. Still, the main leakage point is NE corner of the dotted polygon.*

## The Elephant MMV plan

The MMV plan for the Elephant CCS site follows the full seven-step methodology (**Table 1**) by establishing a high-resolution pre-injection baseline, applying a risk-based framework to identify credible containment and conformance risks, and positioning seismic as the core monitoring technology throughout the project lifecycle. Complementary multi-domain surveillance, combined with digital integration platforms for traceability and real-time insight, ensures that all monitoring results are transparent, auditable, and operationally actionable. These activities are aligned with the CCS lifecycle from baseline characterization through the injection phase, closure, and post-closure long-term monitoring. It is summarized schematically (**Fig. 2**) organized across the four development domains: Pre-Injection, Injection, Closure, and Post-Closure, each showing how the monitoring strategy evolves while maintaining continuity, reducing uncertainty, and demonstrating secure, permanent $CO_2$ storage.

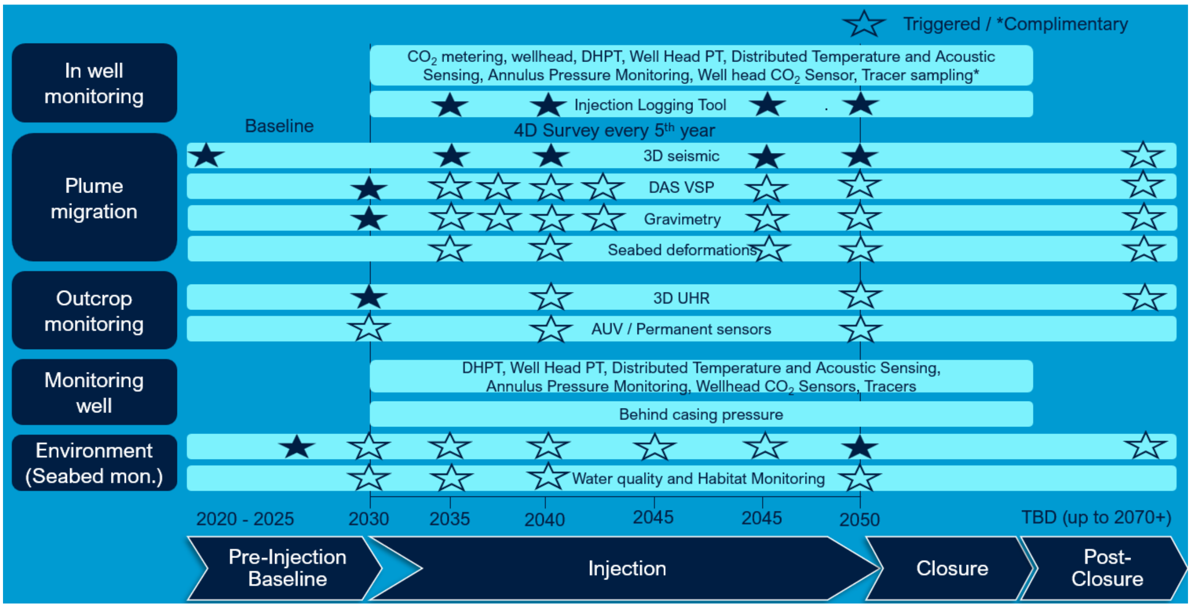


***Figure 2*** *The MMV plan of the Elephant CCS site includes multiple tools to gain optimal insight of the life-span of the carbon storage site to be used as a value-creation tool for reducing uncertainty and cost through confidence building and operational efficiency*

The core set of MMV data acquisition for the Elephant CCS site includes 4D seismic, extended well monitoring and seabed surveys, enabling high-precision $CO_2$ monitoring. A proper baseline seismic survey was acquired before this site was screened out. Repeated UHR3D seismic data are considered a viable alternative to traditional 3D repeats for achieving high-frequency monitoring, and a UHR3D baseline focused on seabed observations critical for future interpretation. In-well fiber sensors (DAS VSP), gravimetry and seabed deformation monitoring can provide essential insights for detecting potential $CO_2$ leakage. New technologies using AUVs and permanent sensors should further support effective seabed monitoring for both $CO_2$ leak detection and environmental impact assessment.

## Conclusions

Overall, the Elephant MMV plan serves as a strategic enabler for secure, verifiable, and scalable $CO_2$ storage in Northern Scandinavia. This systematic approach presented safeguards the integrity of the Elephant storage complex enabling industry, regulators, and society to rely on transparent and data-driven evidence of permanent geological storage. The presented Elephant site MMV program has great merits:

- High-quality regional 3D seismic provides the foundation for accurate characterization, early derisking, and confident $CO_2$ containment at the Elephant site.
- The integrated, risk-based and cost-effective MMV framework combines ultra-high-resolution seismic, advanced streamer acquisition, OBN, and DAS/VSP for long-term storage assurance.
- The MMV plan includes adoption of flexible development pathways—from pipeline connections to floating injection—to ensure the site can adapt to future transport and operational needs.

A carefully curated MMV plan ensures that the injected $CO_2$ behaves as predicted, remains contained within the storage complex, and poses minimal risk to people or the environment (Ringrose, 2020). In practice, this means combining robust subsurface characterization, deployment of fit for purpose monitoring technologies, and transparent data management over decades of operation and post closure stewardship. MMV planning is not just developing a single technology or survey, it is solving a challenge across the life of field that demands data integration across geoscience, engineering, and digital domains.

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