

Results of risk and safety assessment and description of monitoring program

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Executive summary

The goal of the present deliverable D4.5 of the Work Package 4 of the ConsenCUS project is to present an initial risk assessment and monitoring plan for the potential CO₂ storage site at Stenlille. To this end, two risk assessments workshops were organized by BGS, GEUS, and the operator of Stenlille natural gas underground storage site (Gas Storage Denmark). The outcomes of the workshops are summarized in a risk register.

The risk register was subsequently used to draft a monitoring plan for a realistic CO₂ injection scenario at Stenlille. The plan is based on experience with monitoring the natural gas storage facility at Stenlille, and accounts for differences between injection of CO₂ and natural gas.

1 Introduction

The EU Directive 2009/31/EC¹ (“CCS Directive”) establishes a legal framework for the geological storage of CO₂ in the European Economic Area. The Directive describes the procedures for selection of storage sites, the procedures for exploratory and storage permits, the requirements for site operations, and closure and post-closure obligations. A detailed guidance documents² are also available to assist the implementation of the Directive.

According to the CCS Directive (Article 1, 4 and Annex I), a site-specific hazard and risk characterization together with an exposure and effects assessment shall be undertaken at the site selection stage to demonstrate that there is no significant risk of leakage, and that no significant environmental or health risks exist.

Once additional data on the storage complex is acquired at the site exploration stage, a structured risk assessment should be carried out and a monitoring plan should be proposed to underpin the storage permit application (Article 7, 13 of the CCS Directive). The risk assessment and monitoring plan should be updated at the subsequent stages of the project (development, operations, post-closure).

The objective of the present work is to provide an initial risk assessment and to draft a monitoring plan for the potential CO₂ storage site at Stenlille (Denmark). To this end, two risk assessment workshops have been held in March 2023 and March 2024 by BGS, GEUS, and the operator of Stenlille natural gas underground storage site (Gas Storage Denmark). The main findings of the workshops are presented in Section 2.

The Stenlille natural gas storage site has been monitored since the start of operations in 1989 (Laier & Øbro, 2009), and the available data have been utilized for suggesting the monitoring methods for potential CO₂ storage operations in Stenlille. The corresponding recommendations are provided in Section 3.

¹ <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009L0031>

² https://climate.ec.europa.eu/eu-action/industrial-carbon-management/designing-and-implementing-industrial-carbon-management-projects_en#more-information

2 CO₂ storage risk assessment

2.1 Legal requirements

In the context of the CCS Directive (Article 1 and 4), risk management should demonstrate that geological storage of CO₂ within a designated storage complex can be done without significant environmental or health risks. Annex I to the CCS Directive lists the following risk assessment steps to be carried out for characterization of a potential storage complex:

- **Hazard characterization** (e.g., potential leakage events and secondary effects of storage of CO₂).
- **Exposure assessment** of potential leakage on the environment and population above the storage.
- **Effects assessment** of potential leakage on the environment and population above the storage.
- **Risk characterization**, including an assessment of the safety and integrity of the site in the short and long term, an assessment of the risk of leakage under the proposed conditions of use, and of the worst-case environment and health impacts.

The competent authorities can consult the standard ISO 27914:2017³ for guidance on how to evaluate the comprehensiveness and robustness of risk assessments.

According to the standard ISO 27914:2017 (Article 6.7 and 6.9), risk assessments shall include a comprehensive process for risk identification, technically defensible risk analysis, and a transparent, traceable, and consistent process for risk evaluation, which should document the level of risk before any risk treatment, the effect of risk treatment, and the predicted level of risk after risk treatment. The results of risk assessments shall be recorded in a project **risk register**.

According to the standard ISO 27914:2017 (Article 6), the process for risk management should include the following steps:

1. Establishing the **context** for project risk management, which should consist of the elements that may influence assessments or perceptions of risk, such as:
 - a. natural environment and hazards
 - b. regional natural resources and activities
 - c. infrastructure and facilities

³ <https://www.iso.org/standard/64148.html>

- d. social, political, and economic context
 - e. policy, legal and regulatory environment
 - f. industry recommended practices
 - g. project operator and subcontractors
 - h. uncertainties about each aspect of the project
 - i. project scale and duration
2. Identifying the **risk evaluation criteria** for elements of concern such as human health and safety, the environment, and system performance (e.g. injectivity, capacity, containment, and service reliability). Risk evaluation criteria shall serve to distinguish between acceptable, tolerable and unacceptable risk. terms of time, effort, likelihood of success, and secondary risk scenarios potentially entailed by risk treatment. A risk evaluated as unacceptable shall be reduced by implementation of risk controls and evaluated as acceptable before the storage project proceeds to a stage where the risk scenario can occur.
3. Developing and implementing a **risk management plan**, which should, in particular, include
- a. a description of the organizational procedures to be applied to risk management
 - b. a design of the site-specific monitoring plan
 - c. a description of a site-specific modelling and simulation program, incorporating the monitoring results
 - d. an assessment of associated uncertainties

According to the standard ISO 27914:2017 (Article 6.3), the above items should be implemented during the initial site screening, selection, and characterization periods, and be iteratively repeated in a consistent, transparent, and traceable manner throughout the project life cycle.

2.2 Initial CO₂ storage risk assessment at Stenlille

2.2.1 Context

Gas Storage Denmark (GSD) is progressing through the detailed engineering phase of a large-scale, commercially operational onshore CO₂ storage facility. GSD aims to operationalize the subsurface storage facility by 2026.

The project site is the Stenlille structure located in Central Zealand, Denmark, recognized for its over three decades of natural gas storage operation and the support from the local community. The Stenlille structure, a salt-induced anticlinal 4-way closure, presents optimal conditions for the injection and storage of substances like natural gas and CO₂.

Stenlille boasts the most extensive onshore dataset in Denmark, including comprehensive 2D and 3D seismic data along with twenty wells furnished with wireline log data. Fourteen wells are presently functional for natural gas injection production, while the rest serve monitoring purposes. The accumulated data, along with extensive knowledge of the subsurface from long-term gas storage operations, provide a solid foundation for establishing an efficient CO2 storage facility.

The primary reservoir within the Stenlille structure is the Gassum Formation, approximately 150 meters thick, predominantly comprising Upper Triassic to Lower Jurassic sandstones interspersed with clay stringers. Situated roughly 1,500 meters below the surface, this reservoir is capped by around 300 meters of the mud-dominated Jurassic Fjerritslev Formation, further overlain by approximately 1,100 meters of the limestone-rich Cretaceous-Paleocene Chalk Group, with less than 100 meters of Quaternary deposits atop. The Gassum Formation exhibits high average porosities around 25% and permeabilities up to 7 Darcy. The Fjerritslev Formation's proven sealing capacity, established during gas storage operations, boosts confidence in its competency as a seal while additional low porosity chalk adds further reliability.

Despite the advantageous characteristics of the Stenlille structure, the concurrent gas storage and CO2 injection processes present challenges. Ensuring that natural gas storage and production can continue seamlessly alongside CO2 injection is crucial. Scheduled for readiness in 2025, the project will unfold in two stages, beginning with the conversion of one observation well into a CO2-injection well, followed by drilling additional wells further down the flank.

2.2.2 Risk assessments workshops

Two comprehensive risk assessment workshops were conducted at GEUS in March 2023 and March 2024 to evaluate potential threats to the Stenlille storage site. Both workshops were organized by researchers from British Geological Survey (BGS) and GEUS, who were joined by the subsurface team from GSD. The goal of the workshops was to brainstorm on potential risks of CO2 storage at Stenlille, to assess the corresponding probabilities, severities, and associated uncertainties, as well as to put forward a list of mitigation and corrective measures. The 2023 workshop was targeting the risks, associated with CO2 injection via two new wells at the flank of the Stenlille structure. Later, a decision was made by GSD to re-purpose an existing observation well for CO2 injection, which required organizing a second risk assessment workshop in 2024.

The outcome of the workshops is a risk register, which will be used by GSD in preparation for the anticipated CO2 injection operations. This preliminary assessment was qualitative, targeting risks related to injection and storage. Risks concerning CO2 capture and transport, CO2 stream composition, health and safety operations, and financial aspects were deemed beyond the scope

of the ConsenCUS project. However, a comprehensive CCS project would necessitate assessing all such risks for a storage permit application.

2.2.3 Risk register

During the risk assessment workshops, the participants compiled a risk register identifying 50 perceived risks associated with the proposed CO2 storage site at Stenlille. Each risk was categorized in terms of its probability of occurrence, severity of impact, and uncertainty (1=very low, 2=low, 3=moderate, 4=high, 5=very high). The severity assessment included concerns about both human safety and the project’s economy.

The identified risks were ranked based on the product of the estimated probability of occurrence and the severity of impact. A part of the 2024 risk register is presented in Table 1 (the full register is confidential to GSD).

Table 1. Selected risks for CO2 storage at Stenlille.

Risk No.	Risk Description	Unmitigated Risk scores					Mitigation measures (preventative measures)	Remediated Risk scores				
		Probability	Uncertainty	Severity	Uncertainty	Probability x Severity		Probability	Uncertainty	Severity	Uncertainty	Probability x Severity
3	Salt clogging due to high salinity in pore water	4	3	3	3	12	Literature review ; operators' experience; coreflooding experiments; geochemical modeling; participation in research projects; an initial freshw ater flush prior to	2	3	2	1	4
7	Early breakthrough of CO2 into natural gas storage	3	3	4	4	12	Geological facies modelling; CO2 plume monitoring & history-matching.	2	2	3	3	6
12	Degradation of sealing capacity related to geochemical reactions	2	5	4	4	8	Literature review ; core-flooding experiments; geochemical modelling.	1	1	2	3	2
13	CO2 leakage out of the storage complex due to uncertainty in top reservoir topography	2	3	4	4	8	Detailed static geological models; sensitivity studies for CO2 plume migration.	1	2	1	2	1
18	Induced seismicity that can be felt and reported in the media with a negative impact on reputation.	2	1	3	5	6	Establish seismic baseline; monitoring of seismicity; communicating monitoring results with the local	2	1	2	2	4
31	Degradation of reservoir quality related to geochemical	2	2	2	2	4	Literature review ; core-flooding experiments;	2	2	2	2	4

3 CO₂ storage monitoring

3.1 Legal requirements

Monitoring of the CO₂ injection facilities, the storage complex, and the surrounding environment is required by Article 13 of the CCS Directive for the purpose of:

- comparison between the actual and modelled behavior of CO₂ and formation water.
- detecting significant irregularities.
- detecting migration of CO₂.
- detecting leakage of CO₂.
- detecting significant adverse effects for the surrounding environment.
- assessing the effectiveness of any corrective measures.
- updating the assessment of the safety and integrity of the storage complex in the short and long term.

Article 3 of the CCS Directive provides the following definitions for the terms above:

- 'Storage site' means a defined volume area within a geological formation used for the geological storage of CO₂ and associated surface and injection facilities.
- 'Storage complex' means the storage site and surrounding geological domain which can influence overall storage integrity and security; that is, secondary containment formations.
- 'migration' means the movement of CO₂ within the storage complex.
- 'leakage' means any release of CO₂ from the storage complex.

Note that identification and definition of storage complex is critical as leakage is defined as the release of CO₂ from the storage complex whereas movement of CO₂ within the storage complex is defined as migration.

The monitoring should be based on a monitoring plan, which should be based on the risk assessment analysis (presented in Annex I of the CCS Directive). The plan shall be updated pursuant to the requirements laid down in Annex II of the CCS Directive and in any case every five years.

The specific requirements to the monitoring plan are listed in Annex II of the CCS Directive:

- The monitoring plan should be deployed at the main stages of the project (baseline, operational and post-closure).
- At each stage, the plan should contain the parameters monitored, the monitoring technology employed and its justification, monitoring locations and spatial sampling rationale, frequency of application and temporal sampling rationale.
- The following parameters are mandatory for monitoring (other parameters should be selected to fulfil the purposes of monitoring):
 - fugitive emissions of CO₂ at the injection facility.
 - CO₂ volumetric flow at injection wellheads.
 - CO₂ pressure and temperature at injection wellheads.
 - chemical analysis of the injected CO₂.
 - reservoir temperature and pressure.

The choice of monitoring technology shall be based on best practice available at the time of design.

3.2 Development of a monitoring plan for Stenlille

3.2.1 Considered scenario

Consider a scenario, when CO₂ is injected at the flank of the Stenlille structure during concurrent injection and production of natural gas in the center of the structure.

A solution snapshot in Figure 1 illustrates the saturation distribution after 10 years of CO₂ injection in ST-6 at a rate of 300 Kt/year. CO₂ migration is slow due to a relative gentle relief on the flanks of the Stenlille structure. The simulations show that the CO₂ plume will not reach the natural gas accumulation for a post-injection period of more than 100 years.

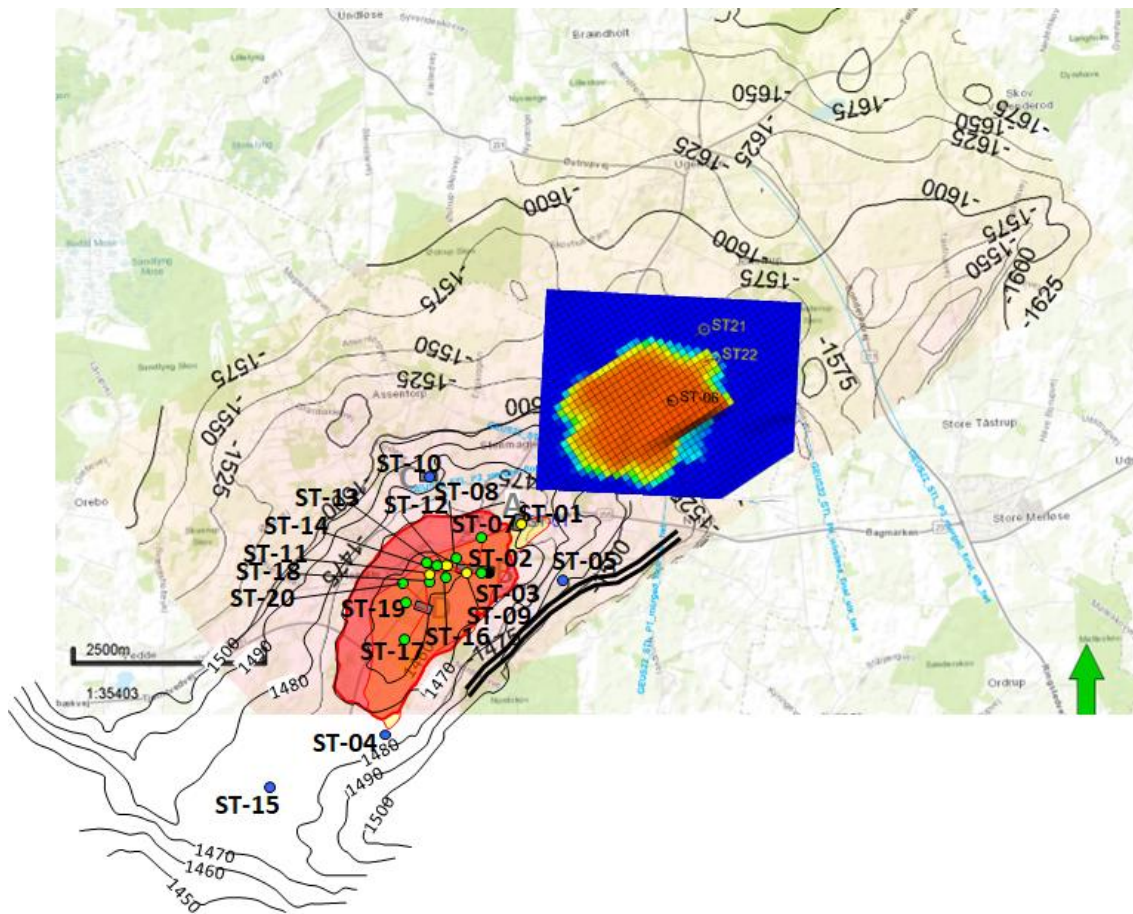


Figure 1. Numerical simulation results after 10 years of CO₂ injection at Stenlille. The red area in the NE part of the reservoir denotes high CO₂ saturation, whereas red area in the SW part corresponds to high CH₄ saturation.

3.2.2 Recommended monitoring methods

The operator will need to demonstrate conformance and containment, i.e. that the subsurface CO₂ plume behaves as expected from simulations, and that there is no leakage. We will describe the possibilities for monitoring the migration of the subsurface CO₂ plume, including lateral migration within the reservoir formation as well as upwards in case of leakage. Important methods for the monitoring of the plume migrations are active and passive seismics and seismicity.

The pressure increase due to CO₂ injection may lead to land uplift. The uplift will typically be a few (millimeters or) centimeters over a large area and is unlikely to pose a risk of settlement damage, however, it is important to monitor the surface movement to detect unintended events, such as unexpected rock-mechanical response or fault reactivation.

Though leakage to ground- and surface water is improbable, it is still an important target for monitoring, especially due to the proximity to surface activities and local population. Leakage of CO₂ to the groundwater can change the water chemistry directly in terms of higher dissolved inorganic carbon content and higher partial pressure of CO₂ P_{CO_2} , but also in site specific ways depending on the CO₂ <-> aquifer mineral interactions of the specific site.

Leakage of CO₂ to the atmosphere may occur along the infrastructure installed for the CO₂ transport and injection, e.g. along well heads, pipelines or processing facilities, or along geological fault zones reaching up towards the surface if such are present in the storage complex. The CO₂ concentration in air may be measured with CO₂ meters installed at the surface, mounted on drones, or with satellite-based sensors.

3.2.2.1 Distributed Acoustic Sensing (DAS)

Distributed Acoustic Sensing (DAS) technology is a sophisticated fiber optic-based monitoring method that transforms standard optical fibers into an array of thousands of vibrational sensors. This technology works by sending short pulses of light down an optical fiber and analyzing the subtle changes in the backscattered light caused by vibrations along the fiber's path. These vibrations could be due to seismic activity, mechanical disturbances, or acoustic waves, allowing DAS to capture and record spatial and temporal acoustic data over large distances, often up to tens of kilometers.

The core principle behind DAS is the interference pattern created by the interaction between the incident light pulse and the backscattered light, which is altered by strain variations due to acoustic or vibrational energy. This process is known as Rayleigh backscatter. By measuring these changes, DAS systems can detect and locate disturbances with high precision along the entire length of the fiber optic cable. Each segment of the cable effectively acts as an individual sensor, providing data that can be used for various applications such as pipeline monitoring, perimeter security, traffic management, and importantly, geological monitoring such as observing subsurface processes in oil and gas fields or carbon capture and sequestration sites.

In the context of environmental monitoring, particularly for carbon sequestration, DAS technology offers an unobtrusive and highly scalable solution. It enables continuous, real-time monitoring of subsurface CO₂ movement and the integrity of geological storage sites. This technology's ability to provide a dense spatial array of sensors over large areas makes it exceptionally valuable for detailed, high-resolution underground imaging and monitoring, enhancing both the safety and efficiency of carbon storage operations.

3.2.2.2 Vertical Seismic Profiling (VSP)

Vertical Seismic Profiling (VSP) is a seismic measurement technique used primarily in the exploration of oil and gas and for monitoring geological storage such as CO₂ sequestration. Unlike traditional surface seismic methods, which predominantly record seismic waves reflected back to the surface, VSP involves placing seismic sensors (geophones, hydrophones or DAS fiber-optics) directly in a borehole. This configuration allows for the collection of seismic data at various depths along the borehole, providing a detailed vertical profile of the earth's subsurface properties.

In VSP, seismic waves are generated at the surface or near the surface and then recorded by the array of geophones in the borehole. These waves can be downward traveling from the source (down going waves) or reflections from the geological layers (upgoing waves). Analyzing the upgoing waves gives direct insights into the properties of the rock layers, including their type, fluid content, and porosity, by evaluating how these layers affect the seismic waves' speed, amplitude, and energy.

The principal benefit of VSP geometry for seismic monitoring is a much smaller degree of disturbance to other land users, such as farmers. This is common for any permanent receiver installation (with a borehole as a 'permanent installation' even if a conventional VSP tool is used through intervention). Much lower noise level than surface seismic, and the high repeatability of the acquisition geometry results in better data repeatability. Thus, the borehole seismic setup detects smaller signals, which is essential for the early detection of CO₂ leaks and in detecting the leading edge of a plume. Borehole seismic allows the use of both down-going and up-going waves. The direct P wave reasonably estimates the far-field source signature and is widely used to perform deconvolution in VSP data processing. This is useful for cross equalizing the different vintages in time-lapse seismic and improving the resolution of the data. There are added benefits of placing seismic receivers all the way down to, or even below, the injection interval. Proximity to the injection interval eliminates blind spots in illumination. Monitoring reflectivity changes above the storage interval and travel time delays within and below the injection interval can help constrain velocity-saturation relations.

While a conventional surface seismic survey, especially with a dense array of source and receiver points covering a large area, offers unparalleled imaging capabilities, the associated survey cost and land impacts can be substantial. In contrast, 4D VSP, while unable to replicate surface seismic spatial coverage, provides a cost-effective approach that meets specific containment and conformance requirements for CO₂ sequestration. A key advantage of VSP for CO₂ sequestration monitoring is its synergy with other monitoring requirements, such as pressure and geochemical monitoring, which necessitate offset monitoring wells. VSP acquisition, with its focus

at the well, also has a low threshold of detection for above-zone leakage that can arise from well integrity issues. The benefits and limitations of DAS Cross-hole/VSP are summarized in Table 2.

Table 2. Benefits and limitations of DAS Cross-hole/VSP.

Benefits	Limitations
High spatial resolution: DAS VSP provides high spatial resolution along the length of the borehole, capturing detailed changes in the subsurface due to CO ₂ injection and migration.	Signal-to-noise ratio: DAS systems, particularly in VSP configurations, can sometimes suffer from lower signal-to-noise ratios compared to conventional geophone-based systems, potentially complicating data interpretation.
Real-time monitoring: Offers continuous, real-time data on the seismic responses from the subsurface, crucial for timely decision-making and intervention in CO ₂ sequestration.	Depth limitation: While DAS provides excellent resolution along the length of the cable, its effectiveness can be limited by the depth and spacing of available boreholes, which might restrict full reservoir characterization.
Cost-effective: DAS systems utilize fiber optic cables, which can be cheaper to install and maintain compared to traditional geophone arrays.	Technical complexity: The interpretation of DAS data can be complex and requires specialized knowledge, particularly in differentiating between meaningful seismic signals and noise.
Flexibility and coverage: The use of fiber optics in multiple boreholes enables extensive coverage and flexible deployment, enhancing the monitoring network's ability to detect anomalies across a broader area.	Sensitivity variability: The sensitivity of DAS can vary along the fiber optic cable due to variations in the coupling of the fiber to the borehole wall, affecting the consistency of data quality.
Durability: Fiber optic sensors are generally more durable and less sensitive to environmental hazards such as corrosion or mechanical wear, which is beneficial in harsh subsurface environments.	

3.2.2.3 Seismic acquisition

Seismic acquisition can be used to image the replacement of brine with CO₂ in the subsurface, because this will lead to a change in the seismic parameters (e.g., AVO response, spectral decomposition). Seismic acquisition may be done with active sources (e.g., vibroseis trucks for onshore surveys) or passive sources (noise from anthropogenic or natural sources, e.g. trains,

traffic, waves). Seismic surveys may be designed as downhole surveys, where the sources or receivers are placed in wells, as surface 2D surveys where source points and receivers are placed along profiles, as surface 3D where source points and receivers are placed in a grid, or as a combination of those. Repeated 3D surveys are referred to as 4D seismics or time-lapse acquisition.

Passive ambient seismic noise methods

Oceanic waves are strong sources of Rayleigh waves at frequencies between 0.1 to 1 Hz. They can be recorded anywhere on Earth, even at large distance (several 100s of km) from the shore. The amplitudes of Rayleigh waves are known to decrease exponentially away from the surface. Suppose the elastic properties of the solid are stratified on a scale much smaller than the wavelength. In that case, the Rayleigh-wave amplitude at a given depth should also be influenced by the formation properties: the softer the medium, the larger the amplitude. The increasing use of fiber-optic cables in wells allows for recording this depth variation of Rayleigh-wave strain amplitudes and their variations over time (due to changes in formation properties) using distributed acoustic sensing (DAS). Rayleigh-wave amplitudes measured with vertical fiber-optic cables can be used to detect thin layers in the subsurface. Time-lapse analysis of these amplitudes should indicate temporal changes in the stiffness of these layers, such as changes in saturation or pressure of the fluid in a porous layer near the borehole. Specifically, Rayleigh-wave amplitudes are sensitive to the presence in the vicinity of the wellbore of a CO₂ plume created due to a small injection into a thin, porous reservoir layer. The effect of a thin layer on Rayleigh-wave amplitudes strongly depends on frequency, providing an opportunity to use amplitude variations with depth at different frequencies to separately estimate changes in bulk and shear moduli.

Coda-wave interferometry

Existing seismic monitoring methods based on wave reflection or transmission probe a limited rock volume and their sensitivity decreases as CO₂ saturation increases, decreasing their utility in quantitative plume mass estimation. Seismic scattered coda waves, acquired during continuous borehole monitoring, can illuminate details of CO₂ plumes. Seismic velocity reduction in the reservoir during and after injection can be measured extremely finely using Coda Wave Interferometry because coda waves repeatedly sample the heterogeneous distribution of cumulative CO₂ in the reservoir zone. Because this approach does not depend on P-wave arrival times or require well-constrained wave reflections, it can be used with many source-receiver geometries, including those external to the reservoir, which reduces the risk introduced by in-reservoir monitoring wells.

Recommended permanent seismic monitoring system components (Isaenkov, et al., 2021)

Distributed Acoustic Sensing (DAS):

- Utilizes fiber optic cables as seismic receivers, offering high spatial resolution and the ability to measure dynamic strain along the cable length.
- Benefits from the installation of advanced DAS systems in wells, allowing continuous, real-time monitoring.

Conventional Seismic Sensors:

- Complement DAS by providing data from different locations and depths, enhancing overall data quality and reliability.
- Typically, geophones or hydrophones are installed at various points to capture broader seismic data.
- A permanent surface dense array of 3-components geophones would be ideal

Permanent Seismic Sources:

- Employ seismic orbital vibrators (SOVs) as permanent, automated sources to generate reliable seismic signals.
- SOVs are programmed to operate sequentially and frequently, ensuring continuous data flow.

Well Geometries:

- Multi-well configurations with deviated drilling to optimize seismic coverage and ensure comprehensive monitoring across the storage site.
- Strategic placement of wells relative to predicted CO₂ plume migration paths, enhancing the detection and monitoring capability.
- Well deviated below the CO₂ reservoir

3.2.2.4 Geochemical monitoring

Geochemical monitoring should preferably be done on relevant parameters that can be monitored remotely with robust (stable) sensors, it can be measured by submerged probes/sensors or using lab-on-a-chip measurements on pumped water samples.

Monitoring far above the geological structure holding the CO₂, in the potable groundwater zone and in surface waters, is faced with several issues. The vertical distance implies that it is difficult to predict precisely where leaked CO₂ will appear, it may even appear in areas not immediately above the storage. Furthermore, in case of presumably limited leakage, the geochemical signal available will be weak due to a combination of the geochemical reactions and the physical dispersion occurring during transport of the CO₂ from the leakage outlet towards the surface. To address these issues the following considerations should be part of the monitoring plan.

Hydrogeological flow model and monitoring points

The overall ground- and surface water flows in the area above the storage is examined in the existing DK-model, a 100 x 100 m grid, hydrogeological model covering all of Denmark. Using this existing model as the boundary conditions a more detailed hydrogeological model is set up for an area above the storage and extending some kilometers further out. The DK-model does not extend to the depth of the storage so the model should be extended vertically downwards to include the geology above the site, extending to the surface. The new knowledge of the geology obtained in the preparation for the geological CO₂ storage should be included in the new detailed hydrogeological model. Assuming that the injection boreholes as well as possible older existing exploration boreholes and known fault zones are the most probable (though probabilities are extremely low) sources of leakage, the volumes around and downstream of these “focus zones” should receive special care in terms of model detail and high-resolution gridding.

In general, the monitoring points should be placed so that they intercept flowlines passing by the focus zones described above. Based on the computed flowlines from the detailed model, monitoring boreholes are chosen from existing boreholes used for water supply and irrigation; in areas where the density of existing boreholes is too low the additional boreholes are installed. When choosing where to monitor, emphasis should be placed on monitoring where flowlines converge as this implies that a given borehole monitors a larger volume of the aquifer, increasing the probability of registering signs of leakage. Likewise monitoring points in surface water bodies should be placed so that they intercept larger volumes of the aquifer. Surface water monitoring, in the surface water as such, is presumably difficult due to fluctuations in chemistry created by biogeochemical processes in the surface water body itself combined with fluctuations in flow, and related to that, the fraction of the water in the surface water body, coming from the groundwater and very near-surface run-off, drainage. Assuming the leakage signal originates from the groundwater part of the flow, installations should probably be made below the bottom of the surface water body, where only the groundwater signal is present, requiring that gaining stream sections or lakes are used. The smaller the leakage amount, flux and duration, the more difficult it will be to detect. The density of monitoring points required to ensure the interception of leakage of any size, reaching the potable groundwater or surface waters, would presumably be unrealistically high. A suggested number of monitoring points could be on the order of 20 downstream and 4 upstream of a given focus zone.

Monitoring parameters

Knowing that the leakage is CO₂, implies that some water chemistry monitoring parameters are obvious. These are DIC (dissolved inorganic carbon), pH (which is lowered with higher CO₂ content) and the EC (electrical conductivity) which indicates the amount of ions in the water, which will increase due to reactions between CO₂ and the water as well as minerals in the aquifer. Regarding EC, uprisings CO₂ could also cause the migration of deeper high salinity water towards

the surface, which could also cause an increase in EC large enough to be seen in the fresh low salinity potable groundwater. Likewise, methane may be carried with the CO₂ if it migrates as a gas phase, or it may come with water migrating due to uprising CO₂. In addition to these parameters, that are directly related to CO₂ and/or its migration, there could be specific ions/dissolved species that are released by minerals in the formations that the CO₂ encounters during the migration upwards through the overlying formations or in the potable groundwater aquifer during transport. The background value and variation for the specific parameters could be low, making the parameters potentially well suited for monitoring. To test for the presence of such parameters, the rock formations overlying the storage could, assuming samples are available from e.g. survey drilling, be incubated with water and a CO₂ atmosphere and the water chemical composition be determined over time, looking for specific monitoring parameters. Depending on the source of the CO₂ it may be possible to monitor for ¹³C (a stable carbon isotope) of the C in the DIC, if the ¹³C value of the injected CO₂ is far from the background ¹³C value in the aquifer being monitored. Likewise the oxygen isotope ¹⁸O in water may also be affected due to exchange with the oxygen in CO₂, if the ¹⁸O value in the CO₂ is different from the groundwater. Together with ¹⁸O the ²H should also be measured, which it normally is, because shifts in ¹⁸O due to exchange with CO₂ will only affect ¹⁸O and not the ²H, in contrast to evaporation and condensation which affects both ¹⁸O and ²H.

Baseline monitoring

After testing for specific parameters, a baseline for the parameters that are relevant for the location needs to be established. In general groundwater systems have not been monitored with high frequency measurements, implying that in order to avoid false positives during monitoring during and after injection it is necessary to establish both a general baseline, but also an assessment of the variability during a period with high frequency sampling and measurements. The most probable cause for natural variation in the groundwater chemistry over time is changes in the flow direction due to pressure distribution changes due to changes in pumping rates or the local infiltration pattern. Both pumping patterns as well as infiltration patterns are expected to vary seasonally. For pumping it can be due to the activation of irrigation wells or changes in water use due to summer guests in summer house areas, or the closing and/or opening of water abstraction wells for normal/constant demand water supplies. Pumping related to both irrigation and water supply will often vary diurnally as well.

Monitoring program

Based on the observed variations of baseline variations of the optimal parameters at the site, the monitoring frequency for a given parameter should be adjusted so that natural transients are not misinterpreted as false positives of leakage. Over time, results of the monitoring will create a

longer baseline that can be used to adjust monitoring frequencies so that they are optimized for detecting relevant signals.

Given that very little will probably happen and that the monitoring program will go on for a long time, a machine learning system should be trained on the accumulated data collection as well as data from other monitoring programs to increase chances of not overlooking relevant signals, but also to enable a consistent monitoring over the long-time frame. If possible, the machine learning could be combined with other sets of observational data from the other disciplines such as geophysics.

3.2.2.5 Satellite-based measurements of land uplift

InSAR (Interferometric Synthetic Aperture Radar) and GNSS (Global navigation Satellite System) are suitable methods to measure land uplift. InSAR provides satellite-based measurements of surface movements with mm precision. A free webservice with InSAR dating back to 2015 is available from the European Ground Motion Service (EGMS) using the data from the Sentinel-1 satellites of the EU Copernicus program. GNSS can provide detailed time series of surface movements at stations installed at the ground. In combination, InSAR and GNSS can provide a good spatial and temporal monitoring of surface uplift.

3.2.3 Monitoring plan template

It is convenient to summarize the monitoring plan using a template, similar to the one, provided in the EU Guidance Document 2⁴, see Table 3.

⁴ https://climate.ec.europa.eu/eu-action/industrial-carbon-management/designing-and-implementing-industrial-carbon-management-projects_en#paragraph-3536-1-title

Table 3. A template for the draft monitoring plan for CO2 injection at Stenlille.

Rationale for monitoring	Parameter to be monitored	Technique adopted	Category of monitoring		Project phase and frequency				Location
			Required	Contingency	Pre-inj.	Inj.	Post-inj.	Long-term stewardship	
Mandatory by CCS Directive	CO2 emissions at the injection facility	Atmosphere CO2 meters, satellite-based sensors	x						
Mandatory by CCS Directive	CO2 injection rate	Flow meter	x			Continuous			
Mandatory by CCS Directive	Wellhead P & T	Manometer, thermometer	x		Baseline data	Continuous			
Mandatory by CCS Directive	Injected CO2 composition	E.g. GC	x						
Salt clogging due to high salinity in pore water	Injection rate, wellhead pressure	Flow meter, manometer	x						
Early breakthrough of CO2 into natural gas storage	Produced CH4 composition, seismicity	E.g. GC, DAS, VSP	x						
Degradation of sealing capacity related to geochemical reactions			x						
CO2 leakage out of the storage complex due to uncertainty in top reservoir topography	Pressure monitoring - plume migration	Perimeter observational wells - repeated seismic, InSAR	x						
Induced seismicity leading to being felt and reported in the media with a negative impact on reputation.	Seismicity		x						
Degradation of reservoir quality related to geochemical reactions			x						
Mandatory by CCS Directive and to facilitate public acceptance	ground- and surface water chemistry possibly affected by CO2 leakage	automatic logging, water sampling with on-line or lab measurements	x		Baseline data	Continuous	Continuous	Continuous	focus zones: near injection wells, legacy wells and fault zones

Conclusions

The present ConsenCUS deliverable D4.5 contains the following main results, which allow for improved estimates of the storage safety at Stenlille for the injection scenario in Section 3.2.1:

1. The severity of the risk that salt precipitation due to dissolution of CO₂ in high salinity formation water at Stenlille seriously reduces the injectivity is estimated to be **moderate** to **low**.
2. The severity of the risk that the seal degrades due to geochemical reactions is estimated to be **low**.
3. The severity of the risk that CO₂ injection will lead to considerable induced seismicity is estimated to be **low**.

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