DigiMon Deliverable D2.8: Project report with guidelines and recommendations for a monitoring system to be applied at a set of planned or active CCS sites

Digital monitoring of CO_2 storage projects

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1 Background

The DigiMon project is concerned with developing a monitoring system that facilitates and accelerates the implementation of large-scale geological storage of CO_2.

1.1 Monitoring objectives

Key components of any CO_2 storage project are measurement, monitoring, and verification (MMV). Each project must show that the project is being executed safely, securely, and according to plan.

The national regulatory requirements for the implementation of CCS in Europe including Norway and UK are following the regulations as provided by the EU. Hence, for the DigiMon project, we follow the EU regulations as specified in the CCS directive 2009/31/EC with amendments[1]. The directive provides a minimum set of requirements, which means that the Member States may adopt more stringent rules on the national level. However, in Schütz, Omar & Carpentier, (2021) no significant new mandatory monitoring phases, monitoring aims, or requirements for specific monitoring technologies is found in national legislation. The aim of the directive is to establish a legal framework for the ‘environmentally safe geological storage of carbon dioxide (CO_2)’ to contribute to the fight against climate change. The purpose is permanent containment of CO_2 ‘to prevent and, where this is not possible, eliminate as far as possible negative effects and any risk to the environment and human health’.

Annex II of the directive gives clear directions related to ‘the choice of monitoring technology’, underlining the situational, site-by-site approach. This choice ‘shall be based on best practice available at the time of design’. Hence certain features ‘shall be considered and used as appropriate’, for example that they ‘can detect the presence, location, and migration paths of CO_2 in the subsurface and at surface’.

The regulations identify different storage phases: pre injection of CO_2, during injection, and after (post) storage is sealed. In the DigiMon project, we are concerned with developing a monitoring system for the injection phase. Hence, the monitoring objectives will in part build on the information available from

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[1] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0031

data collection, analysis and model building performed in the pre injection phase. A description of the storage site and identified risks are presented in Section 4.

The DigiMon system is further to represent a planned, standard “early-warning” monitoring system which would trigger additional data collection only in the case of ‘significant irregularity’. Here ‘significant irregularity’ means any irregularity in the injection or storage operations or in the condition of the storage complex itself, which implies the risk of leakage or risk to the environment or human health. This approach provides the opportunity to combine planned and triggered data acquisitions and consider the long-term nature of CO_2 injection projects.

1.2 The analytical hierarchy process

The DigiMon project has highlighted that monitoring geological storage of CO_2 is a task that spans multiple disciplines from technology to economics and social science. Optimizing a monitoring solution based on very diverse criteria from different disciplines is challenging, so a methodology was needed that was able to take the multi-disciplinarity into account and make a more holistic assessment rather than only assessing a few criteria against each other.

Several methods exist to facilitate making rational decisions involving multiple criteria, and the Analytical Hierarchy Process (AHP), developed by Thomas Saaty (Saaty, 1990) is one such widely used methodology to assist in multi-criteria decision making (MCDM). AHP has been applied to many different areas spanning from politics, engineering, education, industry, and management (Vaidya, Kumar, 2006).

The main idea of AHP is to break down the overall decision goal into sets of criteria, grouped into a hierarchy representing the various aspects to be considered. The criteria can be weighted based on their perceived importance for achieving the main goal. The weighting of the criteria will be storage site dependent and will in addition to some degree depend on the national public perception of risks associated with CO_2 storage.

In the evaluation process, a set of solution alternatives are to be given scores according to their ability to fulfil the individual criteria. By this an overall ranking of the alternatives can be computed and provide a rational basis for deciding on an optimal monitoring solution for a site.

2 Method

The AHP has been applied to the DigiMon project, by first identifying and grouping criteria for the monitoring solution (section 3). The criteria were identified by the project in a joint meeting involving people from different disciplines and have later been harmonized by aligning them with EU regulations[2].

For the site to be monitored, we have chosen a generic brine filled geological structure on the Norwegian Continental Shelf. The main characteristics of the storage site are outlined in section 4.

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[2] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0031

In section 5, we present three alternative monitoring solutions. The alternatives were defined based on literature surveys and internal discussions in the project. The solutions are to be evaluated according to the monitoring criteria defined in section 3.

For gathering the scores used in the assessment of the monitoring alternatives, a dedicated questionnaire was developed. As outlined in section 6, this questionnaire was distributed to the members of the Digimon consortium with the Steering committee and technical advisory board. Section 7 presents the outcome of the evaluation with an overall summary of rankings for all (sub-) criteria.

3 Digimon monitoring criteria

The Digimon project has identified a list of criteria and associated sub-criteria for evaluating a CO_2 storage monitoring system. Below these criteria are outlined in some detail. The descriptions are meant to be technology-agnostic. Any references to specific technologies that may be used to fulfil the different criteria are avoided, as this may introduce bias in the evaluation of the monitoring alternatives.

The defined criteria are summarised as a hierarchy in Figure 1, and each sub-criterion is further described in the following sections.

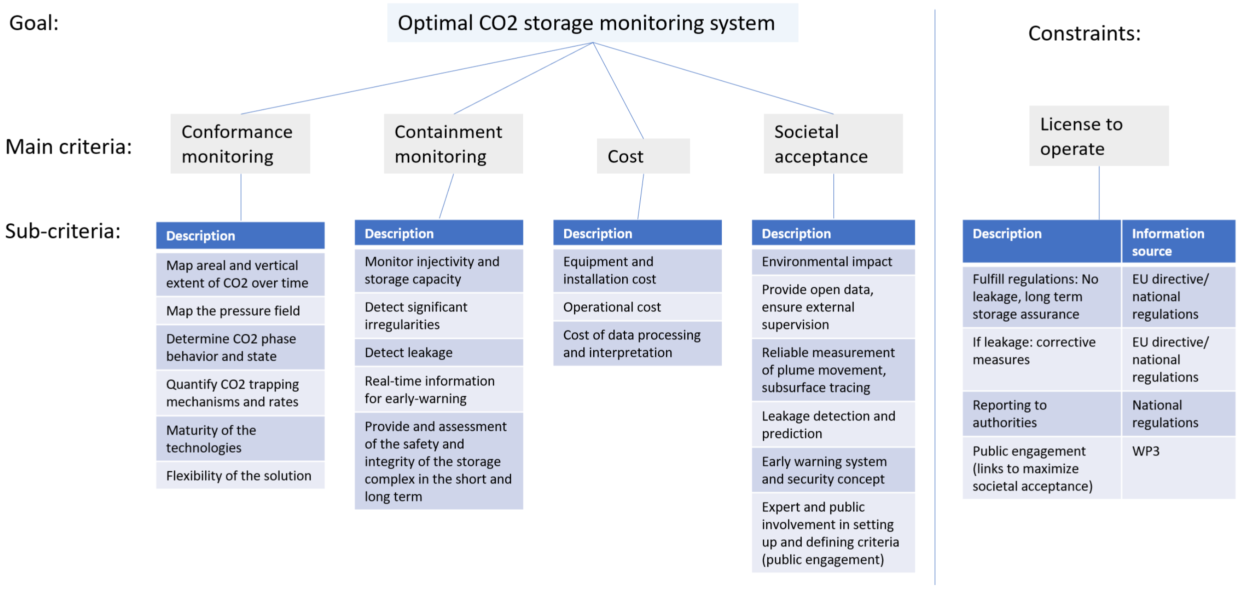

Figure 1 Hierarchy of defined criteria for a CO_2 storage monitoring system

3.1 Conformance monitoring

Conformance monitoring is the first main criterion that the monitoring alternatives are to be evaluated against. The purpose of conformance monitoring is to ensure that the migration of the CO_2 plume and the corresponding evolution of the pressure field are well understood and in conformance with the model predictions and the geological understanding of the storage complex prior to injection.

In Annex I of the EU's CCS directive, parameters and processes to be covered by the geological and dynamic-flow models of the CCS storage site are listed. The list is extensive and includes amongst others the following: the geological structure of the physical trap; fracture systems, and presence of any human-made pathways; pore space volume (including porosity distribution); pressure and temperature of the storage formation as a function of injection rate and accumulative injection amount over time; areal and vertical extent of CO_2 vs time; the nature of CO_2 flow in the reservoir, including phase behaviour; CO_2 trapping mechanisms and rates (including spill points and lateral and vertical seals); secondary containment systems in the overall storage complex; storage capacity and pressure gradients in the storage site; seismicity and elevation at surface level.

Conformance monitoring is an extensive task. However, of primary importance is to ensure that the behaviour of CO_2 in the reservoir is understood and that the model-based flow predictions and risk assessments leading up to being licenced to inject CO_2 are valid.

Following the analytic hierarchy process, this criterion is divided into a set of sub-criteria presented below.

3.1.1 Map the areal and vertical extent of CO_2 vs time

This criterion concerns the tracking of the CO_2 plume location and movement. This is typically done through an inversion process, where well data and geophysical measurements may be combined to provide a 3D map of the CO_2 plume with as low uncertainty as possible (Tveit et al., 2020, Zhu et al., 2015).

In the DigiMon project, a Bayesian inversion framework will be used to evaluate different combinations and configurations of sensors and technologies, as well as how sensor density and frequency influence the ability to accurately map the CO_2 plume.

3.1.2 Map the pressure field

The CO_2 injection will alter the fluid pressure and stress field within the reservoir. Monitoring of the pressure evolution is key to ensuring that reality and model predictions align.

Moreover, mapping the pressure plume is critical to inform about the connectivity within the unit and enables prediction of the risk of fault reactivation and opening of new migration paths in the storage complex.

Fault reactivation and generation of new fracture networks can be monitored through passive seismic monitoring, listening for micro-seismic noise in the subsurface (Stork et al., 2015). However, pressure build-up and fault slip also lead to aseismic subsurface deformations (in terms of pore space expansion or slow slip events) that is best monitored by mapping strain and more long-term deformations in wells and at the subsurface.

3.1.3 Determine CO_2 phase behaviour and state

Determining the phase behaviour and state of the CO_2 is key to predict the plume migration, injectivity, and storage capacity of the reservoir. Especially for shallow storage units, the density and phase behaviour of CO_2 in the reservoir is highly sensitive to pressure and temperature variations; and, hence, difficult to predict by seismic alone.

Hence, for this criterion the ability to monitor the pressure and temperature in wells will be key.

In addition to point measurements of pressure in wells, field-wide information on the pressure plume behaviour can be obtained through the measurement of seafloor deformations across the field. Moreover, seafloor 4D microgravity gives a direct measure of density changes within the storage unit.

3.1.4 Quantify CO_2 trapping mechanisms and rates

In geological storage in saline aquifers, the CO_2 is primarily structurally trapped as a free phase within the brine-saturated host rock.

To confirm structural trapping a thorough understanding of the connectivity across the field including possible compartmentalization of sands and communication across faults is required. In addition, the viscous, gravity and capillary forces determining the flow dynamics need to be understood to accurately predict the evolution of the CO_2 plume.

Dissolution of CO_2 in brine is important in stabilizing and securing long-term storage. However, the estimates of the rates at which CO_2 dissolves in brine vary enormously pending on site-specific flow characteristics. Determining the dissolution rate on the short and long term can be achieved by using natural analogues, field data (microgravity, geochemical methods) and improved understanding of the hydrogeological properties of the storage unit.

Mineralisation is expected to play a minor role for CO_2 storage in saline aquifers consisting of sandstones or carbonates, whereas the reactions with clay minerals are more complex.

3.1.5 Maturity of the technologies

A monitoring setup with technology components considered mature may be given preference over a monitoring setup with less mature technologies, at least during a transition phase before the less mature technologies have been demonstrated successfully in a full-scale system over a certain period.

For an assessment of the technological readiness of different technologies, we refer to DigiMon Deliverable 2.3: TRA of DigiMon components.

3.1.6 Flexibility of the solution

A monitoring solution that can be adapted to changing conditions may be given preference over a more rigid solution. A flexible solution may consist of sensors that are mobile or can be adapted to different purposes.

3.2 Containment monitoring

The purpose of containment monitoring is to ensure that CO_2 stays within the storage unit. For this, technologies providing data that can (following the EU CCS directive) image the presence, location and migration paths of CO_2 are required. For containment, potential irregularities and major deviations relative to model predictions should be detected, for example, unexpected migration paths or indications that the storage has a lower capacity than expected.

3.2.1 Monitor injectivity and storage capacity

Deep saline aquifers are among the most favourable geological sites for short- and long-term carbon geo-sequestration. However, determining the amount of CO_2 that can be stored in deep saline aquifers is a complex task. Their storage capacity is governed by the pore volume available for CO_2 storage and the density of CO_2 at reservoir conditions which are again controlled by the size, temperature, and pressure in the reservoir together with the porosity of the reservoir rock. In addition, connectivity across the field is another key parameter affecting the available storage volume, and the degree of communication across faults is always a source of uncertainty.

The ability to inject the volumes of CO_2 as determined by the storage capacity depends on the injectivity. This capacity of the well(s) to push the CO_2 through the matrix into the storage volume is controlled by transmissibility, connectivity, permeability, pressure gradient in the well together with the skin factor.

3.2.2 Detect significant irregularities

Following the regulations, a significant irregularity means any irregularity in the injection or storage operations or in the condition of the storage complex itself, which implies the risk of a leakage or risk to the environment or human health.

Permanent downhole pressure sensors provide data that can be used for observation and optimization of the injection process. Sudden unexpected changes of the pressure may indicate significant irregularities in the reservoir, like fracturing and opening of new flow paths for CO_2.

The ability to monitor chemical changes in wells may reveal wellbore leakage of CO_2. Damage during well construction or CO_2 injection can allow CO_2 to escape from the reservoir into the water column, and chemical sensing may be able to detect this at an early stage.

In addition, technologies are required that can provide a wide areal spread to capture information on any previously undetected potential leakage pathways across the areal dimensions of the complete storage complex.

3.2.3 Detect leakage

Leakage is here defined as migration of injected CO_2 outside of the storage complex. Risk of leakage may for example increase due to faults and fractures, inadequately sealed wells or loss of well integrity (Iyer et al., 2022)

Detection of such leakage may be through a combination of monitoring techniques including seismic, downhole temperature and pressure sensing with more.

3.2.4 Real-time information for early warning

To detect abrupt changes in the operations or in the condition of the storage complex itself and enable the implementation of mitigating actions in the case of significant irregularities the timeliness of the information obtained from monitoring is key.

Real-time data can be obtained by continuous monitoring by permanently installed sensors in wells or at the seabed.

3.2.5 Provide an assessment of the safety and integrity of the storage complex in the short and long term

This criterion addresses the requirement of the monitoring solution to provide sufficient information to validate the assessment of whether the stored CO_2 will be completely and permanently contained in the storage unit.

3.3 Cost

The cost of a monitoring system includes all costs from acquiring the sensors, installation and operation and maintenance of the sensors. The cost also includes the cost of processing the data from the sensors. When weighting between investment costs and operational costs, the costs may be converted to a lifetime cost where the investment costs are distributed over the expected lifetime of the equipment.

3.3.1 Equipment and installation cost

This type of cost is a one-time investment cost to purchase and install the sensors and the needed infrastructure to have a working monitoring system up and running.

3.3.2 Operation and maintenance cost

This criterium refers to the running cost to maintain and operate the sensors and the infrastructure.

3.3.3 Cost of data processing and interpretation

Data processing and analysis have a cost in terms of person-hours, data storage, and CPU hours. Different data types need processing of different complexities depending on the purpose and nature of the measurements. Moreover, translating the data into knowledge about the subsurface requires expertise and dedicated tools for analysis tailored to the information source at hand.

3.4 Societal acceptance

For societal acceptance, a monitoring system should adhere to the perceptions and expectations that the public and stakeholders have towards CCS and CO_2 storage monitoring systems. The goal of the DigiMon project is to provide design options, including societal concerns and perspectives.

3.4.1 Environmental impact

This criterium addressed whether the monitoring system and the monitoring techniques have negative environmental impact. Some of the sensors may require preparation of the seabed before installation, which may impact the marine vegetation temporarily. Other types of measurements like active seismic surveys, may cause stress, avoidance, and loss of hearing of local animal life, although the scientific literature is not clear regarding the impact (Carrol et al., 2017; Nowacek et al., 2015).

The surveys with the public in Germany, Norway, Greece, and The Netherlands conducted by WP3 find that a low environmental impact of the monitoring system (for instance concerning the impact of monitoring on marine animal life) is a relevant criterion for the perception of monitoring options.

3.4.2 Provide data access, ensure external supervision

Access to monitoring data and external supervision of the data may improve the public and stakeholder trust in the monitoring system. In the interviews conducted in the WP3 assessment it became clear that transparent data access and the supervision of the monitoring process by independent and trusted actors are important characteristics of a socially embedded monitoring technology. This resonates with previous research that highlights transparency as a relevant factor in the communication of CCS projects (e.g. Broecks et al. 2016, Terwel 2015, de Vries et al. 2016; and, for an overview, Otto and Gross 2021). Data provision, however, should be moderated, meaning that data interpreted for easy access should be provided to non-experts to avoid misunderstandings and to transform the raw data output in a comprehensible form. The monitoring data should thus be incorporated in communication and public engagement strategies (see experiences on the Tomakomai CCS project in Japan, Mabon et al. 2017).

Concerning the external supervision, both the perception of the public and the carbon storage site operators needs to be considered when discussing trusted actors to supervise the monitoring process. The WP3 survey finds that there are regional differences in the trust levels allocated to different actors (e.g., Norwegians perceive governmental actors as much more trustworthy than Dutch, German, or Greek respondents) but scientists and environmental NGOs are generally seen as rather trustworthy (see DigiMon Deliverable 3.3 for more details). Interviews with industrial stakeholders in CCS, however, revealed that environmental NGOs are not perceived as trusted actors.

3.4.3 Reliable measurement of plume movement, subsurface tracing

The WP3 survey finds that the reliable measurement and prediction of plume behaviour is a core characteristic that the public expects from a carbon storage monitoring system. More than 80 percent of the respondents in all four countries agreed with the importance of indicating and measuring CO_2 plume movements.

3.4.4 Leakage detection and prediction

Like the measurement of plume movement, the detection and prediction of leakages are seen as a principal element of CO_2 storage monitoring systems.

3.4.5 Early warning system and security concept

Survey and interview results conducted in WP3 also indicate that the monitoring system should be connected to a warning system and a security concept if the observed plume behaviour is unexpected. The actual warning system might be a task more directly linked to the operation of the CO_2 storage site but the WP3 results indicate that the connection between the monitoring, warning and actual security measures should be made transparent (e.g., by explaining different safety measures already in place in the storage complex like multiple barriers or indicating that the most eminent safety measure would be the stop of injection).

3.4.6 Expert and public involvement in setting up and defining criteria (public engagement)

Based on the WP3 results a socially embedded monitoring system should be developed and set up by experts. Most respondents in all countries state that the primary responsibility for information gathering, defining how monitoring is conducted and who is responsible for the monitoring should lie with experts. At the same time the results show that these processes should be open for public participation. This can best be summarized by framing the monitoring system as designed and operated by experts but open to public concerns and interests.

3.5 License to operate

Each potential storage site needs a separate assessment of capacity and leakage risk, and a dedicated risk-based monitoring programme.

The monitoring requirements set forth by regulations are technology-neutral, reflecting the principle of best available technologies. CO_2 monitoring regulations give the site operator considerable freedom and, consequently, responsibility when designing a monitoring programme to satisfy the overall requirements. The main factors to consider are which technologies to use, and the spatial and temporal sampling intervals, factors that influence both cost and information content.

In Annex II point 1.1, it is stated that the following 'shall' be specified for each phase: 'a) parameters monitored; (b) monitoring technology employed and justification for technology choice; c) monitoring locations and spatial sampling rationale; (d) frequency of application and temporal sampling rationale'.

4 Site description

The suitability of a geological formation for use as a storage site is defined through characterization and assessment of the potential storage site by:

I. Building a detailed geological earth model and dynamic flow model predicting, inter alia, the evolution of pressure, temperature, the areal and vertical extent of CO_2, storage capacity, seismicity, and surface elevation

II. Conducting a site-specific risk assessment characterising the potential for leakage from the storage complex, as established through the dynamic modelling and sensitivity analysis

The risk assessment shall include consideration of, among other things:

a) potential leakage pathways
b) the potential magnitude of leakage events for identified leakage pathways (flux rates)
c) critical parameters affecting potential leakage (for example maximum reservoir pressure, maximum injection rate, temperature, sensitivity to various assumptions in the static geological Earth model(s))

The regulations require that a geological formation shall only be selected as a storage site, if under the proposed conditions of use there is no significant risk of leakage, and if no significant environmental or health risks exist. For a description of a possible workflow for containment risk assessment, we refer to Zweigel et al, 2021.

For the evaluation of the monitoring alternatives, a generic brine-filled geological structure on the Norwegian Continental Shelf is selected as the storage site. It is assumed that an initial site description, model building, and risk assessment have been conducted incorporating available information on the site before injection (i.e., from a confirmation well and geophysical data sets). Hence, the next step is to build the base-line monitoring plan for the first years of injection.

Below, a description of the site is provided, listing the key features and identified risk factors.

4.1 Key features of the storage unit

- Feasible for large-scale CO_2 injection of up to ten megatons per year
- Offshore with subsurface storage in a brine aquifer
- Relatively shallow depths between 1000 and 1500 meters below the seafloor
- Laterally extensive covering more than 50x50 square kilometres
- Sand structure interbedded by clay acting as baffles to flow
- Structural definition
- Fault closure at three sides
- Structural spill-point at one side. Here structural spill point refers to the shallowest depth where CO_2 can start to escape the first geological trap as represented by an anticline (see Figure 2).

4.2 Key features of the storage complex

- Layered with multiple stratigraphic formations including permeable sands and impermeable clay layers acting as barriers to flow
- The structural stratigraphy extends laterally beyond both sides of the shown stratigraphic sketch. Hence, laterally leaking CO_2 is assumed to accumulate within adjacent sand structures below the primary seal. However, if the CO_2 migrates beyond the structural spill point, the risk analysis and monitoring plan should be revisited to validate that these structures are able to contain the migrated volumes.

- Faults extend from the storage unit to the top of the storage complex. It can be assumed that pre-injection tests have been performed and that there is no evidence of pressure communication beyond the faults

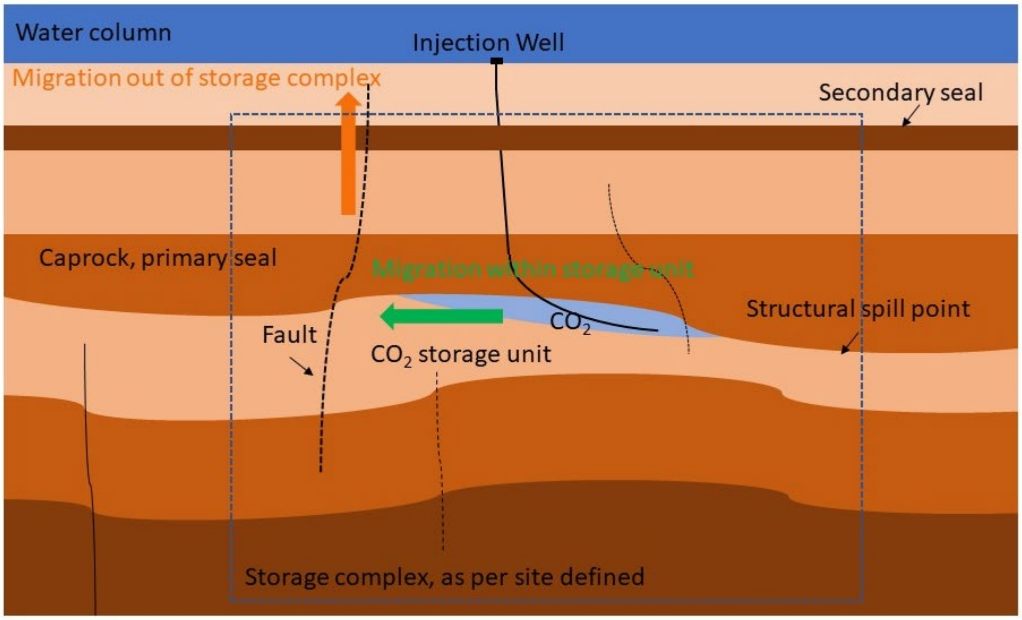

Figure 2: Sketch illustrating the key features of the generic storage site to serve as the benchmark when evaluating the different candidate monitoring solutions in the DigiMon project. Note the sketch is not in scale and is exaggerated in the vertical direction.

4.3 Uncertainties in the site description and model predictions at the time of application for a license to operate

- Lateral heterogeneity and compartmentalization (e.g., are faults sealing or open)
- Storage capacity (prediction of CO_2 phase behaviour)
- Reservoir-internal heterogeneities in permeability and capillary forces (effects evolution of CO_2 plume, magnitude of residual trapping, and the dissolution rate of CO_2 in brine).
- Communication between layers

These uncertainties will be reduced over the first years of injection and monitoring. Some of the monitoring criteria specifically address the reduction of the uncertainties listed above.

4.4 Potential risk factors

- Pressure build-up and reactivation of faults
- Migration out of the storage unit either along faults or towards a structural spill point
- Loss of well integrity and creation of potential leakage pathways through the well

If the normal monitoring, during injection, shows evidence that any of the risk factors may occur, the risk assessment and the monitoring plan should be updated accordingly. The description of such triggered monitoring plans is, however, outside the scope of this study, since these plans will have to be designed according to what caused the trigger. Here we will deal with the baseline monitoring setup to check for conformance, containment, and detection of potential anomalies.

5 Alternative solutions for monitoring large-scale, geological storage of CO_2 offshore

In this section, three alternative monitoring solutions are set up representing different combinations of technologies and data types.

The monitoring alternatives all represent a suggested monitoring solution to provide the information to ensure conformance and containment and detection of significant irregularities. However, they are not designed to answer additional requirements arising in the case that any significant irregularities should be disclosed either operationally or in the understanding of the subsurface and flow dynamics. If irregularities are discovered, a triggered monitoring scheme should be developed tailored to the situation. Such triggered monitoring plans are considered outside the scope of this study.

We will assume that for all three alternatives, there is a topside platform nearby with a fibre optic connection to the injection well so that data from pressure/temperature gauges, DAS/DTS/DSS data and ocean bottom seismometers can be recorded continuously in real-time from the platform. We assume that the platform is close enough for DxS-interrogators to be placed on the platform without significant loss of signal strength. An alternative to a platform might be to have the interrogators on a ship and retrieve the connection to the DAS cables on the sea floor periodically (e.g., from a floating buoy), but with this solution one would not be able to monitor with the DxS cables continuously.

The monitoring plans are to be revisited every fifth year. The monitoring alternatives outlined below are to cover the first ten years of operation given that the project is developed according to plan.

We consider the injection rate for the first five years to be around 1.5 Mt/y. The site is assumed to have a capacity of up to 10 Mt/y, but with a gradual increase in injection rate, a rate of 10 Mt/y will not be achieved until the end of the 10-year period.

Based on literature studies (Hansen et al. 2013, Jenkins 2020, Furre et al. 2017, Furre et al. 2019, Furre et al. 2020, Ringrose et al. 2021), studies of monitoring plans for planned and existing[3,4] storage sites, and discussions within the DigiMon project, we have defined three different monitoring alternatives. We view these alternatives as a way to explore new solutions and build experience and competence in their

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[3] https://nettarkiv.miljodirektoratet.no/hoeringer/tema.miljodirektoratet.no/Global/dokumenter/horinger/Vedtak/Vedtak%20om%20tillatelse%20til%20lagring%20av%20CO2%20p%C3%A5%20Sn%C3%B8hvitfelteta596.pdf?epslanguage=no

[4] https://nettarkiv.miljodirektoratet.no/hoeringer/tema.miljodirektoratet.no/Global/dokumenter/horinger/Vedlegg%201%20-%20M%C3%A5leprogram%20og%20overv%C3%A5kningsplana596.pdf?epslanguage=no

capabilities (weaknesses and strengths as monitoring tools). The three alternatives differ mainly along three lines:

- The use of active seismic surveying with streamers.
- The use of fibre-based sensing (DAS, DSS, DTS) at the seafloor and in wells
- The use of complementary data types (DAS, microgravimetry, seafloor deformation monitoring)

In addition, there are differences between the alternatives regarding sharing of information. The different sharing options are based on learnings in DigiMon WP3, where they find that sharing data with independent experts beyond the regulatory requirements may increase public trust in the process (Otto et al, 2022). Two different options have been assigned to the alternatives, mainly to get feedback on the assessments of the social acceptance criteria (see section 3.4).

After assessing these three monitoring alternatives, it may be possible to create new monitoring solutions based on the feedback, combining the best aspects of each initial alternative.

5.1 Alternative I (active seismic surveying)

- Active seismic streamer providing 3D seismic data (Baseline and repeats every two years or for every 3 Mt of CO_2 injected, depending on which comes first)
- Temperature and pressure gauges after pump and downhole at injection depth
- Measurement of CO_2 injection rates
- Continuous passive seismic monitoring by five ocean bottom seismometers in the vicinity of the well. Suggested placement can be on opposite sides of the faults as indicated in Figure 3.
- Data will be processed and interpreted by the operator[5]. Results will be shared with the government and public according to regulations

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[5] The text prior to the evaluations was unclear on this point. The current text reflects the original intention.

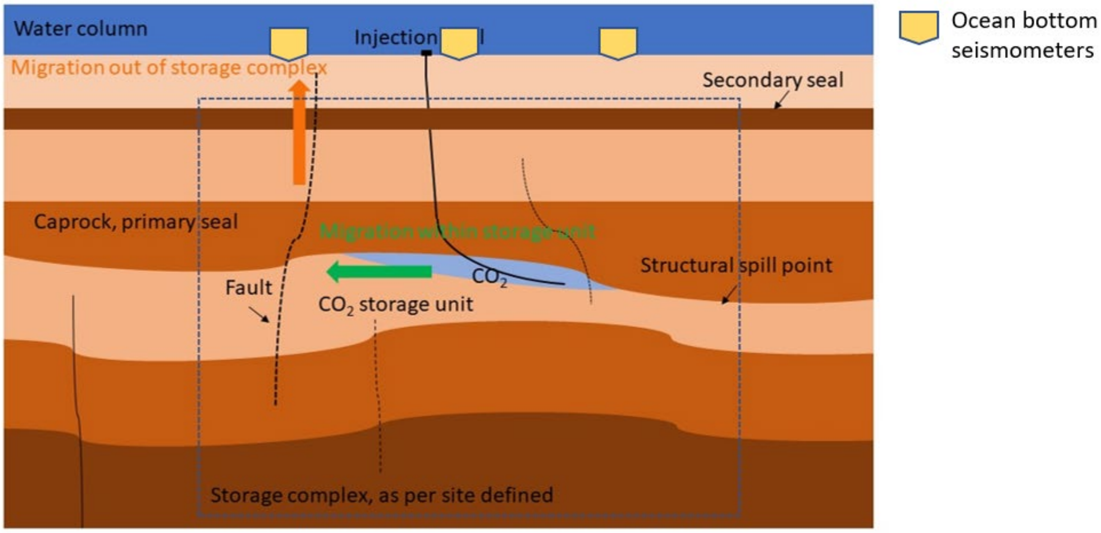


Figure 3 Suggested approximate placement of ocean bottom seismometers

5.2 Alternative II (use of distributed fibre optic sensing)

- Active seismic using lines of DAS on the seabed and DAS cable in the injection well (Baseline and repeats every year or for every 1.5 Mt of CO_2 injected, depending on which comes first). The DAS cable will be clamped on the tubing to avoid introducing potential leakage pathways from installing it outside the casing. Clamping on tubing has led to good-quality images according to Kiyashchenko et al., 2020. The layout of the DAS cables on the seafloor is illustrated in Figure 4 and will be low buoyancy untrenched cables to save costs with trenching. It is assumed that the cables will eventually be covered in mud and provide reasonable coupling and noise levels, as reported by Zhan et al., 2020.
- DSS on the seabed and in the injection well to monitor strain
- Temperature and pressure gauges after pump and downhole at injection depth
- DTS measurements in the injection well
- Measurement of CO_2 injection rates
- Continuous passive seismic by DAS using both the cables at the seabed and the injection well. These can be used for Ambient Noise Interferometry (ANI) and micro-seismic monitoring
- In addition to the data processing and sharing in alternative I, the raw data will be shared with research institutes and universities by request

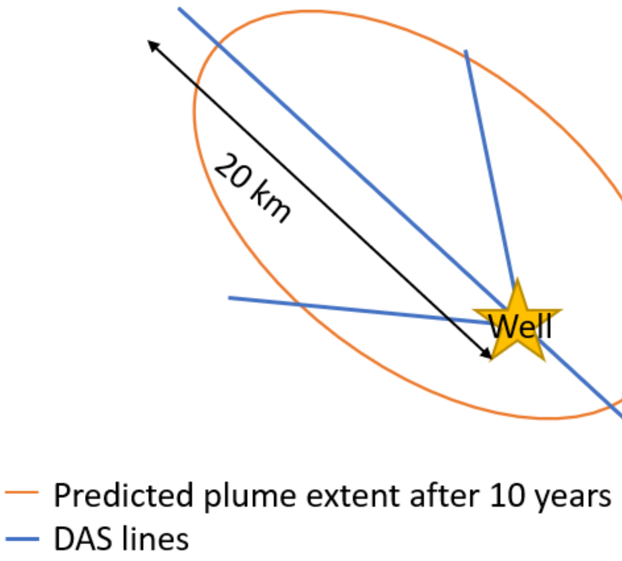


Figure 4 Illustration of the proposed DAS layout on the seabed in alternative II

5.3 Alternative III (use of complementary data types)

- Active seismic streamer (Baseline and one repeat after two years. Then more infrequent repeats every six years)
- Temperature and pressure gauges after pump and downhole at injection depth
- Measurement of CO_2 injection rates
- Microgravimetry and seafloor deformation (Baseline and repeats every two years)
- Continuous passive seismic by DAS in the injection well
- DTS measurements in the injection well
- DSS in the injection well to monitor strain
- In addition to the data processing and sharing in alternative I, the raw data will be shared with research institutes and universities by request

It is assumed that the reduced cost of seismic data acquisition with permanently installed sensors enables more frequent surveying with active seismic sources in alternative II than in alternative I. In alternative III, the use of multiple data sources facilitates reducing the frequency of streamer seismic, see e.g., Vatshelle et al., 2017. There has been progress in the use of continuous seismic monitoring with permanently installed DAS cables and continuous sources with a wide frequency range (Tsuji et al. 2021). However, we view this as a technology that is emerging, and we have decided not to suggest this in any of the alternatives. Still, it may be an option for future monitoring systems.

For a technological readiness overview of the different monitoring techniques, we refer to the TRA report (DigiMon Deliverable 2.3). For a roadmap of developments to implement the technologies, we refer to DigiMon Deliverable 1.10: A roadmap for commercial delivery and implementation of WP1 outcomes.

5.4 Sensitivity of selected measurement types

As an aid in assessing the monitoring alternatives, sample sensitivities for some measurement techniques are given below. More detailed sensitivity studies should build on the dynamic model at the given storage site.

An illustration of the sensitivity of gravimetric measurements is given in Figure 5. For the site described in section 4, with an injection depth of around 1500 meters, we obtain a signal of between 16-18 µGal for 1 Mt CO_2 injected. Here a conservative density contrast between brine and CO2 of 100 kg/m3 is assumed. In practice, this value will depend on the pressure and temperature distribution on the field. The current data accuracy in microgravity at the seafloor is below one µGal (Ruiz H. et al., 2020).

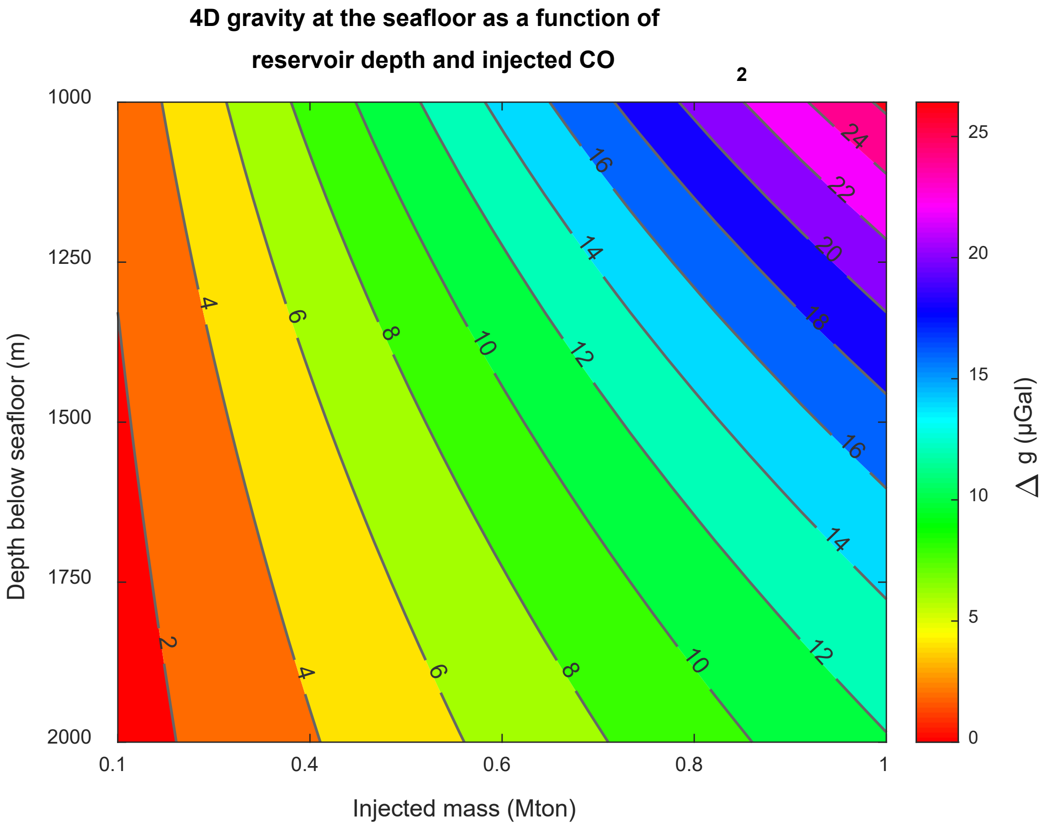


Figure 5 Time-lapse gravity signals at the seafloor for a cylindrical reservoir geometry. The density contrast between brine and CO2 is set to 100 kg/m3, the porosity is 0.2, and the CO2 is assumed to replace brine in 50 % of the pore space. The plume radius is set fixed at 1.5 km. The increasing masses of injected CO2 correspond to increasing the plume height from 1.5 m to 15 m. The observation point at the seafloor is directly above the centre of the plume.

Figure 6 shows seafloor deformation as a function of burial depth and reservoir expansion. To compute reservoir compaction, a linear elastic compaction model with a linear relationship between pressure change, Δp, and pore volume change, ΔV, is assumed: $\Delta Vi = V \Delta p C$. Here V is the initial pore volume, and C is the uniaxial pore compressibility.

The analytical transfer function, T, developed by van Opstal (1974), which accounts for the presence of a stiff basement below the reservoir/aquifer system, is used to model the mechanical response of the subsurface. Combining Van Opstal's transfer function with the compaction field, the total seafloor deformation, S, can be calculated at the desired observation points: $S = \Delta V \cdot T(\overline{r}, \nu)$). The transfer function only depends on Poisson's ratio, ν, and the distance, $\overline{r}$, between the compacting reservoir and the observation point.

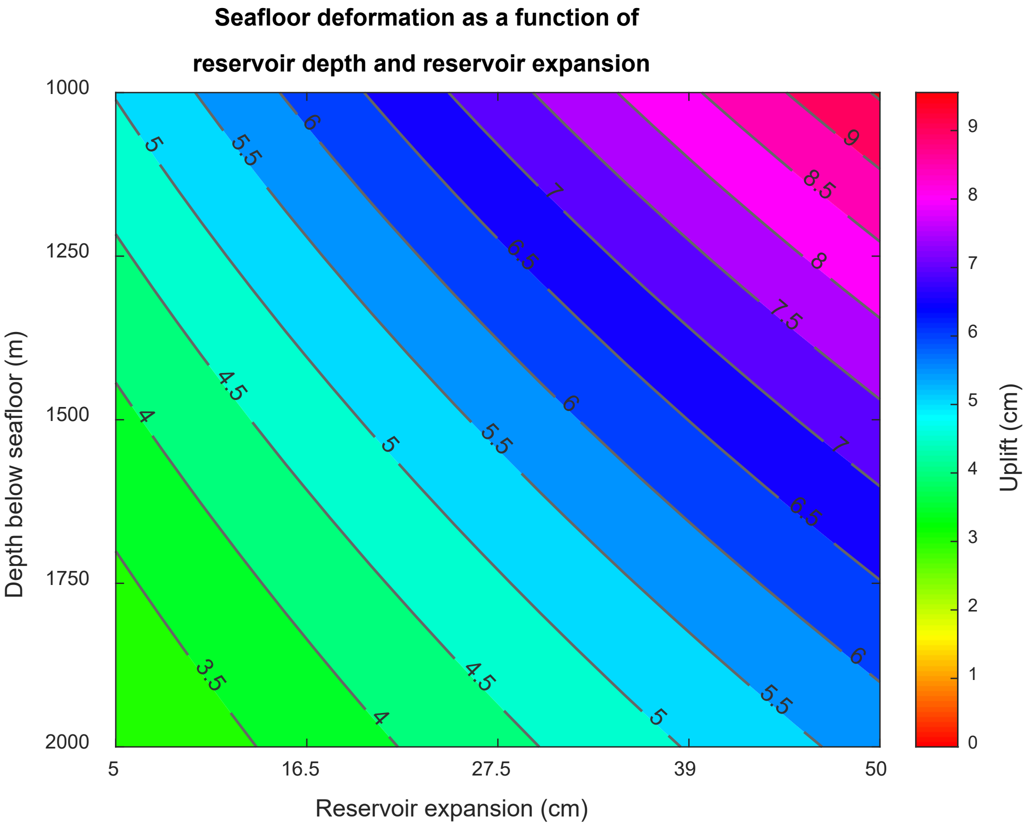


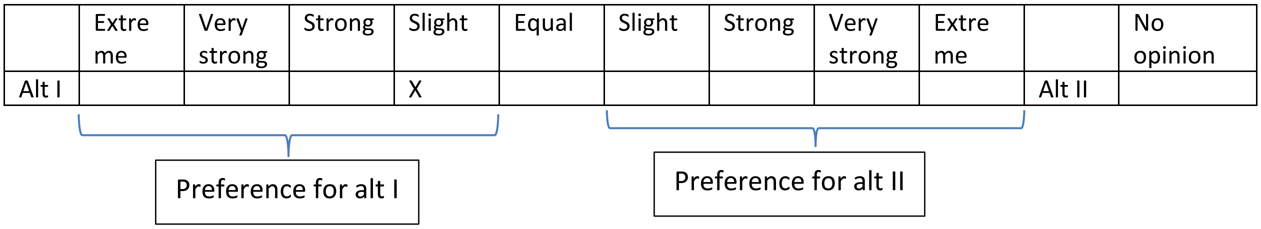
Figure 6 Modelled uplift at the seafloor for a cylindrical reservoir geometry. The reservoir expansion corresponds to a pressure increase ranging from 10 Bar to 100 Bar. The pressure plume is confined within a radius of 2.5 km and a 100 m thick sand interval. The uniaxial pore compressibility is 5E-5 1/Bar. Poisson's ratio is 0.2. The observation point at the seafloor is directly above the centre of the plume.

More information about gravity and seafloor deformation monitoring can be found in the technical readiness assessments provided in (DigiMon Deliverable 2.3), in addition to Alnes et al. 2011, Vatshelle et al., 2017, and Ruiz et al. 2000 with references therein.

Distributed Acoustic Sensing (DAS) has been studied and applied within the petroleum industry and has been demonstrated for the acquisition of borehole seismic data. See Jenkins 2020 for a review of the use of DAS in boreholes at CO_2 storage sites. DAS has also been used as land surface-seismic receivers. See Daley et al. 2013 for results with trenched surface cables at the Otway test site. In a marine environment, the use of DAS to produce subsurface-seismic images is scarcer. However, Taweesintananon et al. 2021 present the use of an existing submarine telecommunication cable for seismic applications and compares it with results from a single-channel hydrophone streamer which is towed behind a research vessel. They find that for water depths larger than the offset range used for DAS imaging, the DAS and hydrophone data have about the same quality. However, the DAS system with straight fibres will only detect strain parallel to the cable axis.

6 Questionnaires

Selected project members and members of the DigiMon steering committee and technical advisory board were asked to answer a questionary to evaluate the alternative monitoring solutions in section 5. Following the recommended practice of AHP, the rankings were done pairwise on the scale ‘Equal’, ‘Slight’, ‘Strong’, ‘Very strong’, and ‘Extreme’. These rankings were associated with the numerical values 1, 3, 5, 7, and 9, respectively, with the reciprocal values for the inverse comparison. If, for example, the respondent prefers alternative I slightly over alternative II, this would be indicated by a checkmark in the box with the heading ‘slight as in Figure 7. Such pairwise assessment is assumed to be easier for humans to perform than ranking multiple alternatives simultaneously.



	Extreme	Very strong	Strong	Slight	Equal	Slight	Strong	Very strong	Extreme		No opinion
Alt I				X						Alt II	

Figure 7 Example of the questionnaire answering sheet where a slight preference for alternative I over alternative II is indicated by a checkmark

The respondents were also encouraged to give comments to accompany the assessments.

6.1 Processing of questionnaires

Eight responses were received, which was considered sufficient to provide a demonstration of the AHP methodology.

The first step was to transform the pairwise rankings into a ranking of the three alternatives. For each criterion, k, the pairwise rankings given by each respondent, l, were assembled into a matrix $A_{k,l}$.

$$A_{k,l} = \begin{bmatrix} 1 & z_{12} & z_{13} \\ 1/z_{12} & 1 & z_{23} \\ 1/z_{13} & 1/z_{23} & 1 \end{bmatrix}, \tag{6-1}$$

where z_{ij} is the ranking given by the respondent between alternative i and alternative j, in the sense that alternative i is evaluated to be z_{ij} better than alternative j. Reciprocal values were then added below the diagonal. The best approximation of the ranking between the alternatives can be shown to be given by the principal eigenvector, $v_{k,l}$, such that:

$$A_{k,l} v_{k,l} = \lambda_{max,k,l} v_{k,l} \tag{6-2}$$

The normalised principal eigenvector, $\overline{v_{k,l}}$, where the elements sum to one, is then defined as the priority vector, or the ranking, between the alternatives for criterion k and respondent l.

6.2 Handling of inconsistent responses

If the responses are entirely consistent, the matrix $A_{k,l}$ in (6-1) will have rank 1. In other words, all rows in A will be scalar multiples of each other. However, in practice, most assessments are not completely consistent. Inconsistencies are partly due to the discrete scale used and partly due to the nature of human judgement being approximate. Some inconsistency is allowed, however, and handling this is part of the AHP.

For a consistent matrix A, the principal eigenvalue λ_{max} is equal to n, where n is the number of alternatives to evaluate. If, however, A is inconsistent, it can be shown that $\lambda_{max} \geq n$. Based on this, Saaty, 1990 introduced a consistency index to measure the level of inconsistency:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{6-3}$$

He then computed the average consistency index of randomly generated comparison matrices, which he called the random consistency index, RI. For $n = 3$, which is the case here, $RI = 0.58$. The consistency ratio, CR, can then be computed as

$$CR = \frac{CI}{CR} \tag{6-4}$$

Saaty, 1990 recommends that for $CR < 10\%$, the judgement is considered acceptable. Otherwise, there may be a reason to ask the respondent to reconsider the judgement, or simply exclude the response from the further processing.

The first part of the processing was, therefore, to exclude inconsistent responses. A cumulative plot of the consistency ratio for all the answers to all the criteria is shown in Figure 8. The jump at around 12 % probably has to do with a combination of the number of alternatives and the discrete scale used in the evaluation. We chose to include all responses with a consistency ratio of less than 12 % instead of the recommended 10 % since, in this case, 12 % seems like a better compromise between the increased robustness by including more responses and the slight increase of the inconsistencies of the responses included.

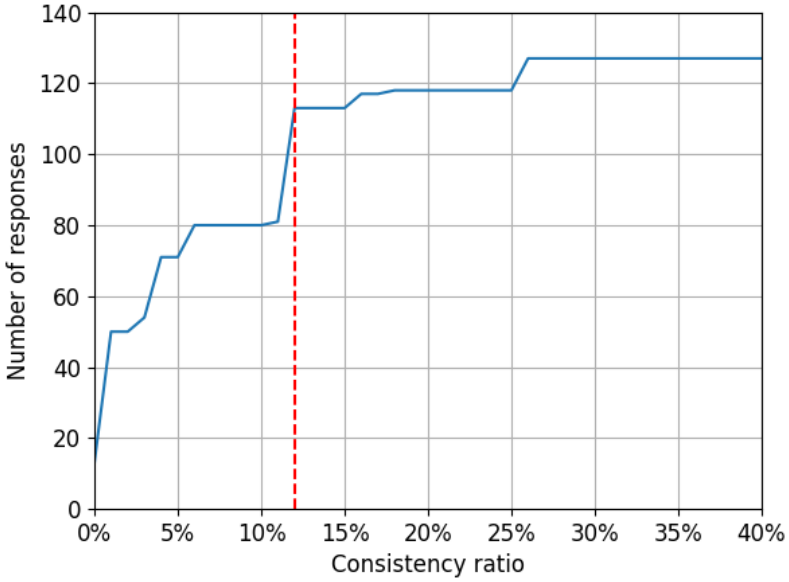


Figure 8 Cumulative plot of the consistency ratio for all responses. The red stippled line is at CR=12%.

6.3 Aggregation of results

The aggregation of the results for each criterion incorporating the feedback from all respondents can be done in several ways. Since the priority vectors are vectors of ratios, a geometric mean is recommended over the more standard arithmetic mean (Krejčí & Stoklasa, 2018). The geometric mean is less sensitive to right (large) outliers than the arithmetic mean. The geometric mean is also used to aggregate results of sub-criteria into results for their parent criteria. The aggregated priority vectors were re-normalized to sum to one since the geometric mean does not preserve the lengths of the aggregated results.

In addition to computing the geometric mean, a measure of the spread is also beneficial when interpreting the results. This spread is something that is usually omitted in the AHP literature, but ought to be included since it can be used to detect disagreement between the responses. As a robust measure of the spread, we use the interquartile range, which is the interval between the 25 % quantile and the 75 % quantile. Note that when there are strong outliers, the geometric mean may sometimes lie outside the interquartile range, although these occurrences are rare.

7 Results

In this section, the aggregated responses for each criterion, including a visualization of the spread, are presented. In all figures, the geometric mean is indicated with a red line, the interquartile range is shown with a filled box, and the max/min is indicated with whiskers. However, for the main criteria, it does not make sense to compute a measure of the spread since they are composed of several sub-criteria, each with their individual distributions. For the main criteria, therefore, only the ranking is shown.

7.1 Conformance monitoring

Assuming equal weighting of all the sub-criteria under the conformance monitoring criterion, we get the ranking of the monitoring alternatives displayed in Table 1. Alternative III is preferred, while the difference between alternative I and II is arguably not significant.

Table 1 Overall ranking for the conformance criterion, assuming equal weighting of the underlying sub-criteria

Alternative I	Alternative II	Alternative III
0.30	0.23	0.47

7.1.1 Map the areal and vertical extent of CO_2 vs time

For this sub-criterion, alternative I is preferred, and alternative II is the least preferred. The deployment of DAS in alternative II (untrenched at the seafloor and outside the well tubing) was identified by some respondents to be probably problematic and outperformed by conventional full 3D streamer seismic. Additional simulations could be done to assess this.

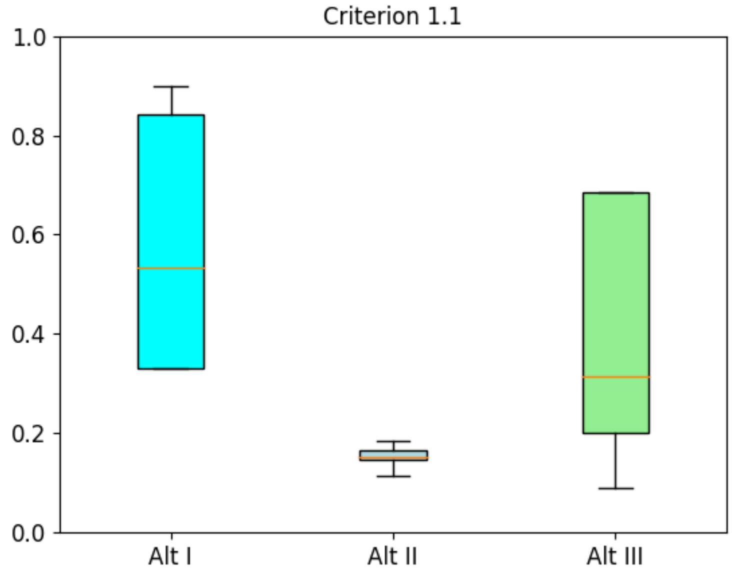


Figure 9 Aggregated results for the criterion “map the areal and vertical extent of CO_2 vs time”

7.1.2 Map the pressure field

Here alternative II comes slightly on top, closely followed by alternative III. Some respondents commented that using DAS/DSS for passive seismic monitoring in alternatives II and III is an advantage. Alternative I include ocean bottom seismometers, but no direct ability to detect vertical reservoir extension. All the alternatives can monitor the near-field pressure by downhole pressure gauges.

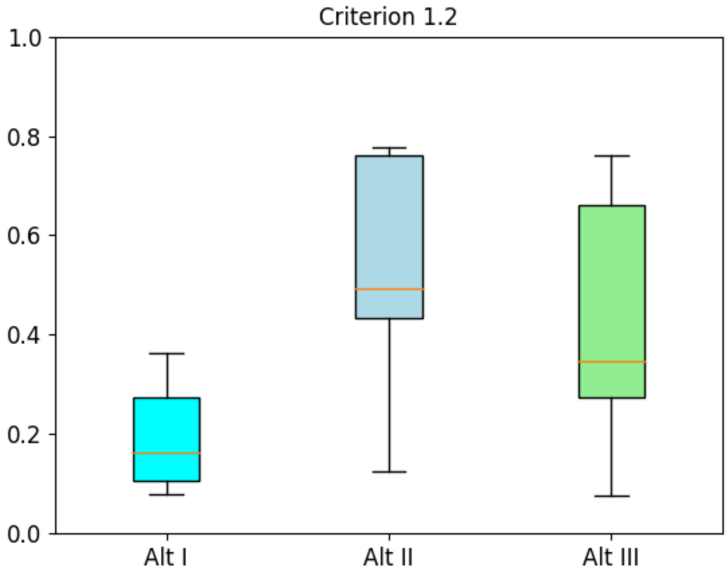


Figure 10 Aggregated results for the criterion “map the pressure field”

7.1.3 Determine CO_2 phase behaviour and state

Alternative III is quite clearly the preferred alternative for this criterion. One respondent commented that the density information from the microgravity information in Alternative III may be the most useful 3D data for this criterion.

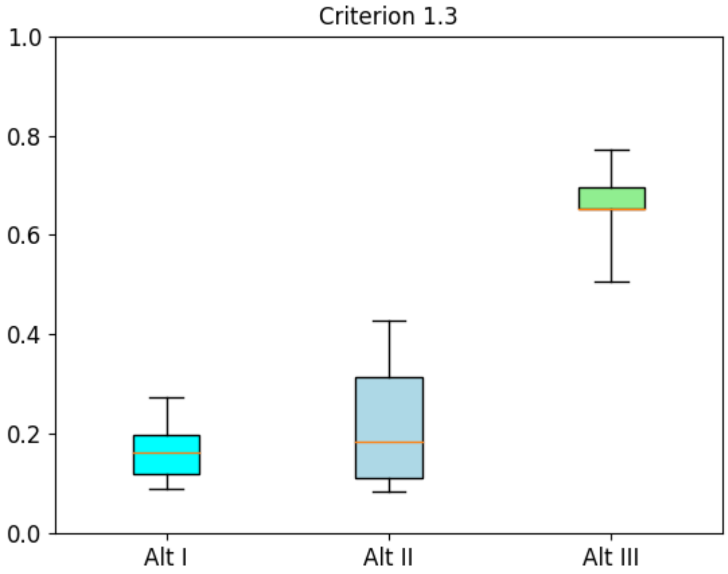


Figure 11 Aggregated results for the criterion “determine CO_2 phase behaviour and state”

7.1.4 Quantify CO_2 trapping mechanisms and rates

Alternative III is the preferred alternative. The combination of 3D seismic with microgravity was commented to give an advantage for alternative III. However, the number of responses for this criterion was lower (four) than for many of the other criteria, indicating missing information or knowledge among the respondents. One respondent commented that there are several trapping mechanisms, each requiring its own monitoring technique. Hence, this criterion could be split into multiple sub-criteria, one for each trapping mechanism, e.g.:

- Structural trapping
- Dissolution trapping
- Pore trapping
- Mineral trapping

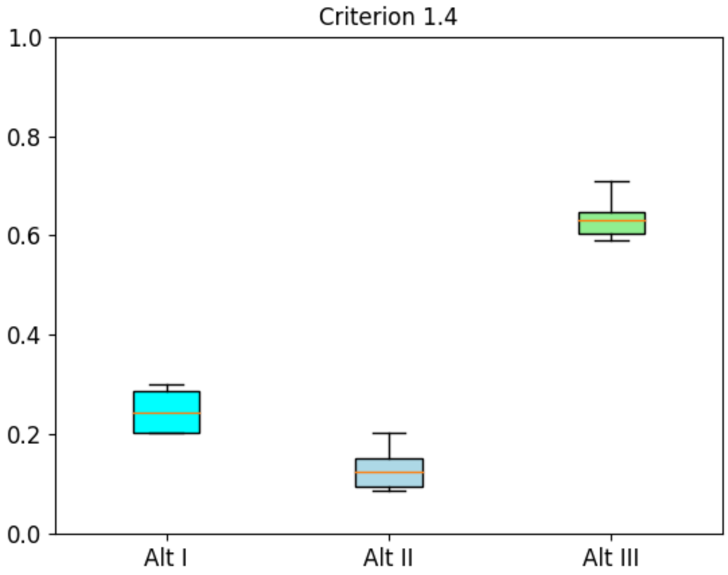


Figure 12 Aggregated results for the criterion "Quantify CO_2 trapping mechanisms and rates"

7.1.5 Maturity of the technologies

Alternative I is the preferred alternative, due to the on average higher TRL levels of its technologies. One respondent rightly commented that key properties are monitored with different methods at different TRLs between the alternatives.

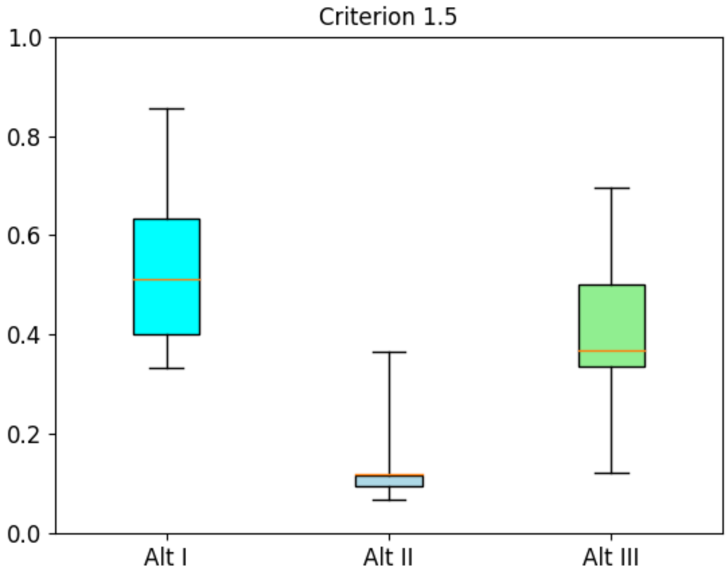


Figure 13 Aggregated results for the criterion "maturity of the technologies"

7.1.6 Flexibility of the solution

The spread of the responses is high on this criterion which may partly be due to different interpretations of the term "flexibility". Flexibility could be understood either as multi-purpose or as mobility of the sensors. In future applications, the criterion should probably be split into the different meanings of flexibility.

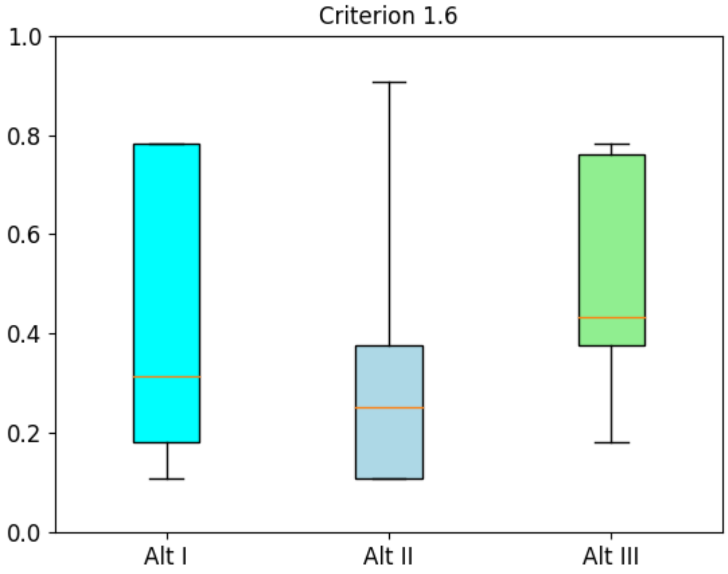


Figure 14 Aggregated results for the criterion "flexibility of the solution"

7.2 Containment monitoring

Assuming equal weighting of all the sub-criteria for the containment monitoring criterion, we get the ranking in Table 2. Alternatives II and III are around twice as preferred as alternative I.

Table 2 Overall ranking for the containment criterion, assuming equal weighting of the underlying sub-criteria

Alternative I	Alternative II	Alternative III
0.21	0.36	0.43

7.2.1 Monitor injectivity and storage capacity

There is almost a tie between alternative I and III for this criterion, while alternative II is less preferred. From the comments, field-wide data is seen as the most valuable to show heterogeneities or areas where CO_2 may not intrude. Alternatives I and III with 3D seismic data are therefore seen as most advantageous for this purpose over alternative II. Alternative III may be slightly more preferential than alternative I with its microgravity measurements to fill in the gap times of non-seismic acquisition.

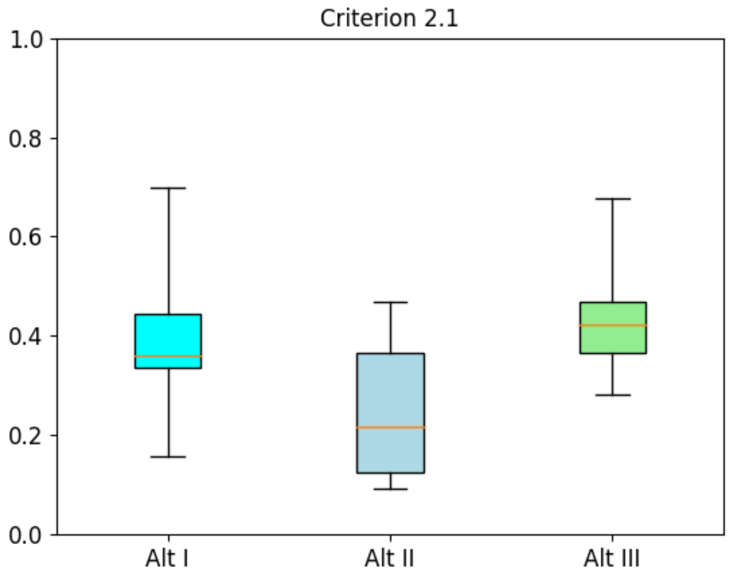


Figure 15 Aggregated results for the criterion "monitor injectivity and storage capacity"

7.2.2 Detect significant irregularities

Alternative III is the most preferred alternative. However, the number of responses for this criterion was lower (four) than for most of the other criteria, indicating missing information among the respondents. From the comments, this criterion should probably be split into sub-criteria. For example, separating irregularities near and far from the well, or even more specifically, splitting between the detection of micro-seismicity along faults, along the wellbore, and other irregularities like CO_2 accumulation in the overburden.

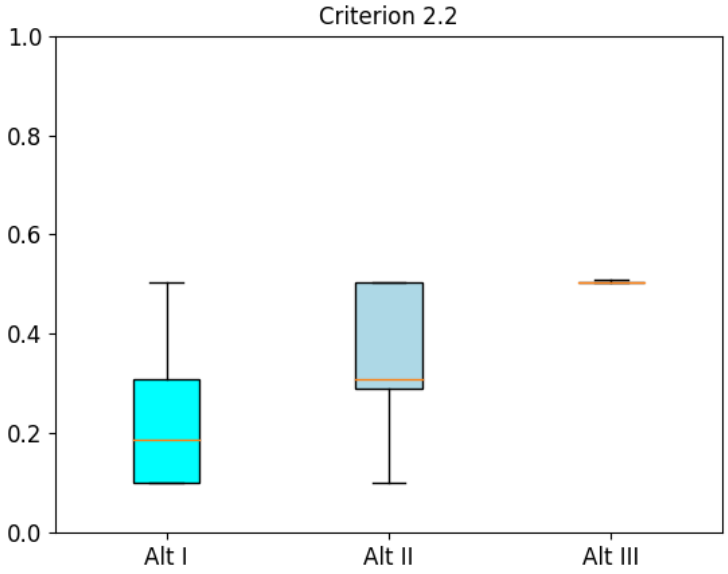


Figure 16 Aggregated results for the criterion "detect significant irregularities"

7.2.3 Detect leakage

Leakage is here defined as the migration of injected CO_2 outside of the storage complex. Alternatives II and III are most preferred. From the comments, this is mainly due to the DTS measurements along the well in those alternatives. This criterion could be split into the detection of leakage along the well and the detection of leakage along faults.

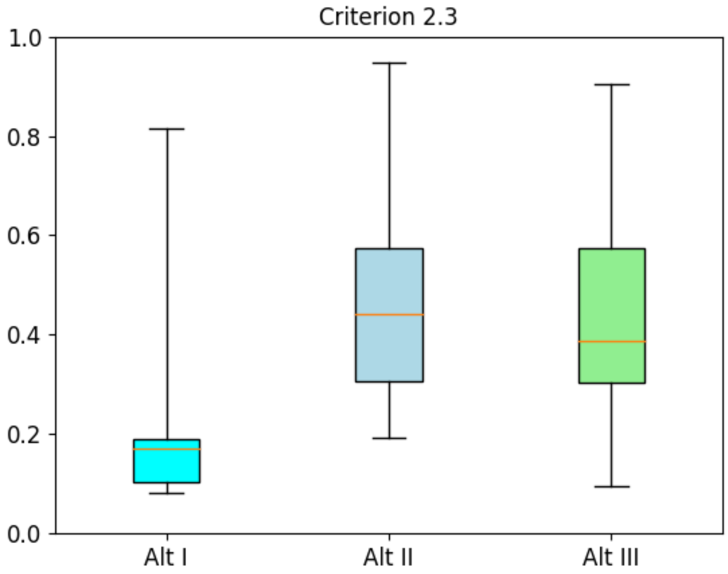


Figure 17 Aggregated results for the criterion “detect leakage”

7.2.4 Real-time information for early warning

Alternatives II and III are the most preferred. From the comments, this is mainly due to the vertical (and for alternative II, horizontal) fibre optic measurements, which can continuously monitor for micro-seismic activity.

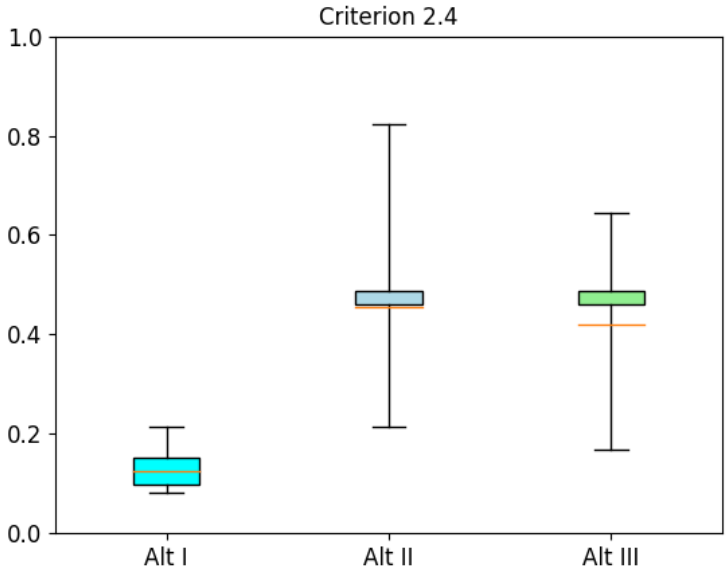


Figure 18 Aggregated results for the criterion “real-time information for early warning”

7.2.5 Provide an assessment of the safety and integrity of the storage complex in the short and long term

Although alternatives II and III are the most preferred on average, the spread is large. From the comments, disagreement between the respondents could be detected. One respondent deemed 3D seismic too cost-intensive to be used post-abandonment, favouring alternatives II and III with their permanent fibre optic installations in the injection well and on the seabed. Other respondents did not consider the cost of seismic an issue and favoured alternative I. A group discussion between the respondents could clarify this further.

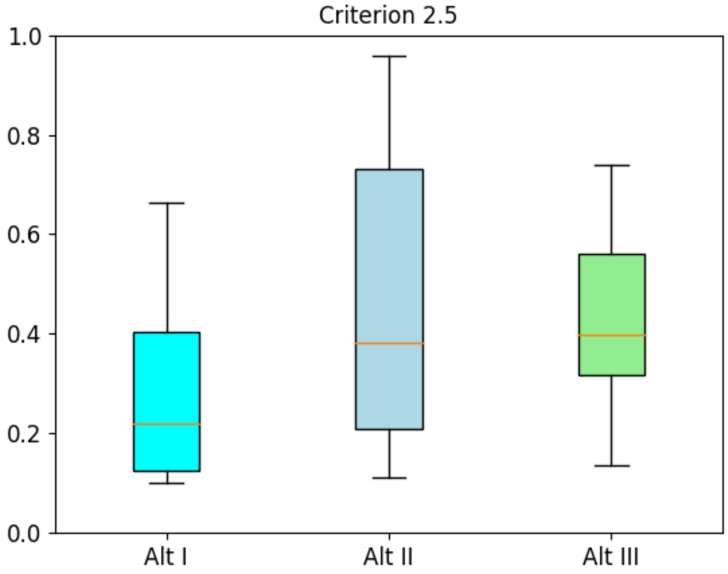


Figure 19 Aggregated results for the criterion "provide an assessment of the safety and integrity of the storage complex in the short and long term"

7.3 Cost

Assuming equal weighting of all the sub-criteria for the cost monitoring criterion, we get the ranking in Table 3. Alternatives II and III are preferred over alternative I.

Table 3 Overall ranking for the cost criterion, assuming equal weighting of the underlying sub-criteria

Alternative I	Alternative II	Alternative III
0.24	0.42	0.34

7.3.1 Equipment and installation cost

As can be seen, the spread of the assessments is significant for this criterion, making it difficult to conclude. From the comments, most of the respondents lack the required information and/or experience to judge the installation costs of the different types of equipment. A group discussion could be useful for identifying the missing information, and for proposing a strategy for gathering the required material.

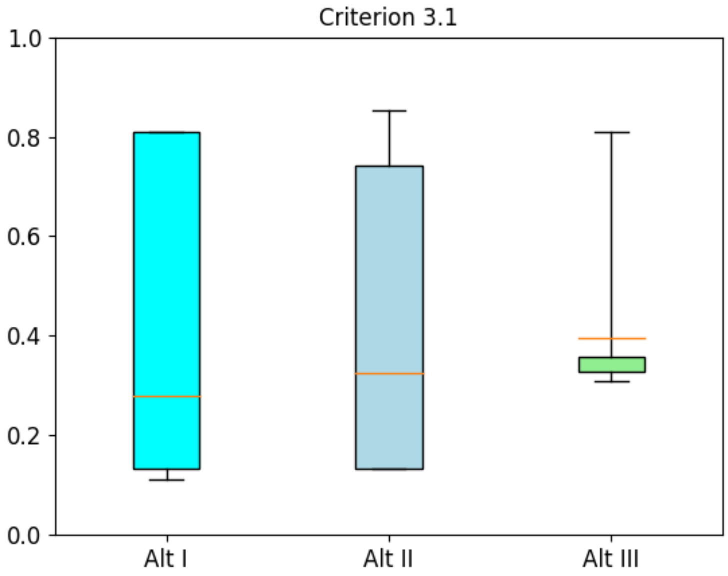


Figure 20 Aggregated results for the criterion "equipment and installation cost"

7.3.2 Operation and maintenance cost

As for criterion 3.1, the spread of the assessments is large. Many respondents judge alternative I with repeated 3D seismic surveys as having a higher operational cost than alternatives II and III.

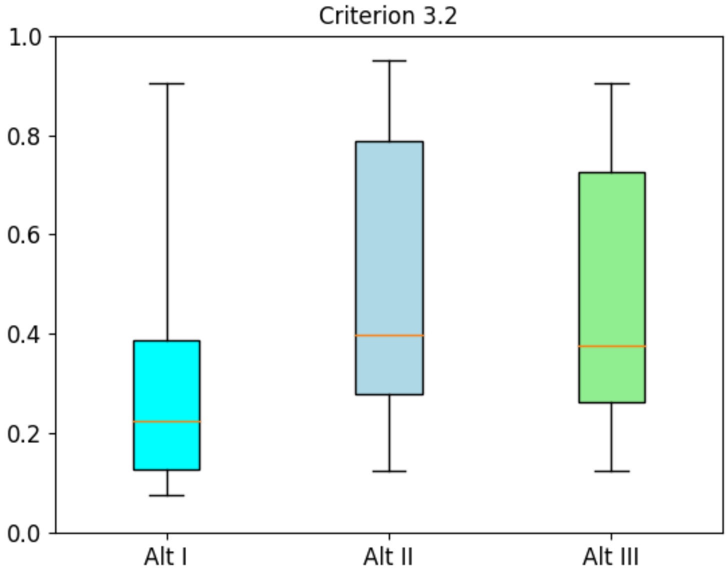


Figure 21 Aggregated results for the criterion "operation and maintenance cost"

7.3.3 Cost of data processing and interpretation

Alternative II is the most preferred alternative. There is an agreement among the respondents that seismic data processing is costly; therefore, alternative I is the least preferred alternative. Some respondents point out that they assume that automatic processing has been developed for continuous monitoring cases.

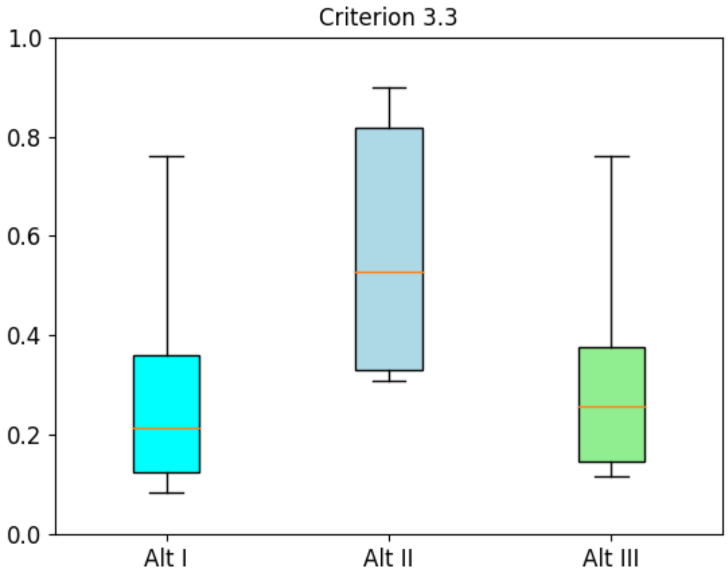


Figure 22 Aggregated results for the criterion "cost of data processing and interpretation"

7.4 Societal acceptance

Assuming equal weighting of all the sub-criteria for the societal acceptance monitoring criterion, we get the ranking in Table 4. Alternative III is preferred, followed by alternative II and then alternative I.

Table 4 Overall ranking for the societal acceptance criterion, assuming equal weighting of the underlying sub-criteria

Alternative I	Alternative II	Alternative III
0.17	0.33	0.49

7.4.1 Environmental impact

There is a preference for alternative III, but there is disagreement among the respondents. The comments range from ocean bottom sensors having minimal to a significant impact on the seabed environment. Part of the spread in the responses is because the environmental impact is interpreted differently among the respondents. Interpretations include both the introduction of constraints on competing activities above the storage site (e.g., limits on trawling activities or the installation of offshore wind farms) to the monitoring having a direct negative impact on the environmental state of the ocean and seafloor above the storage site (e.g., caused by noise from the use of seismic sources or the deployment of permanent installations). The seismic surveys are generally assumed to have a negative impact on marine fauna (fish and mammals). In alternative II, the surveys are 2D, but as one respondent points out, stronger sources might be needed for the DAS cables than for streamer seismic. A more detailed description of possible environmental impacts and consequences under this criterion could be helpful to fill knowledge gaps and align the responses.

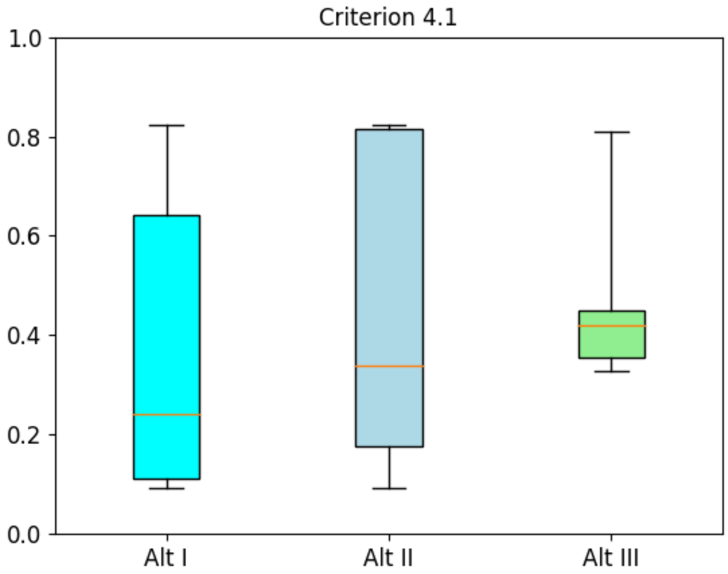


Figure 23 Aggregated results for the criterion "environmental impact"

7.4.2 Provide data access, ensure external supervision

Alternatives II and III are clearly preferred by all respondents since in those alternatives "data will be shared with research institutes and universities by request", giving more transparency and may be advisable to increase trust in some countries. One respondent warns, however, that public sharing of raw data may cause misinterpretations by non-experts which may result in unfavourable media attention and negatively change public opinion.

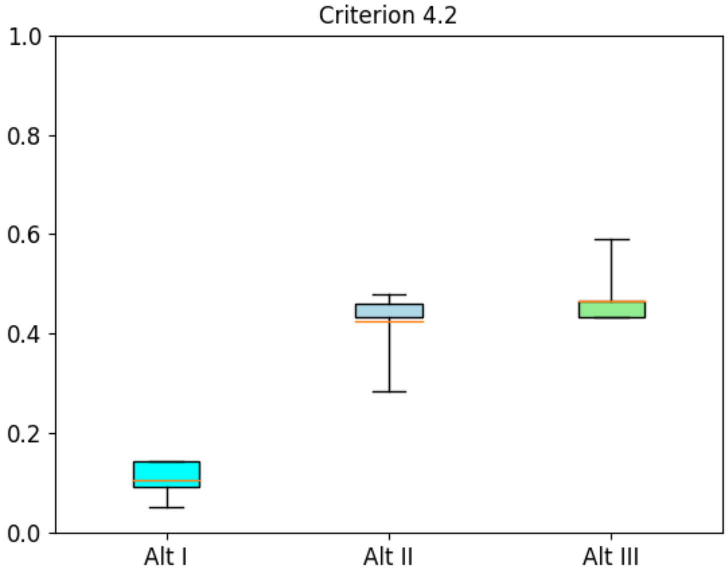


Figure 24 Aggregated results for the criterion "provide data access, ensure external supervision"

7.4.3 Reliable measurement of plume movement, subsurface tracing

Alternatives I and III are preferred over alternative II. The criterion resembles the sub-criterion “Map the areal and vertical extent of CO_2 vs time” under the conformance criterion and naturally has a similar evaluation. However, this criterion is important for the societal acceptance main criterion, which is why it is echoed here. In future versions of the AHP framework it may be possible to come up with a modification which allows certain sub-criteria to contribute to several main criteria.

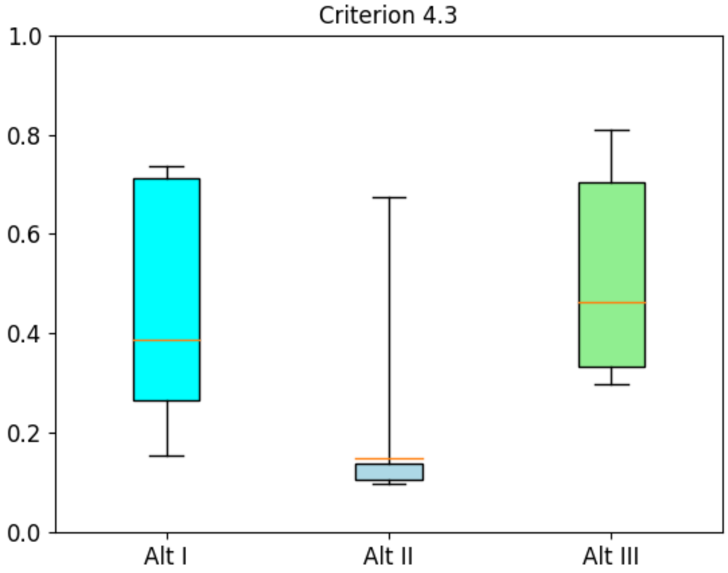


Figure 25 Aggregated results for the criterion “reliable measurement of plume movement, subsurface tracing”

7.4.4 Leakage detection and prediction

Alternatives II and III are preferred over alternative I. This criterion resembles the criterion “Detect leakage” under the containment criterion, and naturally has a similar evaluation. However, this criterion is important for the societal acceptance, which is why it is echoed here. In future versions of the AHP framework it may be possible to come up with a modification which allows certain sub-criteria to contribute to several main criteria.

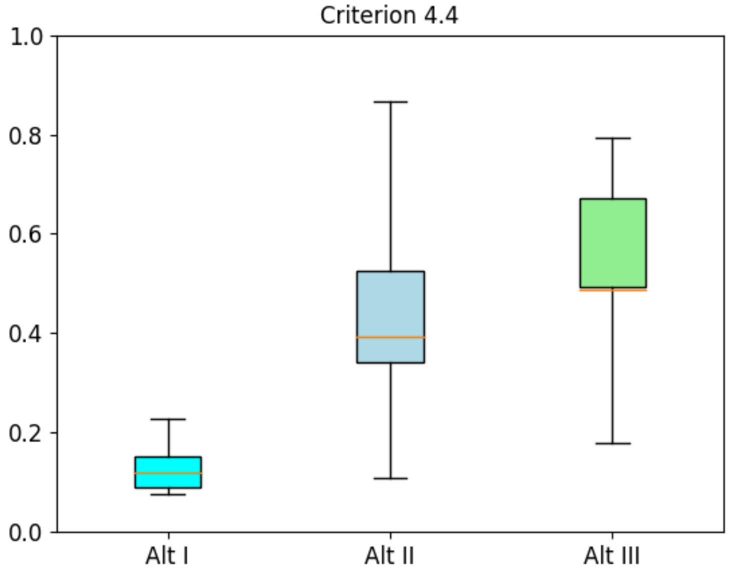


Figure 26 Aggregated results for the criterion "leakage detection and prediction"

7.4.5 Early warning system and security concept

Alternative III is the preferred alternative in the aggregated result. However, several respondents prefer alternative II due to the continuous monitoring with fibre optics both horizontally and vertically. One respondent points out that the sharing of data with independent experts in research institutes and universities in alternatives II and III provides more transparency and may be preferable for an early warning and security concept.

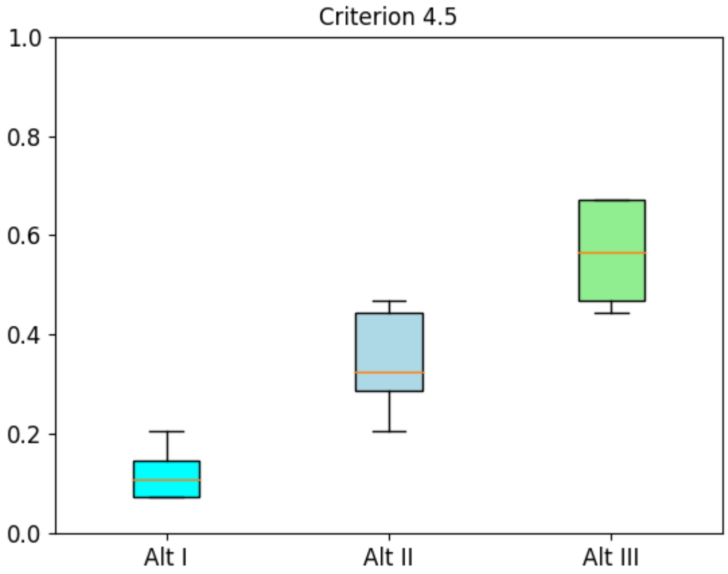


Figure 27 Aggregated results for the criterion "early warning system and security concept"

7.4.6 Expert and public involvement in setting up and defining criteria (public engagement)

This criterion has fewer responses (three) than the other criteria, probably because there is no discussion of the involvement and participation plans in the current description of the monitoring alternatives. The feedback is therefore interpreted to reflect the additional data sharing with stakeholders under alternatives II and III.

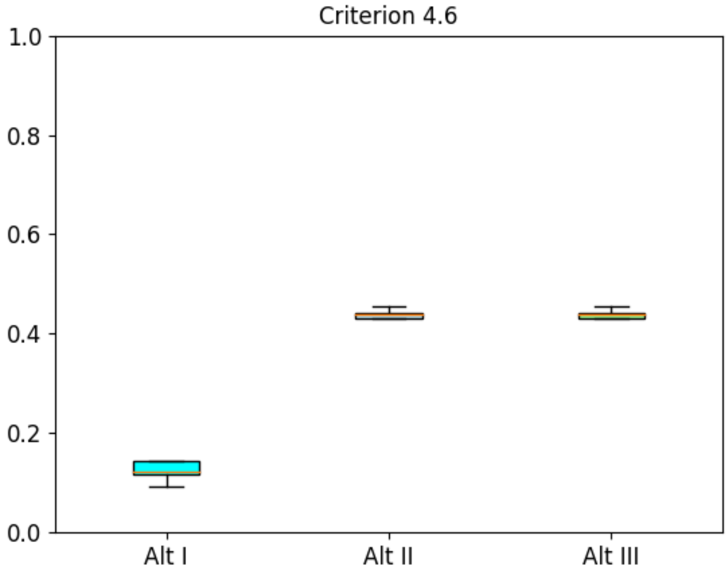


Figure 28 Aggregated results for the criterion "expert and public involvement in setting up and defining criteria (public engagement)"

7.5 Licence to operate

The last question in the questionnaire was whether, in your opinion, the alternatives fulfil the licence to operate. The results are summarized in Table 5.

Table 5 Assessment of the licence to operate criterion

Alternative	Yes	No	No opinion
I	7	0	1
II	4	1	3
III	6	1	1

7.6 Overall summary of rankings for all (sub-)criteria

A summary of all the rankings is shown in Table 6. For simplicity we have omitted the degree to which the rankings differ between the alternatives. This table can be used as an overview of the ordering of the alternatives, whereas the detailed background behind the rankings is provided in sections 7.1-7.5.

Table 6 Summary of rankings of the alternatives for all criteria

Criterion		Alt I	Alt II	Alt III
Conformance	1.1 Map the areal and vertical extent of CO_2 vs time	**1**	3	2
	1.2 Map the pressure field	3	**1**	2
	1.3 Determine CO_2 phase behaviour and state	3	2	**1**
	1.4 Quantify CO2 trapping mechanisms and rates	2	3	**1**
	1.5 Maturity of the technologies	**1**	3	2
	1.6 Flexibility of the solution	2	3	**1**
Containment	2.1 Monitor injectivity and storage capacity	2	3	**1**
	2.2 Detect significant irregularities	3	2	**1**
	2.3 Detect leakage	3	**1**	2
	2.4 Real-time information for early warning	3	**1**	2
	2.5 Provide an assessment of the safety and integrity of the storage complex in the short and long term	3	2	**1**
Cost	3.1 Equipment and installation cost	3	2	**1**
	3.2 Operation and maintenance cost	3	**1**	2
	3.3 Cost of data processing and interpretation	3	**1**	2
Societal acceptance	4.1 Environmental impact	3	2	**1**
	4.2 Provide data access, ensure external supervision	3	2	**1**
	4.3 Reliable measurement of plume movement, subsurface tracing	2	3	**1**
	4.4 Leakage detection and prediction	3	2	**1**
	4.5 Early warning system and security concept	3	2	**1**
	4.6 Expert and public involvement in setting up and defining criteria (public involvement)	3	2	**1**

8 Summary and discussion

The Analytical Hierarchy Process (AHP) has been demonstrated for evaluating three alternative solutions for monitoring geological CO_2 storage in a synthetic brine-filled storage site that is representative of the Norwegian Continental Shelf.

In the evaluation process, the monitoring alternatives were given scores according to their ability to fulfil a list of criteria identified as part of the DigiMon project with the overall goal of securing measurement, monitoring, and verification (MMV) of the CO_2 storage project. From these scores, individual rankings of the monitoring alternatives for each criterion together with an overall ranking of the alternatives were computed, providing a rational basis for deciding on an optimal monitoring solution for the site.

Through analysis of the individual rankings, it is also possible to combine the best aspects of the different monitoring solutions into new alternatives. These may also be evaluated, leading to an iterative process towards deciding on the optimal monitoring solution.

In this demonstration of AHP, the weighting of the criteria was intentionally omitted. Although the weighting between the technical criteria can be informed by a risk analysis of the site, the weighting between technical, economic, and societal aspects of the monitoring solution is to a certain degree a political decision that is best left to developers and operators.

Some lessons could be learned from the evaluation of the different alternatives:

- Some criteria had possibly conflicting interpretations. Some of the respondents had identified this and answered either based on an individual weighting of the different interpretations or by choosing one of the interpretations. Such ambiguity of the criteria should preferably be avoided, and if needed, the criteria should be divided into sub-criteria with more precise interpretations.
- Some criteria contained several aspects where different monitoring techniques could be preferential depending on the aspect. One example is the criterion “Quantify CO2 trapping mechanisms and rates” which could be divided into sub-criteria for the different trapping mechanisms.
- For some criteria, there was a significant disagreement between the respondents, which could indicate either a lack of information, or different experiences among the respondents. In such cases, panel meetings between the respondents might be used to either come to a consensus or reveal information and fill knowledge gaps through information gathering or new research projects. This stepwise assessment will be particularly important for criteria with large weights.
- Some sub-criteria in the societal acceptance criterion were repetitions of sub-criteria from the technical criteria. For future application of AHP, modification to the framework should be explored to enable certain sub-criteria to contribute to several main criteria, possibly with variable weights for each main criterion.

In general, AHP is a dynamic framework in the sense that when new information about risks and concerns is revealed, new criteria can easily be added to the hierarchy.

AHP is a structured and transparent framework for decision-making. In DigiMon, it has been used to bring together technical, economic, and social aspects into a holistic approach. As a side effect, which is not to be underestimated, it has encouraged the development of a common language and a shared understanding of storage projects among experts in different fields.

9 References

Alnes, H. et al. (2011) Results from Sleipner gravity monitoring: updated density and temperature distribution of the CO2 plume. Energy Procedia, 4, 5504-5511.

Broecks, K. P.F., van Egmond, S., van Rijnsoever, F. J. , Verlinde-van den Berg, M., Hekkert, M. P. (2016): Persuasiveness, Importance and Novelty of Arguments about Carbon Capture and Storage. In: Environmental Science & Policy, 59, 58–66.

Carroll, A. G., Przeslawski, R., Duncan, A., Gunning, M., & Bruce, B. (2017). A critical review of the potential impacts of marine seismic surveys on fish & invertebrates. Marine Pollution Bulletin, 114(1), 9 24.

Daley, T. M., Freifeld, B. M., Ajo-Franklin, J., Dou, S., Pevzner, R., Shulakova, V., ... & Lueth, S. (2013). Field testing of fiber-optic distributed acoustic sensing (DAS) for subsurface seismic monitoring. *The Leading Edge*, 32(6), 699-706.

De Vries, G., Terwel, B. W., Ellemers, N. (2016): Perceptions of Manipulation and Judgments of Illegitimacy: Pitfalls in the Use of Emphasis Framing When Communicating about CO2 Capture and Storage. In: Environmental Communication, 10 (2), 206–226.

DigiMon Deliverable 1.10: A Roadmap for Commercial Delivery and Implementation of WP1 Outcomes, Stork, A., Butcher, A., Kendall, M., Paap, B., Lien, M., Thomas, P., Ködel, U, Fechner, T., Thiem, L., Bond, T, Mendrinos, D.

DigiMon Deliverable 2.3: TRA of DigiMon components, Vanderweijer, V., Ködel, U., Lien, M., Bond, T., Candela, T., Zhou, W., Butcher, A., Kendall, M., Stork, A.

DigiMon Deliverable 3.3: Perceptions and preferences for CCS Monitoring and its role in the evaluation of CCS in Norway, The Netherlands, Germany and Greece, Sprenkeling, M., Peuchen, R., Bijvoet, J., Langefeld, A., Nordø A., Veland, S., Karytsas, S., Mendrinos, D. and Polyzou, O., Otto, D.

Dupuy, B., et al., (2018), Norwegian large-scale CO2 storage project (Smeaheia): baseline geophysical models. 14th International Conference on Greenhouse Gas Control Technologies, GHGT-14

Furre, A.-K. et al., (2020) Planning deep subsurface CO2 storage monitoring for the Norwegian full-scale CCS project, First Break, Volume 38

Furre, A.-K. et al. (2019) Building confidence in CCS: From Sleipner to the Northern Lights Project, , First Break, Volume 37

Furre, A.-K. et al., (2017) 20 years of monitoring CO2-injection at Sleipner. Energy Procedia 114, 3916 – 3926

Hansen, O. et al., (2013) Snøhvit: The history of injecting and storing 1 Mt CO2 in the fluvial Tubåen Fm, Energy Procedia, 37, 3565 – 3573

Iyer, J., Lackey, G., Edvardsen, L., Bean, A., Carroll, S. A., Huerta, N., ... & Cerasi, P. (2022). A Review of Well Integrity Based on Field Experience at Carbon Utilization and Storage Sites. *International Journal of Greenhouse Gas Control*, 113, 103533.

Jenkins, C. (2020). The State of the Art in Monitoring and Verification: an update five years on. *International Journal of Greenhouse Gas Control*, 100, 103118.

Kiyashchenko, D., Mateeva, A., Duan, Y., Johnson, D., Pugh, J., Geisslinger, A., & Lopez, J. (2020). Frequent 4D monitoring with DAS 3D VSP in deep water to reveal injected water-sweep dynamics. The Leading Edge, 39(7), 471-479.

Krejčí, J., & Stoklasa, J. (2018). Aggregation in the analytic hierarchy process: Why weighted geometric mean should be used instead of weighted arithmetic mean. Expert Systems with Applications, 114, 97-106.

Mabon, L., Kita, J., Xue, Z. (2017): Challenges for social impact assessment in coastal regions: A case study of the Tomakomai CCS Demonstration Project. In: Marine Policy, Elsevier Ltd, 83, 243–251.

Nowacek, D. P., Clark, C. W., Mann, D., Miller, P. J. O., Rosenbaum, H. C., Golden, J. S., Jasny, M., Kraska, J., Southall, B. L. (2015): Marine Seismic Surveys and Ocean Noise: Time for Coordinated and Prudent Planning. In: Frontiers in Ecology and the Environment, 13 (7), 378–386.

Otto, D., Gross, M. (2021): Stuck on Coal and Persuasion? A Critical Review of Carbon Capture and Storage Communication. In: Energy Research & Social Science, 82, 102306.

Otto, D., Sprenkeling, M., Peuchen, R., Nordø, Å. D., Mendrinos, D., Karytsas, S., ... & Puts, H. (2022). On the Organisation of Translation—An Inter-and Transdisciplinary Approach to Developing Design Options for CO2 Storage Monitoring Systems. *Energies*, 15(15), 5678.

Ringrose, P. S., Furre, A.-K., Gilfillan, S.M.V., Krevor, S,Landrø, M.Leslie, R.Meckel, T., Nazarian, B., Zahid, A. (2021) Storage of Carbon Dioxide in Saline Aquifers: Physichemical Processes, Key Constraints, and Scale up Potential. Annual Review of Chemical and Biomeolecular Engineering, 12, 471-494

Ruiz, H. et al. (2020) Monitoring the Snøhvit gas field using seabed gravimetry and subsidence. SEG Technical Program Expanded Abstracts Saaty, T. L. (1990). How to make a decision: the analytic hierarchy process. European journal of operational research, 48(1), 9-26.

Schütz, Omar & Carpentier, (2021), Report on regulations and technological capabilities for monitoring CO2 storage sites. ACTOM project report. http://actom.w.uib.no/publications/actom-d1-1-report/

Stork, A. L., Verdon, J. P., & Kendall, J. M. (2015). The microseismic response at the In Salah Carbon Capture and Storage (CCS) site. International Journal of Greenhouse Gas Control, 32, 159-171.of Greenhouse Gas Control, 43, 233-246.

Taweesintananon, K., Landrø, M., Brenne, J. K., & Haukanes, A. (2021). Distributed acoustic sensing for near-surface imaging using submarine telecommunication cable: A case study in the Trondheimsfjord, Norway. *Geophysics*, 86(5), B303-B320.

Terwel, B. W. (2015): Public participation under conditions of distrust: Invited commentary on „Effective risk communication and CCS: The road to success in Europe“. In: Journal of Risk Research, Routledge, 18 (6), 692–694.

Tsuji, T., Ikeda, T., Matsuura, R., Mukumoto, K., Hutapea, F. L., Kimura, T., ... & Shinohara, M. (2021). Continuous monitoring system for safe managements of CO2 storage and geothermal reservoirs. *Scientific reports*, 11(1), 1-15.

Tveit, S., Mannseth, T., Park, J., Sauvin, G., & Agersborg, R. (2020). Combining CSEM or gravity inversion with seismic AVO inversion, with application to monitoring of large-scale CO2 injection. Computational Geosciences, 24(3), 1201-1220.

Vaidya, O. S., & Kumar, S. (2006). Analytic hierarchy process: An overview of applications. European Journal of operational research, 169(1), 1-29.

Van Opstal, G.H.C. (1974). EFFECT OF BASE-ROCK RIGIDITY ON SUBSIDENCE DUE TO RESERVOIR COMPACTION

Vatshelle, M., Glegola, M., Lien, M., Noble, T. , Ruiz H. (2017) Monitoring the Ormen Lange Field with 4D Gravity and Seafloor Subsidence. Conference Proceedings, 79th EAGE Conference and Exhibition 2017, Jun 2017, Volume 2017, p.1 - 5. DOI: https://doi.org/10.3997/2214-4609.201700484

Zhan, G., van Gestel, J. P., & Johnston, R. (2020). DAS data recorded by a subsea umbilical cable at Atlantis field. In SEG Technical Program Expanded Abstracts 2020 (pp. 510-514). Society of Exploration Geophysicists.

Zhu, C., Zhang, G., Lu, P., Meng, L., & Ji, X. (2015). Benchmark modeling of the Sleipner CO2 plume: Calibration to seismic data for the uppermost layer and model sensitivity analysis. International Journal

Zweigel, P., Vebenstad, K., Vazquez Anzola, D. and Lidstone, A., 2021, March. Containment Risk Assessment of the Northern Lights Aurora CO2 Storage Site. In Proceedings of the 15th Greenhouse Gas Control Technologies Conference (pp. 15-18).