DigiMon Deliverable
D2.10: WP2 final report

Digital monitoring of CO_2 storage projects

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Scope

This document summarises the significant results in work package 2 of the DigiMon project. Detailed descriptions and results from each task can be found in the referenced deliverables and publications.

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1 Introduction

The Digimon project contains three scientific work packages. The first is on the development of individual monitoring system components, WP1. Here, particular focus has been on various forms of fiberoptic data in addition to gravimetric data. Key outcomes of this work package are summarized in xxx with references therein.

The third work package is on developing a human-centred, societally embedded monitoring system. Through an interdisciplinary approach, this work package has explored how monitoring systems can contribute to overcoming societal challenges towards the commercial deployment of CCS.

This report covers outcomes from the second scientific work package in DigiMon, which is on integrating different system components and optimising the monitoring solution.

1.1 Work package 2 - Integrating the components

The main objective of the DigiMon project is to develop a monitoring system that facilitates and accelerates the implementation of large-scale geological storage of CO_2. To achieve this, WP2 is to provide specifications of the DigiMon system such that it allows for the optimal balance between the ability to secure Containment, Conformance and Contingency monitoring while keeping the costs at a minimum and preserving public acceptance of CCS as a crucial tool for mitigating climate change. This topic is covered both through pairwise comparisons of data types and more holistic approaches to integrate various sources of information in building the monitoring solution.

1.2 The Digimon monitoring system

The DigiMon system consists of a suite of different technologies building on a selection of the critical technology elements developed in WP1.

Close cooperation with WP3 was established to secure the societal embeddedness of the Digimon system. The methodology for system design was adapted to incorporate their findings into the system. Figure 1 provides a sketch illustrating some of the interactions between the main activities in WP1 (blue), WP2 (green) and WP3 (yellow) during the Digimon project.

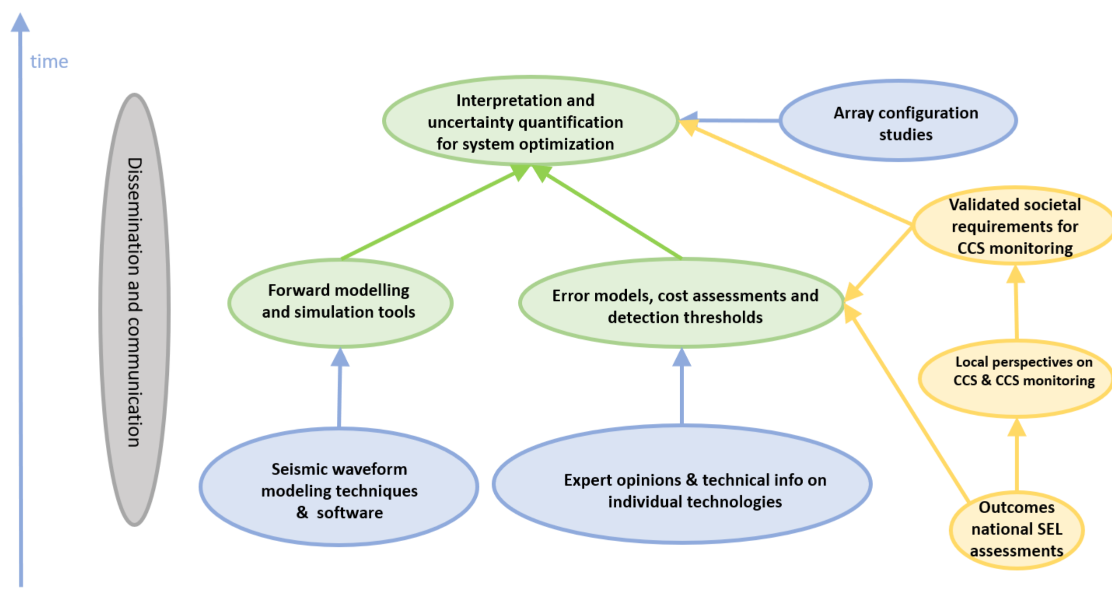

Figure 1: Sketch of the interactions between main activities in WP1 (blue), WP2 (green) and WP3 (yellow) during the Digimon project.

Table 1 lists the Milestones identified for WP2.

Table 1: ***WP2 milestones and associated milestone number***

Number	***Milestone***
M2.1	Forward model simulations available for all DigiMon data components
M2.2	Technology Readiness Assessment (TRA) of the different system components

M2.3	Framework for integrated inversion and uncertainty quantification
M2.4	Specification of data and communication platform
M2.5	Overall system design

Five tasks were identified in WP2 to achieve these milestones: Task 2.2 - Setting up forward modelling framework at selected CCS sites; Task 2.3 - Performing TRA of the system components; Task 2.4 - Integrated interpretation and uncertainty quantification; Task 2.5 - Adapt the system to standards for subsea communication and energy transfer; Task 2.6 - Optimise the monitoring solution.

1.3 Outline

In Section 2 through Section 6, the objectives, deliverables and key outcomes of the individual tasks are presented. Following this is an outline of the impact of WP2 in terms of designing the monitoring system and outcomes relevant to policy, regulatory and industry stakeholders (Section 7). This impact section also contains highlights of the dissemination of the WP2 results to the wider community. Conclusions and outlook are provided in Section 8. An overview of the dissemination activities is presented in Appendices A and B.

2 Task 2.2 - Setting up forward modelling framework at selected CCS sites

2.1 Aims and objectives

Generate required simulated data responses with uncertainties for inverse modelling and system optimisation. Set up a framework for forward modelling the data response of the system components on a generic CCS site reflecting challenges associated with large-scale CO_2 storage offshore.

2.2 Outcomes and deliverables

2.2.1 Framework for forward-modelling of the Digimon data components (D2.1)

Deliverable D2.1 adds to the main goal of WP2 of the ACT DigiMon project, which is to develop the integrated DigiMon system. The key target for WP2 is to optimally integrate various system components into a reliable and usable system.

Deliverable D2.1 describes the key forward modelling tools of the DigiMon monitoring system. In particular, the modelling tools required to simulate the data response for the individual DigiMon system components that is; Distributed Acoustic Sensing (DAS), conventional seismic, 4D gravity data, and seafloor deformation.

Focus was put on general usability of modelling activities for monitoring of an offshore CO_2 injection site. This infers that the models should be complex enough to cover all the essential parameters, but on the other hand be fast and light enough to run on currently available hardware.

The framework designed does not focus on detailed modelling for very specific processes, e.g., the analysis of the transfer function in DAS measurements. But it does take into account the general usability of modelling tools for follow-up activities, like ensemble-based inversion and system optimization workflows.

By building on the developments from WP1 and by combining expertise and available software from the work package team, a framework for forward modelling of the Digimon system components has been set up. This framework consists of algorithms and software for modelling:

- The gravity response
- The ground motion
- The seismic response
- The fault stability and related seismicity

These models enable us to monitor:

- The CO_2 plume, using micro gravity:

4D gravity provides a direct measurement of changes in the mass distribution during injection or production. Hence, gives a quantitative measure of the saturation and density distribution of the injected CO_2.

- The CO_2 plume, and pressure build up using ground movement:

Seafloor deformation is an observable effect of reservoir expansion and compaction, caused by pressure changes due to CO_2 injection. These pressure changes can be caused by fluid migration, fluid phase transitions, temperature changes and even chemical reactions. For DigiMon we focus on seafloor deformation induced by pressure changes caused by fluid migration and transitions in fluid phase.

- CO_2 saturation using seismic methods:

Saturated and pressurised rocks have different seismic properties. The developed workflow enables us to assess CO_2 saturation in and possibly outside the storage reservoir, by making uses of seismic methods including DAS, located in wells and /or on the surface.

- Fault stability via modelled strain-induced fault slip and seismicity:

Fault reactivation, potentially induced by the reservoir pressure build-up during CO_2 injection, enables us to monitor: (i) the pressure build-up, (ii) the reservoir elastic properties, (iii) and the fault frictional properties.

2.2.2 Concept description on the use of fibre-optic measurements for cross-well tomography (D2.2)

The need for wireline operations indicates that conventional cross-well tomography is most suited to land-based and survey-oriented CO_2 storage applications. There are two potential approaches for adapting cross-well seismic tomography to make it more suitable for subsea and continuous monitoring CO_2 storage applications:

- Using ambient noise as the source (No wireline operations for the source)
- Using fibre optics as the receiver (No wireline operations for the receiver)

In Deliverable D2.2, the application of distributed fibre optics sensing, including active seismic and ambient noise, for cross-well seismic tomography is outlined. The document also describes the acquisition layout and infrastructure required for carrying out cross-well, fibre-optic measurements at the Svelvik test site.

2.2.3 Detecting "up-lift" phenomena and stress-induced anisotropy (D2.4)

The Digimon deliverable "D2. 4: Examination & interpretation of the seismic tomography data with respect to "up-lift" phenomena and stress-induced anisotropy" discuss the use of conventional seismic cross-well tomography data to characterise reservoir deformations during CO_2 injection.

A significant issue for storage security is the geomechanical response of the reservoir. Several geochemical and geophysical (such as time-lapse seismic) techniques allow monitoring of the regional distribution of CO_2 in the storage complexes, seal integrity, and pressure evolution in response to the injection.

Shear waves are sensitive to changes in dynamic soil parameters such as shear strength or Young's modulus. During its formation, the soil is exposed to different loading conditions. This can be, for example, the loading pressure due to sedimentation, glaciation, external static load from structures, lowering the groundwater table, or even desiccation. Depending on the soil, these states are conserved and influence the propagation of seismic waves, especially the two kinds of shear waves.

SV- and SH-waves cause rock particles to oscillate perpendicular to the direction that the wavefront is moving, with the SH- and SV-displacement vectors orthogonal to each other. In geotechnical engineering, the stress history of soil is described by the so-called over-consolidation ratio (OCR). The OCR is defined as the ratio of the maximum overburden stress ever experienced by the soil (i.e., with the ice sheet on top) to the present overburden stress (i.e., without the ice sheet). Overconsolidated soil has experienced more significant stresses in the past than currently exists.

The experiment conducted at the Svelvik test site aimed at evaluating "up-lift" phenomena and stress-induced anisotropy by using the P-, SH-, and SV-wave data.

Outcomes and lessons learned

- SH/SV ratio or OCD makes changes in the subsurface stress conditions visible. The temporal behaviour of the derived parameters is coherent for the measured datasets. However, conclusions regarding uplift phenomena or stress-induced anisotropy could not be derived during the experiment.
- Tidal changes during the experiment were superimposed on the effects of CO_2 injection. Separation requires a measurement plan adapted to the tidal fluctuations, i.e., measurement at different tidal range times. A setup of a measurement plan that records the tidal effect at various time steps can help to find a correlation function between the tidal effect and the S-wave changes. Basic correlations were made to distinguish between the up-lift and the tidal-induced effect on S-wave propagation. No obvious effect was found.
- A geological model is required to interpret and separate observed effects. Unfortunately, it was not available to explain the findings.
- Pick accuracy is a primary factor of uncertainty. The proposed approach described in deliverable (D2.4) can be used to quantify the travel time picking accuracy.

2.2.4 On the use of seismicity to calibrate our predictive geomechanical models

In the context of CCS, geomechanical risks (e.g., induced seismicity) should be minimised. However, these treats can be leveraged to enhance our predictive capabilities. This is the objective of the developed workflow "On the use of seismicity to calibrate our predictive geomechanical models" as part of the the Digimon project where observations of seismicity and induced static strains are jointly combined to calibrate our predictions. Observations of seismicity refer to the so called "conventional seismicity monitoring"; and observations of induced static strains refer to DSS (Distributed Strain Sensing), potentially deployed in a close future.

The developed workflow makes use of two fast forward models to compute along-fault induced stresses and slip during CCS operations. An ensemble-based approach (ES-MDA) is then used to jointly assimilate observations of seismicity (i.e., catalog of induced events) and observations of induced static strains from the successive rupture events.

Outcomes and lessons learned

- A model chain has been developed to use 3D real geometrically complex reservoir pressure and temperature grids as input for the modelling of induced seismicity.
- The newly developed model chain generates ensembles of:
  - predictions of the cumulative number of seismic events,
  - predictions of the cumulative seismic moment,
  - predictions of the along-well cumulative volumetric strain.
- Predictions of the cumulative number of seismic events and seismic moment can be directly compared with "conventional seismicity monitoring."
- Predictions of the along-well cumulative volumetric strain can be directly compared with the "Distributed Strain Sensing."

- The model chain has been linked to a data assimilation scheme, the so-called ES-MDA.
- Previous works were restricted to assimilate the cumulative number of seismic events within Digimon for the first time, (1) cumulative number of seismic events, (2) cumulative seismic moment, and (3) along-well cumulative volumetric strain has been jointly assimilated. The success of the newly developed workflow can be assessed with two criteria:
  - Ability to produce seismicity predictions in agreement with observations.
  - Ability to constrain the key physical model parameters (static and dynamic friction) that control the earthquake dynamic.
- We produced a physics-based workflow which paves the route for testing the potential occurrence and severity of geomechanical risks (i.e., induced seismicity) during CCS.
- The current workflow could easily be upgraded to cover uncertainties at each step of the model chain. For now, the focus was on the uncertainties of the frictional process, but clearly, in the near future, also uncertainty at the flow and stress should be covered.
- The relative value of information between “conventional seismicity monitoring” and DSS still needs to be assessed. One way to do that is to test an experiment where the magnitude of completeness of the “conventional seismic monitoring” and errors in the DSS measurements are varied.

3 Task 2.3 - Performing TRA of the system components

3.1 Aims and objectives

To identify the optimal monitoring solution for a specific CCS project, site-specific detection thresholds need to be coupled to the capabilities of the different technology elements applied separately and in combination.

A Technology Readiness Assessment (TRA), critically reviews the technology requirements, acquisition costs, and the demonstrated technology capabilities for the DigiMon components.

3.2 Outcomes and deliverables

3.2.1 Project report for the TRA of all the Digimon data components (D2.3)

The DigiMon project aims to develop an affordable, flexible, societally embedded and smart monitoring system for industrial-scale subsurface CO_2 storage. For this purpose, the DigiMon system is to combine various types of measurements in integrated workflows. The DigiMon system needs to be able to detect CO_2 migration within the storage site and, if it should happen, out of the storage complex. The system should also be able to detect any other significant irregularities, like migration through faults or the reactivation of faults potentially leading to undesired CO_2 migration out of the storage complex. A combination of individual measurement techniques including direct and indirect measurements will be part of the DigiMon system. In the report, we summarize the Technology Readiness Assessment (TRA) performed for the creation of the DigiMon system. The full TRA can be accessed via the ACT Digimon deliverables repository. Below follows a brief summary.

Uses of TRL and TRA

The need for a TRA is widely accepted to characterize technology maturity. The use of Technology Readiness Levels (TRLs) enables consistent, uniform discussions of technical maturity across different types of technologies.

Currently there are more interpretations of the TRL definitions, which could lead to confusion and inconsistencies. For this work we use the nine-level TRL scale as used by the DOE, as presented in Figure 1. TRLs are based on a scale from 1 to 9, with 1 being the least and 9 being the most mature technology level.

Figure 2. Nine-level TRL scale after [1]

Approach

The TRA scores the current TRL of selected Critical Technology Elements (CTEs). The result can be used for assessing program risk and technology maturation planning.

Critical technology elements (CTEs)

Numerous Critical Technology elements CTEs were identified and selected according to their maturity and applicability for industrial scale, offshore CO_2 storage.

The main criteria were:

- Suitable for applications offshore
- Suitable for large-scale CO_2 storage sites
- Suitable for application in near future (relative high TRL)
- High relevance expected for application in the future (but low TRL)
- Cost

We reported on what we regard currently as the most relevant CTEs for developing a low-cost, early-warning, CCS monitoring system, in terms of technologies for field measurements. Different CTEs can sometimes provide the same type of data or information about the CO_2 storage reservoir or operation. This particularly applies in cases where point sensors have a distributed counterpart, e.g., for seismic methods or temperature measurements. Often these CTEs have different sensitivities, accuracies and related costs. Depending on the requirements of the risk analysis a hybrid CTE layout might be one of the appropriate outcomes when designing the monitoring plan.

Within the ACT DigiMon project, improvements on the individual CTEs (covered in the TRA) is obtained through development in instrumentalization, processing and (multi-physics) inversion techniques. For further system integration, additional focus should be on sensitivity studies, uncertainty quantification of CTEs and the inversion of their data streams, linked to (conformance) criteria.

The TRA serves as a valuable tool in the continued work aiding in the structured development, and integrating the various CTEs into the DigiMon system. Follow-up activities are developing in the direction of maturing multi-physics inversion frameworks and to use it in Value of Information (VoI) analysis and conformance assessments. Analysis like these support governments and industry if proposed monitoring activities fulfil their requirements efficiently.

Table 2. CTE and TRL overview.

Application	Class	CTE	TRL	Note
Surface and seabed reflection methods	Seismic reflection surveys	Conventional hydrophone or in case of OBN multi component sensors	9	Mature technology
		DAS	5-6	Recent experiments show good potential

Borehole seismic methods	VSP	Conventional VSP	9	Mature technology
		DAS-VSP	8	Good results only used onshore so far
	Cross hole tomography	DAS and Conventional sensors (Triplet source)	5-6	Few applications in field lab environments
Passive seismic methods	Micro seismics	Geophone/hydrophones	9	Mature technology
		DAS	7-8	Operational but not applied
	Ambient Noise Interferometry	Geophone/hydrophones	4-5	
Microgravity	Microgravity at the seafloor	Point-based, mobile, microgravity sensors	9	Mature technology
Seafloor deformation	Measurements at the seafloor	Pressure sensors	9	Mature technology
		Tiltmeters	4	Good results, only used for other applications so far
		DSS	4-5	Good results, only used for other applications so far
Downhole Pressure sensing	Measurements in well	Conventional pressure sensors	8-9	Commercially available but lack long term use in CCS
		DPS	5-6	
Temperature sensing		DTS	9	Mature technology
Chemical sensing		Conventional sensors	9	Mature technology
		DCS	4	

Conclusions

For large-scale, industrial CCS operations, monitoring plans and their related activities will be designed around risks that have been identified by extensive risk assessment workflows. The goal of monitoring activities is to show conformance and to keep risks at an acceptable level so operations can continue in a safe and cost-efficient manner.

For immediate industrial storage applications, the CTEs with a high TRL score (8-9) can become part of the monitoring plan (e.g., seismic methods with conventional sensors, microgravity, DTS). CTEs with a lower TRL may be included as a supporting technology to a mature CTE or to facilitate further development of the technology.

When designing an optimized setup e.g., to monitor the development of a certain risk, there is also the possibility to combine monitoring data from various CTEs in inversion workflows. A workflow making use of data from multiple CTEs could outperform the capability of a single CTE.

Table 2 presents an overview of the reviewed applications and CTEs together with the resulting TRLs.

[1] DOE, 2011, DOE G 413.3-4A, Technology Readiness Assessment Guide

4 Task 2.4 - Integrated interpretation and uncertainty quantification

4.1 Aims and objectives

The main objective of this task is to further develop a methodology for the integrated interpretation and uncertainty quantification of the system data responses for monitoring large-scale CCS projects.

Within this task, the possibility of coupling fibre deployments to refraction surveys and full-waveform inversion will be investigated using synthetic data, feasibility studies, and, if available, field data. The combination of conventional seismic with more cost-efficient monitoring solutions such as 4D gravity and seafloor deformation monitoring will also be considered.

This task also includes further development of cross-hole measurements by combining conventional and DAS measurements.

4.2 Outcomes and deliverables

4.2.1 A conceptual model for integrating conventional seismic and DAS data into borehole seismic tomography surveying (D2.9)

Aims and objectives

- Application of the tomographic inversion to DAS travel time data
- Comparison of tomographic inversion results of conventional and DAS data
- Evaluation and comparison of data quality (Signal to Noise Ratios - SNR) of conventional and DAS data
- Statement on the suitability of linear and HWC cable to the three sources (P, SH, SV)
- Assessment of uncertainty (picking accuracy)

Outcomes and lessons learned

- The inversion of seismic traveltime tomography data is a well-established procedure. The quality of the seismic data significantly influences the accuracy of the arrival time picking but is generally not considered in the inversion. If the related uncertainty of travel time picks is not addressed within a tomographic inversion process, all picked traveltimes have the same weight and contribute equally to determining the seismic velocities within a seismic tomogram. To account for the traveltime picking error, a data quality-dependent weighting into the well-known simultaneous iterations reconstruction technique (SIRT) tomography inversion procedure was introduced to this project.
- The weighted tomographic inversion procedure was applied to conventional, HWC, and LIN DAS data.
- To assess the suitability of linear and HWC for P- and S-wave surveys, the data are compared using arrival SNR values. The values proved that the HWC cable provides the best sensitivity to P-waves arriving at small source-receiver offsets. It can be seen that SNR observed in the S-wave surveys is generally lower than for the P-wave. Further work is required to assess DAS data for S-wave surveys.
- DAS data can be used to produce accurate P-wave tomography models using HWC cable.
- Data quality values were calculated based on the SNR of the seismic data. The data quality of the DAS data was generally lower than that of conventional seismic data.
- Also, the application of state-of-the-art automatic picking routines for first arrival picking of the DAS data indicates some restrictions due to reduced data quality.
- A manual re-picking of the DAS data improved the data quality and, therefore, the tomographic inversion results. Hence, the tomographic inversion results of the conventional and the DAS data generally are comparable to some extent. Differences show that DAS data is less well-constrained on large source-receiver offsets.
- With its reduced logistical effort and high acquisition speed, DAS is a promising low-cost alternative for conventional geophone-based systems. However, research is needed, e.g., to increase the signal-to-noise ratio or find good automatic picking routines.
- The joint application of conventional seismic and DAS would significantly increase the data interpretability in cross-hole CO_2 imaging and for short-range cross-hole surveys in general.

4.2.2 Algorithms for integrated inversion of individual Digimon data components (D2.5)

For the integrated interpretation and uncertainty quantification, the following main activities have been conducted:

- Couple the individual forward models with a dynamic flow simulator in the ensemble-based inversion framework.
- Inverse modelling studies with individual data components
- Inverse modelling studies with combinations of two or more data components

An important aim of the DigiMon project is to qualify a *cost-efficient* monitoring system for use with large-scale CO_2 sequestration. In addition to comparing the monitoring performances of the individual data types, we have therefore also compared the performance of gravimetric and DAS data combined to that of conventional seismic data (whose acquisition is considerably more costly). We have developed an inversion modelling framework for geophysical monitoring with the abovementioned geophysical data types. The framework utilises an ensemble-based Bayesian technique that, in addition to the best estimate of the monitoring target, also quantifies the uncertainty in that estimate.

We test the performances of the different data types (including relevant data-type combinations) by applying this framework on a sector model of the Smeaheia saline aquifer with synthetic data. CO_2 is injected in a single well, and data are acquired right before injection starts and after 13 years of injection. We compare results using quantitative measures (data mismatch and root mean squared error between the reference and estimated CO_2 saturation and pressure changes) in addition to visual inspection of plots of means and standard deviations of the monitoring results.

Results obtained with conventional seismic data were generally better than those obtained with gravimetric data. Results obtained by combining gravimetric and DAS data were, however, of comparable quality to those obtained with conventional seismic data. For the examples considered, sequential inversion of gravimetric and DAS data, therefore, seems a less costly, viable alternative to conventional seismic data for monitoring CO_2 sequestration. The investigation considered is, however, far from comprehensive, and more work is needed before any conclusion with some generality can be drawn. The inversion framework developed in the project is well suited to be applied in a more comprehensive investigation, aiming for more general conclusions.

A more comprehensive description of the work in Task 2.4 is found in the DigiMon Deliverable D2.5: Project report and algorithms for integrated inversion of individual DigiMon data components, by T. Bhakta, T. Mannseth, M. Lien, B. Paap, and V. Vandeweijer, 2022

4.2.3 Q-value estimation using the Oseberg Permanent Reservoir Monitoring (PRM) system

Estimation of average Qp- and Qs-values in marine sediments by using a dense receiver array and passive seismic events. Seismic waves attenuate when travelling through the subsurface. A measure for the "efficiency" of the propagation of a seismic wave is the quality factor Q. Conversely, by looking at the value of Q, one can conclude the geology that the wave travelled through.

As Q-values allow for the characterisation of the subsurface, they reveal valuable information about environments where the DigiMon system might be applied in the future.

A subset of 172 ocean bottom nodes of the Oseberg PRM (see *Figure 4.1.1*) was used to measure the attenuation of P- and S-waves in sediment. Furthermore, a seismometer located in Bergen, Norway, was used to measure the wave attenuation in bedrock (see *Figure 4.1.2 C*). Local earthquakes, with magnitudes down to 2.4 for P-waves and 2.1 for S-waves, were used as passive seismic sources.

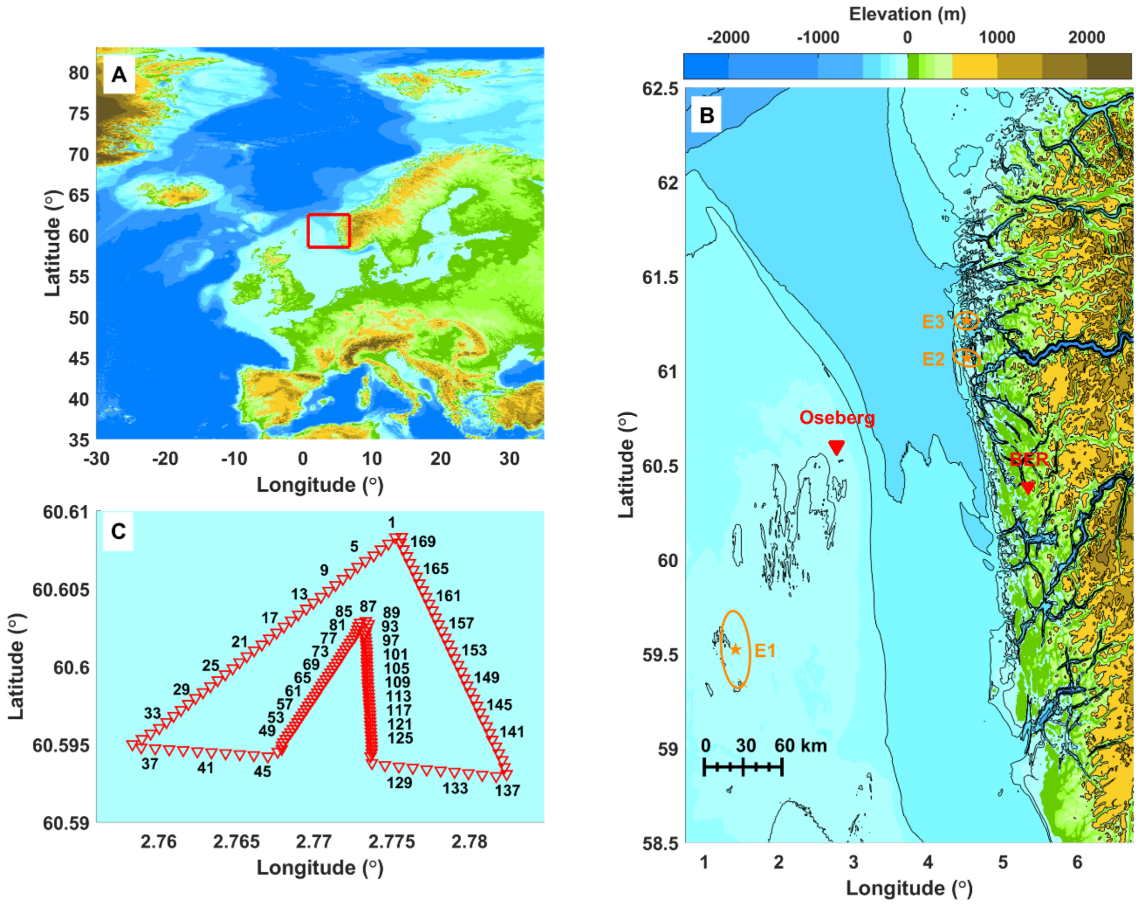

Figure 4.1.1 A-C: Overview of the region of interest. A) The study area relative to Europe. The red rectangle shows the study area (bathymetry map from GEBCO (2021)). B) The location of the earthquakes (orange stars) with associated error ellipses and the receivers (red triangles). C) The receiver geometry of the 172 ocean bottom nodes just south of the Oseberg C platform.

Eventually, the Q-values were estimated by applying a new spectral division method to the signal recorded at the Oseberg PRM and the seismometer station in Bergen. The Q-values for sediments found in this work agree with the findings of other authors.

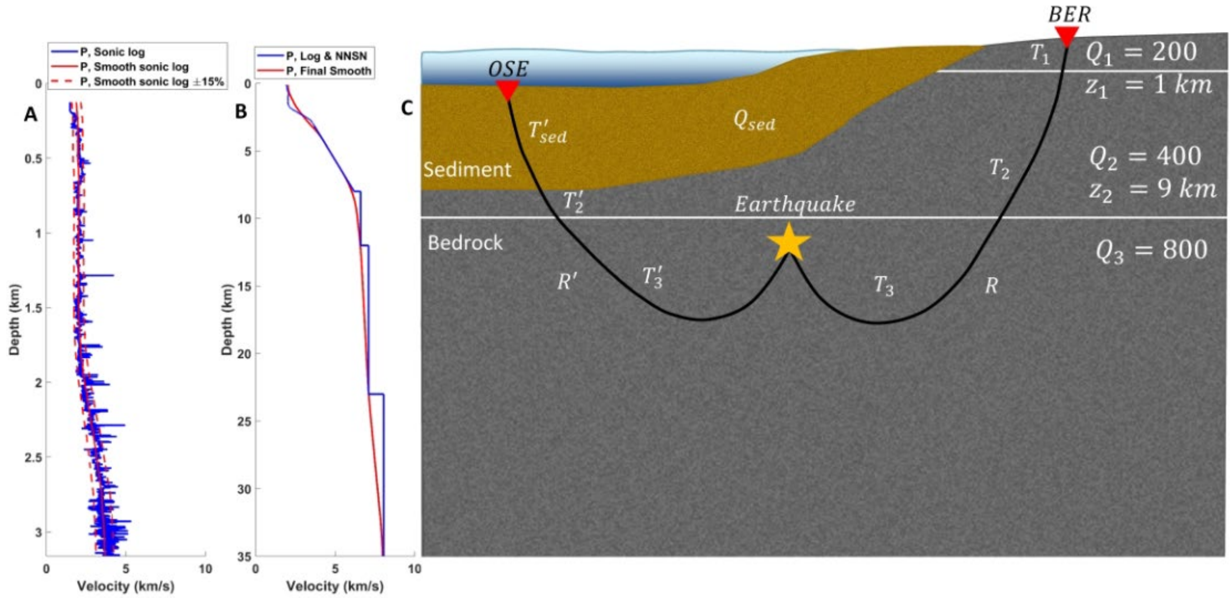

Figure 4.1.2 A-C: Velocity model and conceptual sketch. A) The sonic log from well 30/6-1 (blue) and the smoothed version (red) with the assumed 15% uncertainty indicated (red dashed lines). B) The final velocity model (red), combining the smoothed sonic log and the Norwegian National Seismic Network (NNSN) and the P-wave crustal velocity model (blue). C) The ray paths to the seismic station in Bergen (BER) are assumed to be dominated by attenuation in bedrock, while the travel path to Oseberg is affected by attenuation from a 5-7 km thick sediment package and the same bedrock model as for the ray path to BER. The Q-model of the bedrock is assumed to be known, while the value (Qsed) for the sediment package is estimated.

An in-depth discussion of the results and the spectral division method is published by Rørstadbotnen et al., 2022[1].

5 Task 2.5 - Adapt the system to standards for subsea communication and energy transfer

[1] Rørstadbotnen and Landrø, Average Qp and Qs estimation in marine sediemnts using a dense receiver array. Geophysics, Mar. 2023

5.1 Aims and objectives

Ensure that the different data components adhere to the prevailing and emerging open standard data and communication platform solutions to secure cost-effectiveness and seamless integration of the various system components.

5.2 Outcomes and deliverables

5.2.1 Recommendations on communication platforms and data standards to facilitate autonomous operations, high-performance computing, and the integration of large data sets (D2.6)

In this task, we will take part in and influence the development of standards for subsea communication and energy transfer in a direction that is suitable for future CCS applications and makes sure that all developments within DigiMon follow the prevailing standards of the industry.

Monitoring of carbon storage at sea requires a communication infrastructure that can operate and function under demanding conditions. Delivery D2.6 deals with various communication solutions and examples.

The report shows that collaboration on standardisation and solutions is the key to a successful platform for CO_2 storage. The offshore and the oil industry are leaders in the route towards standardisation and will guide future developments. A key example is the collaboration in this industry with the standardisation group SWiG for wireless underwater communication and energy transfer. This standardisation work paves the way for a cost-effective solution and facilitates the physical implementation needed to reach the offshore sites where CO_2 storage takes place.

In addition to establishing a good physical route to where the CO_2 storage takes place, there is also a need to follow established data standards for the communication itself. Established protocols used to transfer data from the sensor to the system that will perform the analysis. An example of a protocol is OPC UA, an open-source industrial standard (IEC62541) for data exchange from the sensor to the cloud application. Another example is the MQTT protocol, which is a commercial solution but suitable for a large number of sensors.

Integration of large data sets is best handled with current technology using databases in cloud solutions. Standardisation through alternatives such as SWiG builds the physical road. The transport itself is best solved by choosing protocols that can handle many possibly different sensor types and collect these in an effective system for further analysis and processing. Examples of leading providers of integration of large data sets and high-performance computing are Microsoft Azure, Google Analytics and Amazon AWS.

6 Task 2.6 - Optimise the monitoring solution

6.1 Aims and objectives

The main objective of this task is to secure the cost-efficiency and societal embeddedness of the DigiMon system by optimal integration of system components into a holistic, viable and reliable system.

This task also includes an assessment of the capability of 3D finite difference codes to model Distributed Acoustic Sensors (DAS) at reservoir scale for monitoring CO_2 sequestration.

6.2 Outcomes and deliverables

6.2.1 Validation of geometry factors comparing DAS and geophone (D2.7)

In Deliverable D2.7, Project report and validation of geometry factors comparing DAS and geophones, the capability of 3D finite difference codes to model Distributed Acoustic Sensors (DAS) at reservoir scale for monitoring CO_2 sequestration is assessed.

The assessment includes

1) evaluation of the computational load and trade-offs needed to model Distributed Acoustic Sensing (DAS) signals from a 3D (~14x14x3 km) model of a CO_2 sequestration reservoir
2) sensitivity of various DAS deployment models (borehole versus surface)
3) comparison of DAS (linear and helical) with respect to geophones for both vertical and surface installations; and
4) measurements of possible induced seismicity with DAS.

We find that a 3D elastic model of a reservoir that is 14x14x3 km with a grid spacing of 12 m and an upper frequency of 40 Hz is sufficient to model the expected frequencies and observations of DAS. This model required approximately 4 hours of wall clock time while running on 2304 CPU (64 nodes at 36 CPU/node).

Changes in the reservoir due to CO_2 injection cause changes in both the reflected and transmitted seismic waves from surface sources. These changes occur both in amplitude and phase. DAS installed in a vertical monitoring well is more sensitive than DAS on a horizontal surface cable. This is due in part to the increased longitudinal sensitivity of DAS to compressional waves as well as proximity to the reservoir.

Comparisons between the modelled response for DAS and geophones suggested that the expected sensitivity (ignoring instrument self-noise) is comparable for the vertical borehole, but that horizontal DAS cables on the surface are less sensitive than geophones. The use of helical DAS fibre appears to show a slight improvement, but we are still evaluating the validity of numerical approximation near the surface.

Simulations of induced events are also recorded better on vertical monitoring wells than on the surface for DAS.

Recommendations for future work:

- Coupling of a reservoir model to the elastic to provide a more accurate simulation of the changes and to assess resolution. This is particularly critical for calibrating changes in saturation.
- A more comprehensive understanding of the effect of reservoir changes on S wave amplitudes.
- Comparisons with data from ongoing CO_2 sequestration projects in similar geology and focused DAS testbeds. The goal is to understand and model the DAS response and coupling to achieve accuracies comparable with standard seismic sensors.
- Verifying these results with other code to ensure that the water layer, which has not been included in these models due to limitations in SW4, does not significantly influence the results.

6.2.2 Integrated system for increasing operational safety in units subject to technological risk

The report "Integrated system for increasing operational safety in units subject to technological risk" is provided by the SEDONA team, where they have developed a risk management system for the DigiMon CCS monitoring solution. The system is based on experience from their unified system of risk management at the Heavy Water Factory, a high-risk unit located about 12 km from the border of Romania with Serbia.

The capabilities of the system as described in the report are:

- Integration of the constituent subsystems of the DigiMon system in a coherent and unitary informatics system aiming to ensure the functions proposed by the project.
- The elaboration of the structure of an IT system for increasing the safety in operation in units subject to technological risk.
- The definition of a communication system between the sensors/equipment in the technological field and the control room.
- The definition of the subsystems and the functions they assure.
- The elaboration of the structure of an IT system to communicate with social partners.
- Homogenisation of information between the social partners interested in the system.

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

The DigiMon project has highlighted that monitoring the geological storage of CO_2 is a task that spans multiple disciplines, from technology to economics and social science. Optimising a monitoring solution based on very diverse criteria from different disciplines is challenging, so a methodology was needed 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 (1990)[2], is one such widely used methodology to assist in multi-criteria decision-making (MCDM). AHP has been applied to many different areas spanning politics, engineering, education, industry, and management (Vaidya, Kumar, 2006)[3].

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 being 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, to some degree, depend on the national public perception of risks associated with CO_2 storage.

In the DigiMon project, 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.

The AHP has been applied to the DigiMon project by first identifying and grouping the criteria the monitoring solution should fulfil with the overall goal of securing measurement, monitoring, and verification (MMV) of the CO_2 storage project. The criteria were identified by the project in a joint meeting involving people from different disciplines and have later been harmonised by aligning them with EU regulations

In the evaluation process, the monitoring alternatives were given scores according to their ability to fulfil the criteria identified as part of the DigiMon 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 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.

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[2] Saaty, T. L. (1990). How to make a decision: the analytic hierarchy process. European journal of operational research, 48(1), 9-26.

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

7 WP2 Impact

The overall expected result of the DigiMon project is the validation of an “affordable, smart and societal embedded digital monitoring early-warning system” for MMV of CO_2 storage that combines proven and less mature system components into a holistic, integrated system. Developments towards this end goal is the main contribution from WP2 which can impact on the emergence of CCUS.

The WP2 impact on key stakeholders is addressed next.

7.1 CCS industry

For accelerating the implementation of CCS, low-cost monitoring solutions are key. DigiMon WP2 address this challenge along multiple fronts.

The technical readiness analysis (Deliverable D2.3, Section 3.2.1) documents recent developments and the technological readiness of alternative cost-efficient technologies like fibre-optic sensing, seafloor deformation measurements, and 4D gravity monitoring to help reduce costs and improve monitoring effectiveness over present state-of-the-art.

The value of fibre-optic sensing is explored within several applications (e.g., cross-well tomography, full waveform inversion, and seafloor refraction studies), and different acquisition geometries including instrumentations in wells and at the seafloor. For cross-well tomography the joint application of conventional seismic and DAS would significantly increase the data interpretability in cross-hole CO_2 imaging and for short-range cross-hole surveys in general (see, Sections 2.2.3 and 4.2.1). The results obtained in Deliverable D2.5 (see, Section 4.2.2) obtained with full waveform inversion of conventional seismic data were generally better than those obtained with gravimetric or DAS data alone. Results obtained by combining gravimetric and DAS data were, however, of comparable quality to those obtained with conventional seismic data. For the examples considered, sequential inversion of gravimetric and DAS data, therefore, seems a less costly, viable alternative to conventional seismic data for monitoring CO_2 sequestration. In Deliverable D2.7 (see, Section 6.2.1) the capability of 3D finite difference codes to model Distributed Acoustic Sensors (DAS) at reservoir scale for monitoring CO_2 sequestration is assessed. Comparisons between the modelled response for DAS and geophones suggested that the expected sensitivity (ignoring instrument self-noise) is comparable for the vertical borehole, but that horizontal DAS cables on the surface are less sensitive than geophones. The use of helical DAS fibre appeared to show a slight improvement, but the validity of numerical approximation near the surface we are still under evaluation.

Monitoring of carbon storage at sea requires a communication infrastructure that can operate and function under demanding conditions. Deliverable D2.6 (see, Section 5.2.1) deals with various communication solutions and provides recommendations for handling of large data sets, choice of standardisation alternative and protocols for processing and handling many different sensor types.

7.2 Policy makers and regulators

The needs of policy makers and regulators direct a CO_2 storage field monitoring system. A suitable monitoring system should monitor conformance and containment and be linked to a safety concept in case of CO_2 migration to nearby subsurface formations or to the atmosphere. The report "Integrated system for increasing operational safety in units subject to technological risk" is provided by the SEDONA team, where they have developed a risk management system for the DigiMon CCS monitoring solution (Section 6.2.2).

The DigiMon project has highlighted that monitoring the geological storage of CO_2 is a task that spans multiple disciplines, from technology to economics and social science. Optimising a monitoring solution based on very diverse criteria from different disciplines is challenging, so a methodology was needed to take the multi-disciplinarity into account and make a more holistic assessment rather than only assessing a few criteria against each other. In the DigiMon project, 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 (Section 6.2.3).

7.3 Other environmental or socially important impacts, such as public acceptance.

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.

7.4 Research results

The DigiMon project has made significant steps in addressing the storage and crosscutting Priority Research Directions (PRDs) for Carbon Capture, Utilisation, and Storage[4]. The PRDs are impacting on the cost, acceptability, and efficiency of monitoring CO_2 storage sites. The specific PRDs tackled by WP2 are given in Table 3.

Table 3: Mission Innovation PRDs addressed in WP2 of the DigiMon project

PRD	WP2 Outcome

[4] Mission Innovation Report on Accelerating Breakthrough Innovation in Carbon Capture, Utilization and Storage. Report of the Mission Innovation Carbon, Capture, Utilization, and Storage Experts' Workshop, September 2017.

S-4	Developing Smart Convergence Monitoring to Demonstrate Containment and Enable Storage Site Closure	Optimisation of the integration and interpretation of data sets (Sections 4 and 6)
S-5	Realising Smart Monitoring to Assess Anomalies and Provide Assurance	Development of a smart monitoring system (Section 6) Applying a new spectral division method for estimating the value of Q, to conclude on the geology that the seismic wave travelled through (Section 4.2.3).
S-6	Improving Characterisation of Fault and Fracture Systems	Framework for the separate and joint use of seismicity and induced static strains to calibrate our predictions of geomechanical risks in the context of CCS (Section 2.2.4)
S-7	Achieving Next-Generation Seismic Risk Forecasting	Assessment of the impact of various monitoring strategies on the ability to reduce the risk of induced seismicity (Section 2.2.4)
CC-3	Incorporating Social Aspects into Decision-Making	Social aspects incorporated into monitoring system design (Section 6.2.3)
CC-4	Developing Tools to Integrate Life Cycle Technoeconomic, Environmental, and Social Considerations to Guide Technology Portfolio Optimization	Development of techniques to understand uncertainties in monitoring systems (Section 4) Framework for decision-making bringing technical, economic, and social aspects together into a holistic approach (Sections 6.2.2 and 6.2.3)

7.5 Dissemination of results

In addition to the Deliverables listed in Appendix A, dissemination of WP2 results took place in a series of over 40 scientific publications in scientific journals, conferences and dedicated webinars organized for this purpose, as shown in Appendix B. Presentations were given at international conferences throughout the project to highlight the ongoing developments in the project.

8 Conclusions and Outlook

Work Package 2 of the DigiMon project has made a significant contribution to accelerate the emergence of CCUS through the integration of cost-effective and robust technologies for the monitoring of the subsurface CO_2 in the reservoir, overburden, and flow barriers. The work performed has achieved the expected outcome of WP2, more specifically, WP2 has provided the following main results:

- A unified framework for forward modelling the data response of the various system components on a generic CCS site reflecting challenges associated with large-scale CO_2 storage offshore
- Further developments of methodology for the integrated interpretation and uncertainty quantification of the system data responses for monitoring large-scale CCS projects
- Concept report and field trial for cross-well seismic tomography combining conventional and DAS measurements (with different cable designs) using active seismic and ambient noise
- A technical readiness assessment providing
    - Identification of critical technology elements (CTEs) for monitoring carbon capture and storage projects.
    - Objective scoring of the level of technology maturity for each CTE.
    - A report documenting the findings of the assessment.
- Methodology for assessing the separate and joint use of seismicity and induced static strains to calibrate our predictions of geomechanical risks (e.g., induced seismicity) in the context of CCS.
- Recommendations on communication platforms and data standards to facilitate autonomous operations, high-performance computing, and the integration of large data sets
- A demonstration of the Analytical Hierarchy Process (AHP) for optimising the monitoring solution. AHP is a structured and transparent framework for decision-making bringing together technical, economic, and social aspects into a holistic approach for system design

Building on the above outcomes, the research and implementation of the scientific breakthroughs have enabled the DigiMon partners to successfully meet the technical milestones:

- Technology Readiness Assessment (TRA) of the different system components
- Framework for integrated inversion and uncertainty quantification
- A system communication platform
- Overall system design

Here the "Overall system design" is interpreted as a framework providing the key criteria that a monitoring system must fulfill, and a methodology to optimize the monitoring solution based on site specific conditions (i.e., technical risk assessments) together with economic and societal consideration.

Though, WP2 in the ACT II DigiMon project has provided new insights in monitoring of CO_2 storage sites, i.e., by development of new workflows and methodologies for inversion of multi-physics data and system design there is an urgent need for scale-up to build sufficient capacity for CO_2 storage to meet climate targets. In a further work, the modelling and inversion framework developed in DigiMon would serve as an excellent starting point for full field scale applications. Moreover, the proposed AHP methodology for system design and decision making is suitable for further developments combining societal challenges and requirements, as well as cost, to draw risk governance strategies for industry and regulators and incorporate them in decision support tools.

Appendix A: WP2 Deliverables

The following are WP2 deliverables, available as reports from the DigiMon project.

Deliverables	Task
D.1. Framework for forward-modelling of the Digimon data components	2.2
D.2. Concept description for the use of fibre-optic measurements for seismic tomography.	2.3
D.3. Project report for the TRA of all the Digimon data components	2.3
D.4. Examination & interpretation of the seismic tomography data in respect to “up-lift” phenomena and stress-induced Anisotropy	2.6
D.5. Project report and algorithms for integrated inversion of individual Digimon data components	2.4
D.6. Recommendations on communication platform and data standards to facilitate autonomous operations, high-performance computing, and the integration of large data sets	2.5
D.7. Project report and algorithms for optimising acquisition layout and frequency	2.6
D.8. Project report with guidelines and recommendations for a monitoring system to be applied at a set of planned or active CCS sites	2.6
D.9. Project report on seismic tomography data interpretation and conceptual model for integrating DAS into borehole seismic tomography surveying	2.6
D.10. WP2 final report	2.1

Appendix B: WP2 Publications and Dissemination Activities

Author(s)	Title	Reference	Project partners involved
Landrø, M., Amundsen, L.	From Arrhenius to CO2 storage Part III: A Simple Greenhouse Model	GeoExpro, Recent Advances in Technology May 2019	NTNU
Poletto, Bellezza, Corubolo, Goertz, Bergfjord, Lindgård	Seismic While Drilling Using a Large-Aperture Ocean Bottom Array.	SEG International Exposition 89th Annual meeting, Sep. 2019	OCTIO
Midttømme, Kirsti	DigiMon - Digital monitoring of CO_2 storage projects	Safe and Cost-efficient CO2 Storage for Europ. Indust., seminar. SINTEF/ PreAct, Brussel, October 10, 2019	NORCE, all partners
Landrø, M., Amundsen, Ringrose, P.	From Arrhenius to CO2 storage Part IV: Challenges and Some Practical Issues	GeoExpro Recent Advances in Technology May 2019	NTNU
Nøttvedt, Arvid	Presentation of new ACT-2 projects: DigiMon	4th ACT Knowledge Sharing Workshop. Athene Greece, Nov. 6-7, 2019	NTNU, Equinor
Midttømme, K. Nøttvedt, A., Holstad, M.	Digital monitoring of CO_2 storage projects	Bergen CCUS seminar, Dec. 3-4, 2019	NORCE
Halland, E., Landrø, M., Amundsen, L.	From Arrhenius to CO2 storage, Part V: Underground Storage of CO2	GeoExpro, Recent Advances in Technology Dec. 2019	NORCE
Midttømme, Nøttvedt, Holstad, Stork, Lien, Puts	Digital monitoring of CO_2 storage projects (DigiMon)	Nordic Geological Winter Meeting 2020, Oslo	NTNU
Nøttvedt, A.	DigiMon- Digital Monitoring of CO_2 storage projects	ACT projects and international activities, Pre meeting STEM- CCS workshop, Bergen	NORCE, Silixa, OCTIO, TNO
Ruiz, H., Lien, M.	Cost-effective reservoir monitoring using seafloor measurements of gravity changes and subsidence,	Norwegian Petroleum Society, the Biennial Geophysical Seminar, Oslo, Norway, March 9-11, 2020	OCTIO, Monviro

Author(s)	Title	Reference	Project partners involved
Nøttvedt, A.	DigiMon - Digital monitoring of CO_2 storage projects	ACT knowledge sharing workshop (digital), Nov 16, 2020	NORCE and all partners
Nøttvedt, Midttømme, Stork, Lien, Puts	Digital monitoring of CO_2 storage projects (DigiMon) https://www.norceresearch.no/en/insight/digimon-ccs-project-at-climit-digit-2021	Climit 2021 Digits, Feb 10, 2021	NORCE and all partners
Nøttvedt, Lien, Midttømme, Puts, Stork	Digital monitoring of CO_2 storage projects (DigiMon) http://ssrn.com/abstract=3823153	GHGT, Greenhouse Gas Control Technologies, March 15-18, 2021	NORCE, Silixa, OCTIO, TNO
Nøttvedt, Lien, Midttømme, Puts, Stork	DigiMon	SPE Virtual Workshop: Offshore CCUS - The Size of the Prize and the Way Forward, April 6-13, 2021	NORCE, OCTIO EM, TNO, Silixa
Pitarka, Thomas, Paap, Heggelund, Butcher, Matzel, Mellors	Understanding Fiber Response with Lab-Scale Tests and Modeling	SSA Seismological Society of America Annual Meeting 2021, April 19-23, 2021	LLNL, NORCE, TNO, UoB
Bhakta, T., Mannseth, T.	Monitoring of CO_2 saturation plume movement from time-lapse inverted-seismic and gravity data using an ensemble-based method	82nd EAGE Annual Conference and Exhibition, Amsterdam, June 2021	NORCE
Taweesintananon, K., Landrø, M., Brenne, J.K., Haukanes, A.	Distributed acoustic sensing for near-surface imaging using submarine telecommunication cable: A case study in the Trondheimsfjord, Norway	Geophysics, Volume 86, Issue 5, Sep. 2021, https://doi.org/10.1190/geo2020-0834.1	NTNU
S. Veland. Å. D. Nordø, M. Lien	Stakeholder Workshop Norway: Design Options for Carbon Storage Monitoring Systems	Online Meeting, May 4th, 2022	NORCE, Monviro
Paap, B., Bhakta, T., Vanderweijer, V. Mannseth, T	Modeling approach for evaluating time-lapse effects of CO_2 storage on particle velocity and strain rate data	EAGE Geotech- Third EAGE Workshop on Distributed Fibre Optic, April 4-6, 2022	TNO, NORCE
Nøttvedt, Arvid	DigiMon - Digital monitoring of CO_2 storage projects	CCUS Event, Rotterdam, 8-10 June 2022	NORCE

Author(s)	**Title**	**Reference**	**Project partners involved**
Nøttveit, A., Midttømme, K.,	DigiMon Digital Monitoring of CO_2 Storage Projects	Northern Lights seminar, Aug. 30, 2022	NORCE
Otto, Sprenkeling, Peuchen, Nordo, Mendrinos, Karytsas, Veland, Polyzou, Lien, Heggelund, Piek, Gross, Puts	On the Organisation of Translation—An Inter- and Transdisciplinary Approach to Developing Design Options for CO_2 Storage Monitoring Systems	Energies, 15 (15), 5678.https://doi.org/10.3390/en15155678, August 2022	UFZ, TNO, NORCE, CRES, OCTIO EM
Ködel, U.	Crosswell tomography using DAS and conventional seismic methods	New Developments Within Fiberoptic and Gravimetric Monitoring of Geological CO2 Storage, DigiMon Webinar, October 12, 2022	Geotomographie
Candela, T.	Comparison of DSS and conventional seismic for fault stability monitoring	New Developments Within Fiberoptic and Gravimetric Monitoring of Geological CO2 Storage, DigiMon Webinar, October 12, 2022	TNO
Mellors, R., Pitarka, A., White, J.	Forward modelling of (near) reservoir scale DAS signals	New Developments Within Fiberoptic and Gravimetric Monitoring of Geological CO2 Storage, DigiMon Webinar, October 12, 2022	LLNL, UCSD
J., Bhakta, T., Mannseth, V, Vandeweijer, B. Paap, Lien, M.	Integrated interpretation and uncertainty quantification, with application to geophysical monitoring of a North Sea sector model	New Developments Within Fiberoptic and Gravimetric Monitoring of Geological CO2 Storage, DigiMon Webinar, October 12, 2022	NORCE, TNO, Monviro
Hegglund, Y., Lien, M.	Application of the Analytical Hierarchy Process to assess the DigiMon system	New Developments Within Fiberoptic and Gravimetric Monitoring of Geological CO2 Storage, DigiMon Webinar, October 12, 2022	NORCE, Monviro
Koedel, Stork, Thomas, Zhou, David, Maurer, Soeding, Fechner	Seismic Cross-hole Surveying to Monitor a CO_2 Injection at the Svelvik Test-site in Norway	16th International Conference on Greenhouse Gas Control Technologies GHGT-16, October, 2022	Geotomographie, UFZ, Silixa, NORCE, UoB, ETH Zurich

Author(s)	**Title**	**Reference**	**Project partners involved**
Vandeweijer, Candela, Lien, Koedel, Fechner, Bond, Zhou, Butcher, Kendall, Stork & Mellors	A Technology Readiness Assessment for CCS site monitoring systems	16th International Conference on Greenhouse Gas Control Technologies GHGT-16, October 2022	TNO, Monviro, Geotomographie, LLNL, UoB, UoO, Silixa, UCSD
M. Lien, A. Goertz, S. Catherine V. (OCTIO), C. Ward, M. Ackers, T. Pujol, A. Fletcher (Spirit Energy)	Feasibility of 4D microgravimetric monitoring of a CO_2 flood in a depleted gas reservoir	Accepted for oral presentation at the Energy Geoscience Conference (EGC) in Aberdeen, May 2023	OCTIO, Monviro, Spririt Energy
Midttømme, K.	DigiMon: Digitalt tidlig varslingssystem for CO2 lagringsfelt, Kirsti Midttømme, sjefsforsker i NORCE	HAVlunsj , GCE Ocean Technology, Bergen, October 27th, 2022	NORCE
Vladut, G.	Integrated informatics system structure for digital monitoring of the CO_2 storage	FOREN 2022, WEC Central & Eastern Europe Regional Energy Forum, Energy transition needs regional cooperation, 12-15 June 2022, Costinesti, Romania,	Sedona
Vladut, G.	System functions and informatic programs for integrated digital monitoring of CO_2 storage	Open Access Journal of Biogeneric Science and Research, Volume 12 Issue 1. USA. June, 2022	Sedona
Vladut, G., Mendrinos, D.	What do stakeholders expect from an integrated system for informing social partners and decision makers in digital monitoring of CO_2 storage	Submitted to SBE23 - Sustainable built environments; Paving the way for achieving the targets of 2030 and beyond. Thessaloniki, Greece, 22-24 March 2023	Sedona, CRES
Vladut G.	Integrated system for digital monitoring of CO_2 storage and information of the social partners	Journal of Mining Science and Technology, USA. July, 2022	Sedona
Vladut G.	Digital monitoring and information system regarding the operational safety of CO_2 storages,	Book name: Current Overview on Science and Technology Research, https://www.bpinternational.org/, July, 2022	Sedona
Vladut, G., Mendrinos, D.	The design of an integrated informatics system for digital monitoring, management, and	Submitted to Annals of Reviews & Research – Juniper Publishers,	Sedona, CRES

Author(s)	Title	Reference	Project partners involved
	information of social partners regarding the safety of CO_2 storage	California, US., August, 2022	
S. Veland, Å. D. Nordø, M. Lien	Stakeholder Workshop Norway: Design Options for Carbon Storage Monitoring Systems	Online Meeting, May 4th, 2022	NORCE, Monviro,
M. Lien	Microgravimetry-a cost efficient monitoring solution for CCS with minimal Environmental footprint	Vestland CCUS 2022, November 22-23, 2022	MonViro, Reach Subsea
T. Candela	On the use of seismicity to calibrate our predictive geomechanical models	To be submitted	TNO
Rørstadbotnen, R. A.; Landrø, M.	Average Qp and Qs estimation in marine sediments using a dense receiver array.	*Geophysics.* volume 88 (2), 2023	NTNU