DigiMon Final Report

Digital monitoring of CO_2 storage projects

Prepared by Arvid Nøttveit, Kirsti Midttømme, Anna Stork, Martha Lien and Hanneke Puts

with contributions from all DigiMon partners: CRES, Equinor, Geotomographie, LLNL, Monviro (now ReachSubsea), NORCE, NTNU, Repsol Norge, Sedona, Silixa Ltd, TNO ,UFZ Helmholtz Centre for Environmental Research, University of Bristol, University of Oxford

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Scope

DigiMon D. 4.9 “DigiMon Final Report” summarizes the ACT DigiMon project. The report is following the ACT Program template for Final report and was sent to the ACT Cooridinator on April 18, 2023

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Document distribution

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DigiMon partners

- NORCE Norwegian Research Centre AS (CMR <2020)
- OCTIO Environmental Monitoring AS (Monviro 2021-2023 and ReachSubsea 2023-)
- NTNU Norwegian University of Science and Technology
- University of Bristol
- CRES Centre for Renewable Energy Sources and Saving
- Helmholtz–Centre for Environmental Research
- Sedona Development SRL
- TNO Nederlandse Organisatie voor toegepast -natuurwetenschappelijk Onderzoek
- Geotomographie GmbH
- LLC Lawrence Livermore National Security
- SILIXA LTD
- EQUINOR ASA
- REPSOL –NORGE AS

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1. Identification of the project and report

Project title	DigiMon - Digital Monitoring of CO_2 Storage projects
Project ID	299622
Coordinator	NORCE Norwegian Research Centre AS
Project website	
Reporting period	01.10.2019 - 31.12.2022

Participants

Table 1 Participants

Organisation	Main contact(s) + E-mail	Role in the project
NORCE	Kirsti Midttømme kimi@norceresearch.no	Coordinator WP1, WP2, WP3, WP4
Centre for Renewable Energy Sources and Saving (CRES)	Dimitris Mendrinos dmendrin@cres.gr	WP3 (WP1, WP2, WP4)
Equinor ASA	Anne-Kari Furre akafu@equinor.com	Leader Steering Committee WP1, WP2, WP3
Geotomographie GmbH	Uta Ködel ukoedel@geotomographie.de	Partner WP1, WP2
LLNL	Joshua White white230@llnl.gov	Partner WP1, WP2
MonViro AS **(OCTIO Environmental Monitoring)**	Bjarte Fagerås Bjarte bjarte.fageraas@reachsubsea.com	WP2 leader, Partner WP1
NTNU	Lukas Thiem, lukas.thiem@ntnu.no Martin Landrø, martin.landro@ntnu.no	WP1, WP2
Repsol Norge AS	Øyvind Aasarød OAASAROD@REPSOL.COM	WP1, WP2
UFZ	Danny Otto, danny.otto@ufz.de Matthias Gross, matthias.gross@ufz.de	Partner: WP3
SEDONA	Gabriel Vladut, office@ipacv.ro	Partner WP1, WP 2, WP 3
Silixa Ltd	Anna Stork Anna.Stork@silixa.com	WP1 leader, Partner WP2
TNO	Pim Piek, pim.piek@tno.nl Hanneke Puts, hanneke.puts@tno.nl	Partner: WP1, WP2 Work Package lead: WP3 Orchestration of interdisciplinary collaboration process
University of Bristol	Antony Butcher antony.butcher@bristol.ac.uk	WP1, WP2
University of Oxford	Mike Kendall mike.kendall@earth.ox.ac.uk	WP1, WP2

2. Executive summary

Whilst a number of demonstration projects have shown the feasibility of CCS, operations need to be cost effective and easily scalable in size and number. A key component in the operation of any CCS project is measurement, monitoring and verification (MMV), which must demonstrate that projects are planned and executed in a societally acceptable manner and ensure safety and containment of injected CO_2. Analogue / digital sensors and single purpose systems are available for CO_2 monitoring and detection, providing accurate and comprehensive measurements with a significant range of resolution and uncertainties. This is often at prohibitive costs, and seldom in combined systems. A key scientific challenge is to deploy a cost-effective optimal combination of technologies that can reduce the uncertainties, collectively improving the probability of successfully verifying containment or detecting breach in CO_2 barriers.

The overall objective of the DigiMon project was to "*accelerate the implementation of CCS by developing and demonstrating an affordable, flexible, societally embedded and smart Digital Monitoring early-warning system*", for monitoring any CO_2 storage reservoir and subsurface barrier system, receiving CO_2 from fossil fuel power plants, oil refineries, process plants and other industries (Figure 2.1).

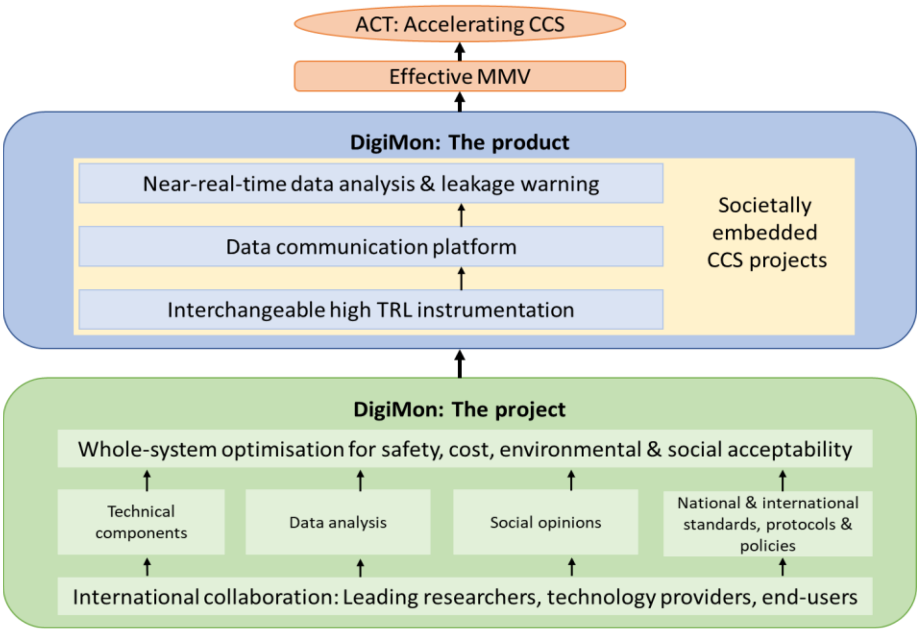

Figure 2.1: The DigiMon project.

Sub-objectives for the DigiMon project included:

1. Provide a system for monitoring the CO_2 plume and identify and provide early-warning of actual or potential breaches in the subsurface barriers.

2. Provide a flexible and interchangeable system with respect to the environment (offshore or onshore) and new system components provided by market-driven technology development.

3. Provide a societally relevant monitoring system that addresses the views and worries of various stakeholder groups and citizens.

4. Provide knowledge communication and dissemination to the public and policy makers.

Physical parameters that are influenced by migration and saturation of CO_2 outside the predicted flow path can be measured using a variety of geophysical methods, including acoustic, electro-magnetic (EM) and gravity measurements. The DigiMon concept focused on geophysical monitoring (Figure 2.2).

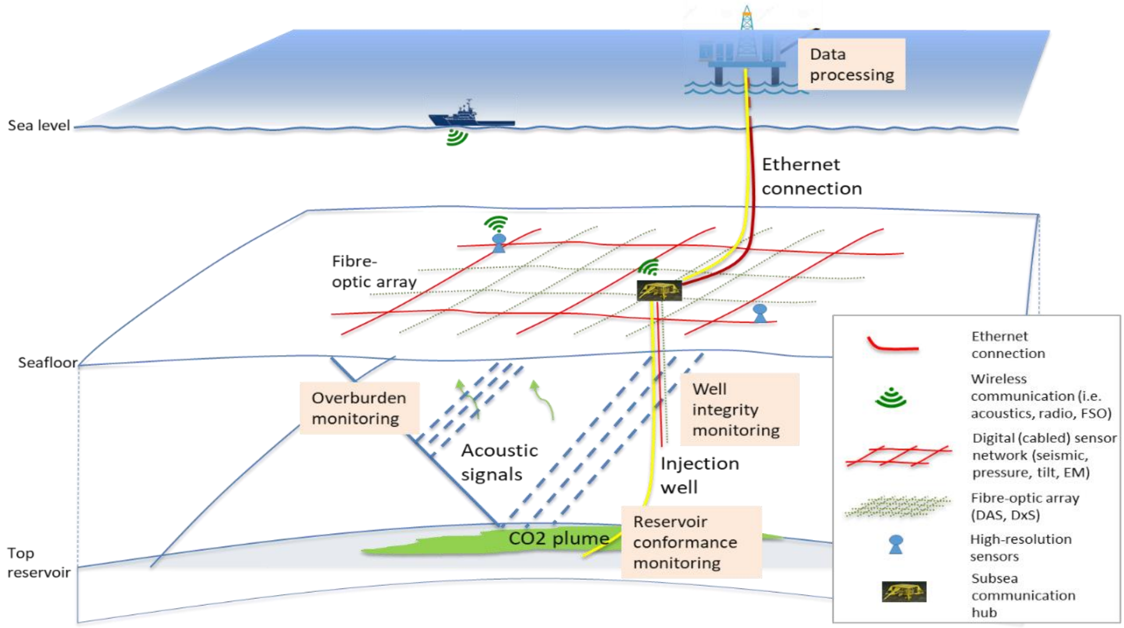

Figure 2.2: The DigiMon Digital Monitoring System

The DigiMon project assembled a strong international and interdisciplinary consortium with leading research institutions and industry from Norway, the Netherlands, Germany, United Kingdom, USA, Romania and Greece., with professional capabilities and skills from both natural and social sciences.

The innovation of the DigiMon approach lies in the integration of a broad range of technologies for MMV at CO_2 storage sites (i.e. distributed fibre-optic sensing technology (DxS), seismic point sensors and gravimetry). The DigiMon project has involved development and integration of system components that are available at intermediate to high Technology Readiness Levels (TRLs) and raising them to a uniformly high TRL.

DigiMon has also succeeded in bridging technology and social science research, particularly through development of the Societal embeddedness Level (SEL) methodology for evaluating social readiness or maturity of CCS projects.

3. Role and contributions of each project partners

NORCE Norwegian Research Centre AS (NORCE)

NORCE has served as the host institution for the DigiMon project and leader of WP4 Project Management. In addition, NORCE has participated with scientific research in WPs 1, 2 and 3.

In WP1 Critical Technology Elements NORCE

- coordinated the Svelvik field work (D1.1 add 3).
- was responsible for DAS lab experiments (D1.1 add 4).
- in addition, contributed to tasks 1.1, 1.2 and 1.4 and deliverables D1.10-14).

In WP2 Integrating the components NORCE

- led task 2.4 "Integrated interpretation and uncertainty quantification" (D2.5).
- led task 2.6 Optimize the monitoring solutions (D.2.8)
- in addition, contributed to tasks 2.1, 2.2, 2.3 and deliverables D2.1, D2.2, D2.10

In WP3 Design a human centred monitoring system NORCE

- was responsible for gathering and analysing data for the Norwegian case study.
- Contributed in all WP3 tasks and deliverables D3.2, D3.3, D3.4 and D3.5

Centre for Renewable Energy Sources and Saving (CRES)

CRES, in collaboration with other project partners, prepared deliverable D3.2 "Report on the SEL of four countries: Norway, the Netherlands, Greece and Germany" and also contributed to the following deliverables: D1.10-A roadmap for commercial delivery and implementation of WP1 outcomes, D1.11-Project report on WP1 outcomes relevant to other WP, D1.12-WP1 results summary report suitable for policy makers, D1.13-WP1 final report, D2.10-WP2 final report, D3.1-Guideline for applying the SEL concept on CCS, D3.3-State of the art report on the SEL of three local case studies in Norway, Germany and The Netherlands, D3.4-Report on validated monitoring criteria and indicators for three local case studies, D3.5-Report on the best practices of the co-design processes with local stakeholders and the validation of the tailored human centred CO2 monitoring system, D4.8-Scientific publications. In addition, CRES participated and provided expert opinion in all project meetings, either in person or online, relevant to WP1, WP2 and WP3, as well as in the interdisciplinary events of WP4. CRES also carried out public opinion survey and expert interviews on CCS in Greece for WP3, organized online the Greek CCS Stakeholders workshop for WP3 and disseminated project results in Greek technical press, as well as in international scientific journals and conferences in collaboration with project partners concerned. In addition, CRES organized a second workshop for Greek Stakeholders in person this time, in Athens, in February 2023.

Equinor ASA

In addition to providing financial support, Equinor also shared data and contributed with advice and knowledge to DigiMon.

Data sharing: A passive seismic dataset from Oseberg field was provided to DigiMon for analysis of earthquakes. The dataset consisted of three separate time periods of 172 4-component seismic data in the absence of an active seismic source vessel above the seismic cable.

Equinor and Gassnova has released the Smeaheia dataset openly to the scientific community through Sintef's CO2Datashare portal. This dataset consists of seismic and well data, and a simulation model. It was used actively by DigiMon for modelling and inversion studies. During DigiMon's lifetime the Smeaheia dataset was complemented with pressure data from well 32/4-3S ("Gladsheim" well - drilled September to October 2019).

Advice and knowledge sharing: Equinor contributed to two committees during DigiMon's lifetime (Anne-Kari Furre was leader of the steering committee and Kjetil Johannesen participated in the Technical Advisory Committee). Equinor representatives were represented and active in all partner meetings conducted during the project's lifetime. Equinor representatives contributed to quality controlling several reports.

Geotomographie (GmbH)

Geotomographie GmbH was one of the industrial partners in this project, whose tasks was mainly the development of a novel SV source, the modification of the Multistation Borehole Acquisition System (MBAS) to conditions prevailing at the CCS test site, the conception and execution of seismic measurements including simulations for the optimal test sequence in Svelvik and the adaptation, as well as the evaluation of the results of the fiber-optic measurement data compared to conventional seismic data.

Geotomographie GmbH contributed in particular within the work in WP1 to the instrumentation, execution and evaluation of tomographic cross-hole measurements, data processing and thereby in particular to the validation of the fiber-optic sensors in comparison to conventional methods.

The development of the novel SV source included several working steps such as:

- the design and construction of a test rig,
- the execution of experiments to determine the optimal coil configuration (number of turns, wire thickness) in order to obtain statements regarding the effective immersion depth of the soft metal core for a resulting optimal acceleration strength and a measurement of the rise time up to the max. acceleration,
- Since we could not say with certainty for a long-time which principle of action delivers the best signals, we pursued a parallel source development with two different principles of action based on the induction principle and the alternating current principle.
- Design of both sources with a selection of optimal materials,
- Necessary optimization of laboratory tests for both operating principles,
- Construction of the prototype of the novel SV probe,
- Field tests for handling and reproducibility of the measured signals of the novel SV probe in Hannover, Germany,
- 10-day field experiment at the CCS site in Svelvik/Norway; successful test of the novel SV-source,
- Improvement of the SV source design especially with respect to the coil formers and materials based on the experiences during the first field tests,
- Further field tests from May- October 2022,
- The novel SV source will be added to Geotomographie's portfolio and marketed starting in spring 2023

The long-standing expertise of Geotomographie GmbH also contributed to the development of efficient data processing especially for seismic tomography, visualization and modeling tools in WP2. During the project period, Geotomographie GmbH also conducted the following studies: (1) Study of the application of new machine-learning methods to assess the quality (pickability) of seismic data and (2) literature review of cross-hole experiments already published in the literature to filter out points for effective comparison experiments and clarify important characteristics of the SV source to be developed. The results of the several studies were reported in the project deliverables (D1.1, D1.7, D2.4, D2.2, D2.9).

Helmholtz Centre for Environmental Research (UFZ)

The UFZ was mainly involved in WP3 and was responsible for gathering and analysing data for the German case study. To do this, the UFZ conducted expert interviews and stakeholder interviews, conducted a public opinion survey, and organized an online stakeholder workshop. It contributed to all deliverables of WP3, namely: D3.1-Guideline for applying the SEL concept on CCS, D3.2 “Report on the SEL of four countries: Norway, the Netherlands, Greece and Germany”, D3.3- “State of the art report on the SEL of three local case studies in Norway, Germany and The Netherlands”, D3.5-Report on the best practices of the co-design processes with local stakeholders and the validation of the tailored human centred CO2 monitoring system. UFZ was in the lead for D3.4 – Report on validated monitoring criteria. In this function, the UFZ took a coordinating role in the interdisciplinary exchange for the development of design options for a human centred monitoring system and was able to publish an article based on this deliverable within the runtime of the project. Through this interdisciplinary exchange, the UFZ also contributed to WP2 deliverables (especially D2.8: “Project report with guidelines and recommendations for a monitoring system to be applied at a set of planned or active CCS sites”). The UFZ furthermore led or was involved in several publications and presented the work of the DigiMon project at a number of international conferences. The UFZ played an active role in all project meetings and workshops.

Lawrence Livermore National Laboratory (LLNL)

LLNL contributions focused mainly on WP1 and WP2. The effort fell into two main areas: Modelling and analysis of Distributed Acoustic Sensor (DAS) data (WP1 tasks 1.2 and 1.3) and fiber-based Distributed Chemical Sensing (DCS). LLNL staff were co-authors on several conference proceedings based on the DIGIMON work.

With respect to DAS, LLNL participated in deliverable D1.3 “DAS synthetic dataset” and led the work on deliverable D2.7 “Validation of geometry factors comparing DAS and geophones”. LLNL also provided input for the Technology Readiness Level (TRL) assessment. A key contribution was the application of high-performance computing to 3D full-waveform seismic models to model synthetic DAS response, as well as contributions to the advancement of the TRL level for DAS technologies. With respect to DCS, a prototype hollow-core gas-sensing fiber was tested in benchtop gas exposure experiments, showing good sensitivity to CO2. LLNL also worked with industrial partners to identify deployment challenges and develop a roadmap to increasing the TRL of DCS.

Netherlands Organization for Applied Scientific Research (TNO) (In Dutch: Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek TNO)

TNO was actively involved in all work packages with a diverse and interdisciplinary team of experts from several relevant disciplines: geosciences, CCS and social sciences.

In WP 1: Critical Technology Elements, TNO contributed to all defined tasks, in particular dealing with Distributed Acoustic Sensing (DAS) as monitoring technology for CCS: determining the DAS transfer function; DAS data processing and comparing DAS responses with geophone technology.

Also in WP 2: Integrating the components, TNO contributed to almost all the defined tasks and acting as task leader for task 2.2 ‘Setting up forward modelling framework’ and task 2.3 ‘Perform a Technology Readiness Assessment of the system components. In this leading role TNO was responsible for two project deliverables:

- D2.1 Framework for forward modelling of the DigiMon data components
- D2.3 Project report for the TRA of all the DigiMon data components

For WP 3: Designing a human centered monitoring system, TNO acted as the overall WP3 coordinator and had a leading role in multiple tasks: ‘Framing of the Societal Embeddedness Level for CCS’, ‘Researching the Societal Embeddedness Level at local level’ and ‘Best practices for designing a societal embedded CO2 monitoring system’. As such TNO contributed to all deliverables of WP3. As a WP-coordinator, TNO also took care of the team building process with the German, Greek, Norwegian and Dutch researchers involved, i.e. by initiating 2- or 3-days working sessions with the WP3 partner group. Luckily, at the very beginning of the Corona Pandemic (March 2020), TNO was able to organize and host a partner meeting for WP3 in Amsterdam.

Besides the expert roles in the three work packages, TNO also acted as the orchestrator of the interdisciplinary collaboration process to optimize the exchange between all partners and experts involved in the DigiMon research program. The interdisciplinary collaboration activities contributed to 1) overbridging the research in each of the work packages, 2) adding value by combining knowledge and enriching intermediate results, and 4) creating synergy between the developments were possible. For being successful in this orchestrating innovation role, it was important for TNO and NORCE to work closely together in preparing all major and/or strategic project meetings.

Finally, TNO contributed to the project's steering committee and all major dissemination activities organized by the project lead.

Norwegian University of Science and Technology (NTNU)

NTNU participated in WP1 and WP2. Active and passive seismic datasets on ocean bottom distributed acoustic sensing (DAS) were acquired in the Trondheimsfjord and Svalbard, both in Norway. These datasets were shared with TNO and used by them to study the signal-to-noise ratio of DAS across different fibers and deployment scenarios.

The dataset from the Trondheimsfjord compared the near-surface imaging capabilities of an ocean-bottom fibre to those of a conventional hydrophone streamer.

The passive seismic dataset from the Oseberg field that was provided by Equinor and OCTIO, was used to study earthquakes. This work studied the attenuation of P- and S-waves in the sedimentary sequence below the Oseberg permanent reservoir monitoring system.

Furthermore, NTNU contributed the project deliverable: D1.14 "Report on Optimization of Seafloor Deployments for Permanent Reservoir Monitoring". This deliverable summarizes NTNU´s contribution to the Digimon project. It includes the two publications as well as preliminary results from ongoing studies of DAS for marine traffic monitoring.

OCTIO Environmental Monitoring (MonViro and OCTIO)

MonViro was actively involved in all work packages. In WP 1: Critical Technology Elements, MonViro was the responsible for deliverable

- D1.9_Improved algorithms to aquire and process gravity and deformation data

In addition, the companies also contributed in WP1 with expertise in active and passive seismic data acquisition and processing from being the service provider of the Oseberg field 172 4-component seismic data set. Another contribution to the project was a velocity model over Smeaheia from Project 616212; Cost-effective microseismic monitoring and processing solutions.

For WP 2: Integrating the components, MonViro acted as the overall WP2 coordinator and contributed to all the tasks, in particular

- D2.1 Framework for forward modelling of the DigiMon data components
- D2.3 Project report for the TRA of all the DigiMon data components
- D.5. Project report and algorithms for integrated inversion of individual Digimon data components
- D.8. Project report with guidelines and recommendations for a monitoring system to be applied at a set of planned or active CCS sites

Moreover, MonViro was responsible for two project deliverables:

- D.6. Recommendations on communication platform and data standards to facilitate autonomous operations, high-performance computing, and the integration of large data sets
- D.10. WP2 final report

For WP 3: Designing a human centered monitoring system, MonViro had on a key role in the integration of the social and technical disciplines together with NORCE and TNO and contributing in particular to the tasks: 'Best practices for designing a societal embedded CO2 monitoring system'.

Finally, as part of the project, MonViro representatives contributed to quality controlling several reports, contributed to the project's steering committee, and major dissemination activities organized by the project lead.

Repsol Norge AS

Repsol have provided financial support, as well as advice and active participation in work packages and partner meetings.

Sedona Development SRL (S-D)

The role was as Partner. SEDONA has participated with scientific research in WPs 1, 2 and 3. More specifically:

In WP1 : Critical Technology Elements, we were involved in Task 1.7: Develop roadmap for commercial delivery and implementation of WP1 results. We developed "Technology Readiness Levels (TRLs)", "Considerations on seismicity in Romania", "Considerations on seismicity in Black Sea", "Analysis of identified seismic sources in the Black Sea" and "Seismic zoning for the Black Sea region".

In WP2: Integrating the components, we developed the Study "Integrated system for increasing operational safety in units subject to technological risk"

In WP3, we were involved in D1.11: Project Report on WP1 outcomes relevant for WP 3: The Study:

"DigiMon technology development of CO2 storage system components relevant to societal embeddedness of CCS monitoring system".

We presented our concept into 6 scientific articles / books, two with CRES partner:

- Integrated informatics system structure for digital monitoring of the CO2 storage,
- System functions and informatic programs for integrated digital monitoring of CO2 storage,
- What do stakeholders expect from an integrated system for informing social partners and decision makers in digital monitoring of CO2 storage,
- Integrated system for digital monitoring of CO2 storage and information of the social partners,
- Book: Digital monitoring and information system regarding the operational safety of CO2 storages,

The design of an integrated informatics system for digital monitoring, management and information of social partners regarding the safety of CO2 storage

Silixa Ltd

Silixa Ltd has been actively involved in project activities and project management. As WP1 Leader Silixa has coordinated the tasks in WP1 to monitor progress in each task and ensure deliverables have been submitted. The management of WP1 has included attending whole project management meetings with other WP leaders; coordinating monthly WP meetings on Teams; and presenting WP1 results at project meetings and to the wider community. This has resulted in WP1 fulfilling the deliverables according to the DigiMon project proposal.

Silixa has also provided DAS instrumentation and staff for data collection for Tasks 1.2, 1.3 and 2.9 to study the DAS transfer function and facilitate the development of DAS data processing techniques for seismic applications. Field engineers and a geophysicist optimised DAS data collection and pre-processing for passive and active seismic surveys at the CaMI Field Research Station (FRS) in Alberta, Canada and the SINTEF Svelvik CO_2 Test Injection Site, Norway. This has resulted in several publications and conference presentations in collaboration with DigiMon partners, the Universities of Bristol and Oxford, TNO and Geotomographie.

University of Bristol

UoB has led on the acquisition of DAS datasets and the development of workflows for implementation in the DigiMon system within WP1. Datasets were acquired alongside other DigiMon partners, which include synthetic DAS seismograms and field datasets from Antarctica and CaMi FRS, Alberta, Canada. We have also contributed to several different tasks across all DigiMon WPs, which have included technology readiness assessments, societal studies and the general DigiMon project management.

Synthetic DAS data were generated through a series of increasing complex models using both SW4 and SPECFEM3D, and through these models we were able to accurately create strain seismograms. The Antarctica field dataset comprised on surface deployed fibre optic arrays at the Rutford Ice Stream and borehole fibre at the Skytrain Ice Rise. At Rutford, three different array configurations were used to image the ice stream and monitor icequakes originating from its base. These data were used to develop novel processing methods for DAS, which included microseismic event detection/ characterisation methods, seismic noise interferometry and machine learning approaches. The Canadian dataset was acquired towards the end of the project, and the data have been used to assess the capability of DAS to monitor the near surface. Research is still ongoing with this dataset. Several papers relating to this work have been published in peer reviewed journals and presented at international conferences during the project period.

University of Oxford

UoO coordinated the fieldwork in the Antarctic and at the CaMi FRS site in Canada. This included logistics associated with shipping, customs and permissions. It also helped with project management via the DigiMon steering committee.

The Antarctic fieldwork required close collaboration with the British Antarctic Survey (BAS) and funding from the Collaborative Antarctic Support Scheme (CASS) administered by the Natural Environment Research Council (NERC), UK. A grant from the NERC Geophysical Research Facility provided seismic recording systems, which augmented the DAS equipment (Silixa iDAS). Transportation into the deep field (aircraft and snowmobile) and fieldguides, tents, food and power were provided by BAS – this included comprehensive safety training, both at BAS in the UK and at the Rothera Research Station. The fieldwork was conducted in the Austral summer (2019/20) just before the pandemic lockdown.

Logistical support for the FRS site experiments was generously provided by Global Seismic Repairs in Calgary and CaMi. UoO deployed the latest generation of Sercel seismic nodes, which complimented other nodal data from TNO and the University of Calgary, DAS (Silixa) and broadband sensors (UoB). Fibre had been previously deployed by CaMi along a surface line and within two boreholes. Seismic sources were provided by the University of Calgary (mini-vibe) and GSR (Internal Combustion Impulse Source). Data collection was delayed twice due to the pandemic, eventually happening in August 2021.

UoO led the analysis of microseismic data (Rutford Ice Stream) and the VSP data (Skytrain Ice Rise) recorded by DAS - both studies have led to numerous papers and conference presentations. It was shown that events could be located and source mechanisms could be derived using the DAS data. Furthermore, it was shown that shear-wave splitting parameters could be determined using certain geometries of cable deployment. Finally, it was shown that source mechanisms could be determined using DAS data. The results from FRS are still being analysed.

4. Short description of activities and final results

Description of DigiMon work package activities and results are described in the following sections, including deviations from the original work plan. Objectives and targets for the scientific work packages are shown in Figure 4.1.

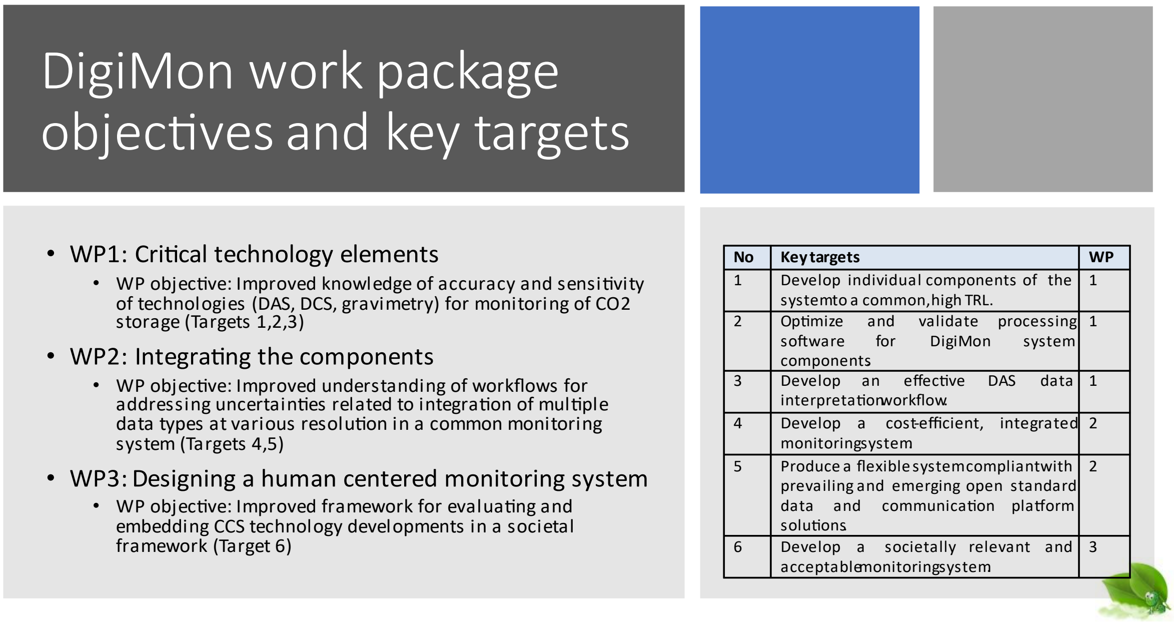

Figure 4.1: DigiMon scientific work package objectives and targets

4.1 WP1: Critical Technology elements

Activities

Within the DigiMon project, the objective of WP1 was to develop individual technologies, data acquisition, analysis techniques and workflows in preparation for inclusion in the DigiMon system.

Five milestones as were defined for WP1 (Table 4.1).

Number	*Milestone*
M2.1	Technology Readiness Assessment (TRA) of the different system components
M2.2	Framework for integrated inversion and uncertainty quantification
M2.3	A system communication platform/A system communication platform available for data collection and communication at standardized formats
M2.4	Overall system design

Table 4.1: WP1 milestones and associated milestone number

The work in WP1 consisted of distinct areas of research in six tasks:

- Task 1.2 - Determining the DAS transfer function
- Task 1.3 - Develop DAS data processing techniques and workflow
- Task 1.4 - Active source technology development
- Task 1.5 - Feasibility studies for DCS
- Task 1.6 - 4D gravity and seafloor subsidence data acquisition development
- Task 1.11 - Seismic monitoring design

The activities included the development of data processing techniques and algorithms for distributed fibre-optic sensing (DFOS) for seismic surveys and chemical sensing, 4D gravity and seafloor deformation measurements and seismic monitoring survey design. A new seismic SV-wave source was also designed, built and laboratory and field tested under WP1. Under Task 1.5 modelling and laboratory tests were designed and carried out for DCS development. The delivery of DAS field datasets for use within the project, in particular in Task 1.3, was also an important part of WP1 and active and passive seismic data were collected at the CaMI FRS site, Alberta (Figure 4.2), and cross-well seismic measurements were carried out at the Svelvik test site, Norway (Figure 4.3).

Figure 4.2: Field campaign at the CaMI FRS-site, Alberta.

Figure 4.3: Field campaign at the Svelvik site, Norway.

Final results

Specific results achieved in WP1 the project include:

- Development of modelling techniques to produce synthetic DAS data and advanced workflows to detect and locate microseismicity recorded on fibre-optic cables.
- Development of DAS data workflows for microseismic monitoring and assessment of ambient noise interferometry methods using DAS.
- Improved TRL and monitoring efficiency of critical DigiMon system components including gravity, seismic and chemical sensing technology.
- The successful completion of fieldwork in Norway, at the Svelvik test site, and Canada, at the Field Research Station (FRS) test site in Alberta.

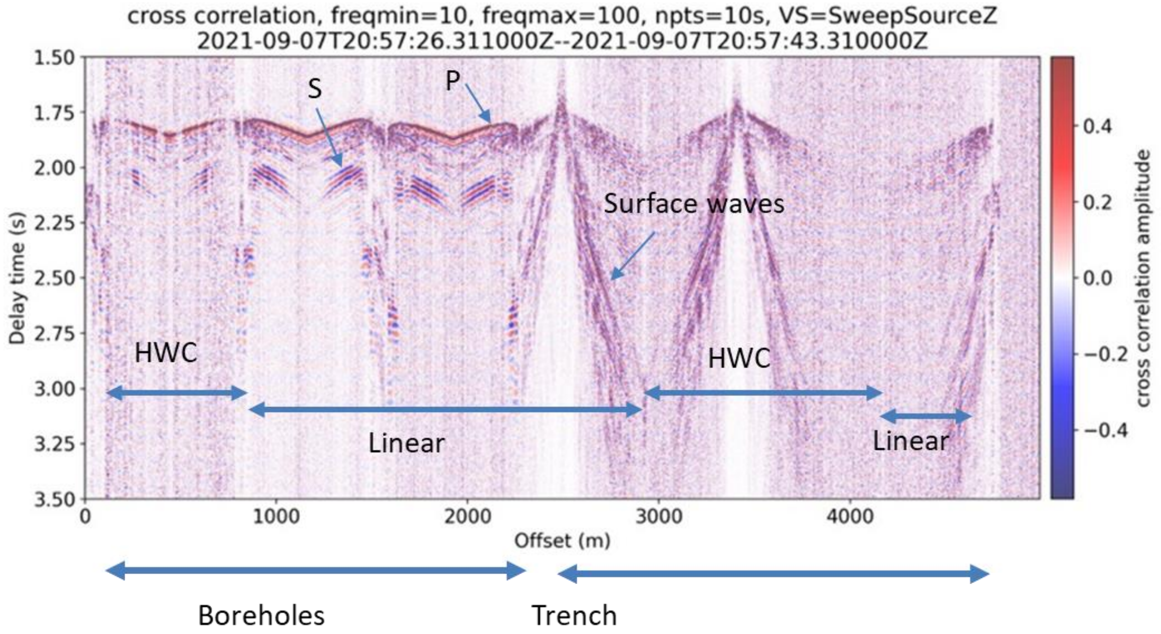

Figure 4.4: Cami FRS field test: Detection of CO2 injection; ambient noise interferometry; transfer Function; response of straight and helical wound fibre.

The research tasks carried out for WP1 of the DigiMon project produced new data processing methods and routines for DAS monitoring by using the data collected during DigiMon fieldwork and also making use of pre-existing data including an active and passive DAS dataset acquired by the British Antarctic Survey (BAS) and the University of Oxford in Antarctica in 2020. A DAS pre-processing workflow, processing algorithms, a transfer function and processing workflow were developed, which brought forward the technology for DAS microseismic monitoring, DAS ANI, 4D DAS active seismic tomography and DAS seismic reflection (Figure 4.5).

Figure 4.5: WP1 workflow

Table 4.2 presents a summary Technology Readiness Level (TRL) improvements made for distributed fibre-optic sensing in WP1.

Application	TRL at DigiMon start	TRL brought forward by DigiMon
DAS surface and seabed seismic reflection	4	5-6
DAS Vertical Seismic Profiling (VSP)	8	8
DAS seismic crosshole tomography	3	5-6
DAS microseismic monitoring	5-6	7-8
DAS ambient noise interferometry (ANI)	3	4-5
Distributed chemical sensing (DCS)	2	3

Table 4.2. Summary of distributed fibre optic sensing TRL advancement by WP1 of the DigiMon project

The field testing of a novel SV-wave seismic source and a redesigned Multilevel Borehole Acquisition System (MBAS), as well as acquisition of cross hole DAS data on straight and helical cables with P-, SH- and SV- seismic waves, took place at the Svelvik field laboratory (Figure 4.6). These tests demonstrate the technology in a relevant environment and so advanced the TRL level of SV-source cross well surveys and also DAS cross-well surveys from TRL 3 to TRL 5-6.

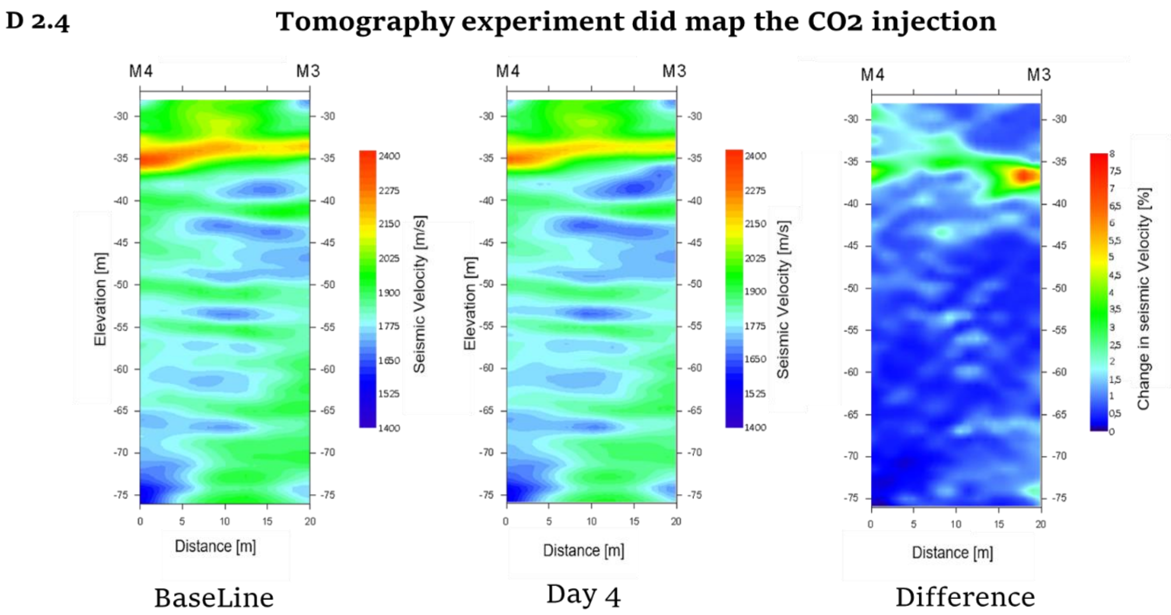

Figure 4.6: WP1 workflow

Concerning DCS, design, fabrication, and characterization of commercially available hollow core fibre for IR/Raman spectroscopy experiments carried out during the project advanced the TRL from 2 (technology concept formulated) to TRL 3 (experimental proof-of-concept).

As microgravity and vertical seafloor deformation monitoring surveying were already at TRL 9 (actual system proved in operational environment) at project commencement, developments carried out by the DigiMon project resulted in cost reductions and accuracy improvement rather than TRL development (Ruiz et al., 2020; Lien et al., 2023).

Overall, the data processing developments and efficiency improvements made in WP1 resulted in:

- Development of individual components of the DigiMon system to raise individual technology readiness levels (TRLs),
- Validation and optimisation of processing software for individual system components,
- Development of an effective Distributed Acoustic Sensing (DAS) data interpretation workflow.

Deviations from proposal/work plan

Overall, in the lifetime of the project, WP1 has delivered the results outlined in the proposal and work plan. However, there were some delays in fieldwork and hence data collection and analysis due to travel restrictions imposed during the Covid-19 pandemic. The planned fieldwork to collect active and passive seismic data at the CaMI FRS site in Alberta was delayed by more than one year and took place in in September 2021. Similarly, the test of the new SV-wave seismic source at the SINTEF Svelvik test site in Norway was delayed until September 2021. Analysis of this data is therefore ongoing, unfunded, post-project. Despite this delay there have been presentations and publications from fieldwork funded through DigiMon (Butcher et al., 2022a and b; Koedel et al., 2022).

Before fieldwork was possible, the project was also able to make use of publicly available DAS datasets (e.g., Utah FORGE geothermal project, Boullenger et al., in prep.) and also data collected by the University of Oxford in Antarctica (Kendall et al., 2020 and 2021; Hudson et al., 2021a and b; Brisbourne et al., 2021; Butcher et al., 2021; Zhou et al., 2022a and b; Lapins et al., in prep).

As a result of laboratory closures due to Covid-19, there were also delays in the laboratory work on DCS technology carried out by Lawrence Livermore National Laboratory. However, these delays did not affect other partners or the final deliverables of the project (Bond et al., 2022).

Following project start-up it became obvious that Task 1.6 “Active source technology development and optimising monitoring design” was in fact two separate task and therefore it was split into two tasks:

- Task 1.4 “Active source technology development” and
- Task 1.11 “Seismic monitoring design” to test seismic monitoring set-ups will be tested for their ability to provide results with the required resolution (Taweesintananon et al., 2021).

These tasks had separate deliverables: D1.7 –Project report on capabilities of new SV-wave source and D1.14 - Report on optimization of seafloor deployments for PRM.

There were minor delays to some deliverables but at closure of the project all planned deliverables have been submitted.

4.2 WP2: 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.

Activities

Four milestones as listed in the Table 4.3 below were defined for WP2.

Number	*Milestone*
M1.1	Raising of DAS TRL for passive seismic monitoring
M1.2	Assessment of DCS feasibility for CO2 detection
M1.3	Reduction in cost of 4D gravity and seafloor deformation measurements
M1.4	Availability of a new SV-wave source for active seismic surveys

Table 4.3: WP2 milestones and associated milestone number

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.

Final results

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
- Inversion framework set up for selected case Smeaheia, including conventional seismic, DAS, 4D gravity, and seafloor deformation data
- 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

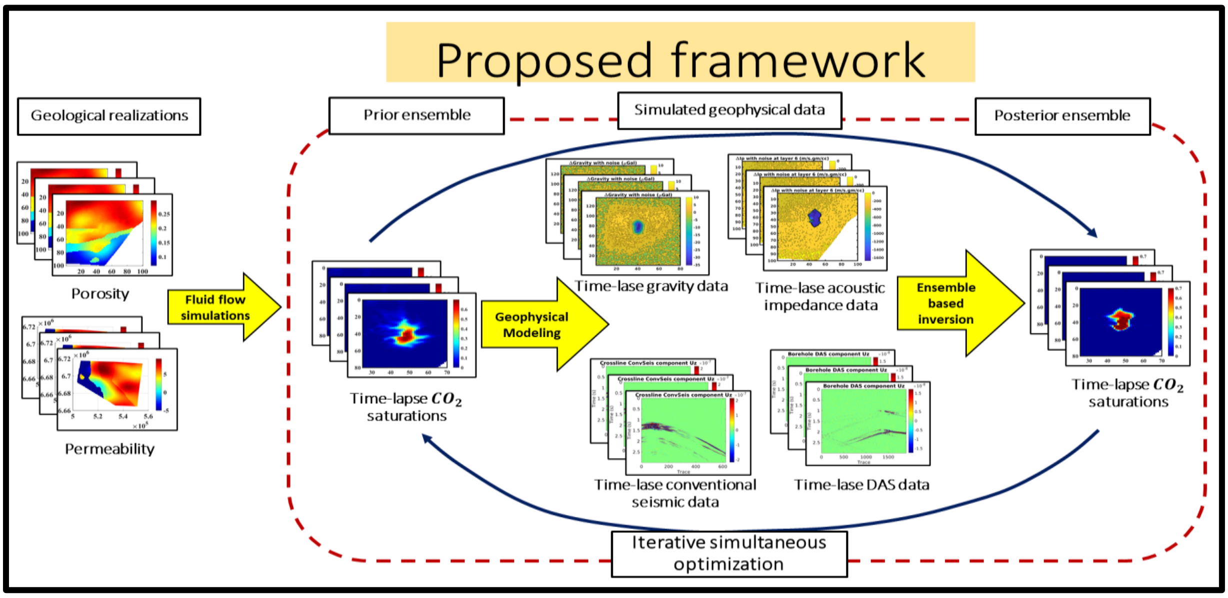

Figure 4.7. Proposed framework for inversion of multi-physics monitoring data

Application	Class	CTE	TRL	Note
Surface and seabed reflection methods	Seismic reflection surveys	Conventional hydrophone of 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 sofar
	Crosshole tomography	Conventional sensors (Novel SV source)	5-6	In testing phase at different environments
Passive seismic methods	Microseismics	Geophone/hydrophones	9	Mature technology
		DAS	7-8	Operational but not applied
	Ambient Noise Interferometry	Geophone/hydrophones	4-5	
		DAS	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 sofar
		DSS	4-5	Good results, only used for other applications sofar
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	3	

Table 4.4. Technology Readiness Assessment (TRA) of DigiMon system components.

Deviations from proposal/work plan

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.

4.3 WP3: Designing a Human Centered Monitoring System

The main objectives for the research activities in WP3 as described in the Digimon proposal are:

- Developing and tailoring the Societal Embeddedness Level (SEL) concept for CCS.
- Analyzing the Societal Embeddedness Level for CCS at the national level.
- Setting up a collaboration process with local stakeholders, engineers, and natural scientists for developing a human-centered CO_2 monitoring system at the local level.
- Defining building blocks for developing a human centered CO_2 monitoring system.
- Drawing best practices for collaborating with local stakeholders in designing a human centered monitoring system for CCS projects.

All objectives have been achieved during the 3 years of DigiMon research. For achieving these key objectives, multiple interdisciplinary events with **all Digimon partners** were integrated in the WP3 research process.

Activities

Four milestones were defined for WP3 (Table 4.5).

Number	*Milestone*
M3.1	All partners instructed on how to apply the SEL concept to CCS,
M3.2	Jointly identification of main focus areas for a societally embedded CCS monitoring system for the selected field sites with input from WP's 1, 2 and 3 (Norway, UK, Netherlands),
M3.3	Requirements & design specifications identified for the technical development of the CO2 monitoring system.

Table 4.5: WP3 milestones and associated milestone number

The research in WP3 has been structured as pictured in Figure 4.8. Each research phase benefits from the collaborative and interdisciplinary research process. In the following section, we elaborate on the main outcomes of this research process and how it contributed to achieving the research goals.

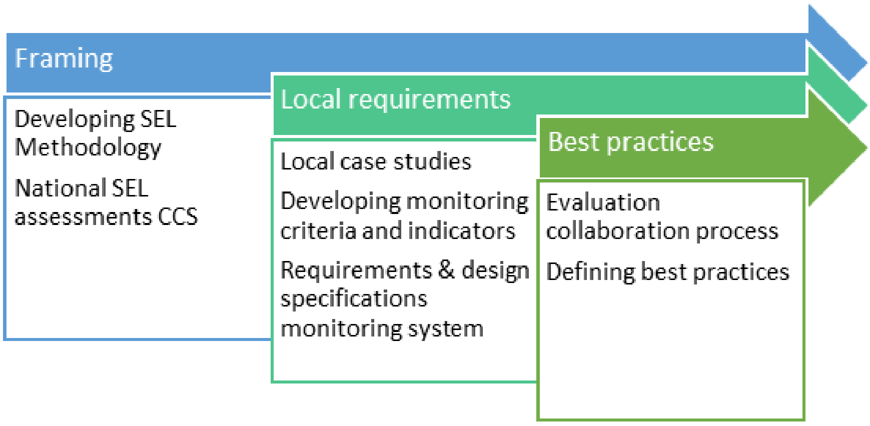

Figure 4.8: Schematic overview of the steps in the WP3 research process

Final results

SEL guideline D3.1: The objective to tailor the SEL methodology to CO_2-storage turned out to be a challenging research process. After discovering some scientific inconsistencies in connecting the SEL methodology to the TRL levels, the team showed its persistency and creativity to solve this scientific challenge. Despite the delay in the planning of the deliverable, the final Guideline for the Societal Embeddedness Assessment D3.1 formed a solid basis for achieving the WP3 objectives. (Geerdink et al. 2020).

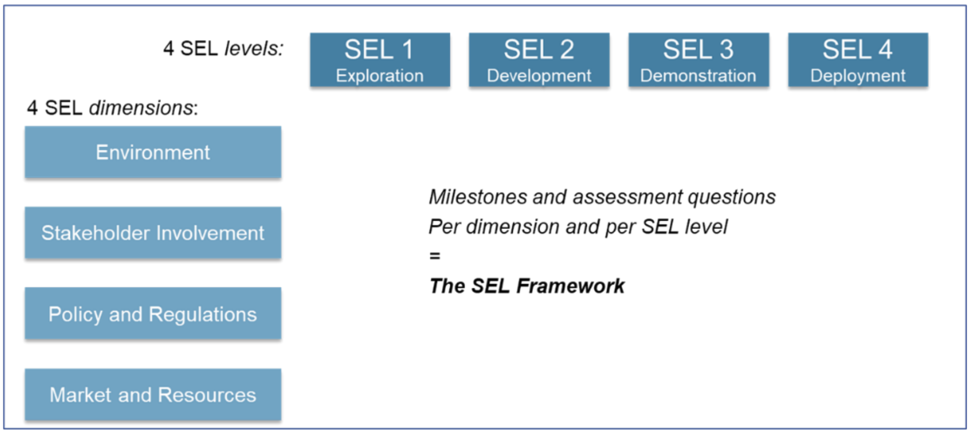

Figure 4.9: SEL methodology

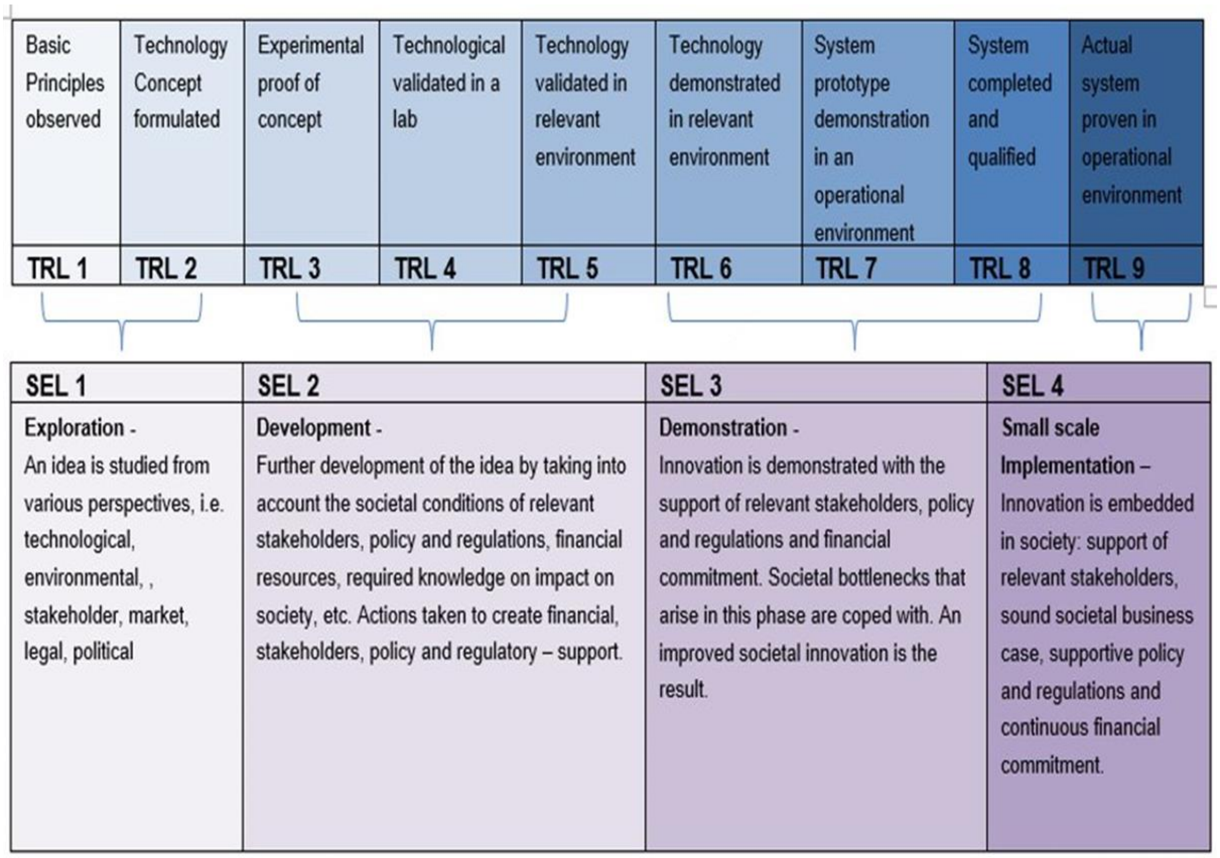

Figure 4.10: Comparison between SEL and TRL scales

Reflections from Digimon partners on D3.1: We have received positive feedback on the design and principles of the Societal Embeddedness Assessment Framework from within the Digimon community. Both industrial and non-governmental Digimon partners, so to say end users, recognize the value of the SEL instrument for developing and deploying technological innovations in their societal environment. Furthermore, from their perspective, other policy domains than the geo-energy domain might also benefit from the SEL methodology as it provides concrete insights for development and implementation strategies.

The interdisciplinary training event on the Societal Embeddedness Level methodology (March 2020) was experienced as a successful event for overarching different research perspectives, technical and social disciplines, work packages and research tasks. This event served as a crucial step into laying the groundwork for creating a common language among DigiMon researchers and an understanding of how the SEL methodology could bridge work packages and tasks. Finally, it was one of the last events that could be hosted in person, before the Covid-19 pandemic hit the world.

Four national case studies in challenging times (D3.2): Like other tasks in the Digimon project, the research activities regarding the national SEL assessments in four national case studies took place under challenging circumstances due to the COVID19- pandemic and the corresponding lock down measures all over Europe. As a result, interviews with CO_2-storage stakeholders, reflections sessions with CO2-storage experts, and the collaborative research process with all Digimon researchers involved had to take place online. Especially when assessing and discussing technological developments with corresponding societal debates about the needs and necessity of the developments, the preference is to meet each other face to face. However, the COVID19-pandemic did not impact the research outcomes. The WP3 team has been able to gather the required information to assess the Societal Embeddedness Level for CCS at national level in four countries and to derive key challenges for meeting societal requirements towards CCS deployment. The results are presented in D3.2 Report on the outcomes of the Societal Embeddedness Level Assessment for CCS in four countries: Norway, the Netherlands, Greece, and Germany (Mendrinos et al 2021).

Four local case studies giving insight in societal requirements regarding CO_2 monitoring (D3.3): During an interdisciplinary event with all DigiMon partners the design for the local research process was shaped, based on a mutual understanding of the key insights from the national case studies. The key question to all DigiMon partners was how the local case studies could provide the most relevant information for developing the human centered cost-efficient innovative monitoring system and how the outcomes could serve as input for the technical oriented tasks as part of WP1 and WP2. The key research question for achieving this was *“How can the Digimon monitoring system contribute to the societal embeddedness of CO_2-storage projects by integrating societal requirements in its design and implementation strategy?”*

To do the local case studies an Informed Questionnaire (IQ) was conducted in Norway, The Netherlands, Germany, and Greece. In all countries, at least 1000 respondents were surveyed for the national sample (see table 1). For the local samples, a minimum of 200 respondents were surveyed. In Greece we only did a national sample. Additionally, 45 interviews were conducted.

The results of the four case studies form a narrative on the current state of CCS and CCS monitoring in the four countries and how monitoring can contribute to the societal embeddedness of CO_2 storage. The results are presented in D3.3 Stakeholder perceptions and preferences regarding monitoring CO_2 storage and its’ contribution to optimizing the societal embeddedness of CO_2 storage projects (Sprenkeling et al., 2021).

Towards indicators for integrating societal requirements into an innovative CO_2 storage monitoring system (D3.4): Based on the outcomes of the local case studies the WP3 team derived key indicators for CO_2-storage monitoring and explored how these could be integrated in the design and implementation strategy of the Digimon system. To incorporate knowledge from all disciplines in this process, an interdisciplinary taskforce of researchers from all work packages was set up. The main result of this process was that there is no ‘one size fits all’ solution for monitoring, as the societal requirements and technical characteristics are different for each four countries. The team developed a set of design options and tradeoffs for CO_2 storage monitoring set-ups that can serve as a general guideline that needs to be adapted to environment, societal and technical contexts. The design options and tradeoffs can be used to facilitate discussions and development processes. The results of this process are presented in D3.4 *On the Organisation of Translation—An Inter- and Transdisciplinary Approach to Developing Design Options for CO_2 Storage Monitoring Systems* (Otto et al., 2022).

Best practices interdisciplinary research approach (D3.5): The interdisciplinary research process was embedded in the DigiMon project with the aim of delivering results that consider all relevant disciplines. This process consisted of (1.) interdisciplinary knowledge sharing events throughout the whole project, (2.) working in an interdisciplinary task force for developing design requirements for a societally embedded monitoring system and (3.) interdisciplinary collaboration for developing research designs. In the final task, the WP3 team evaluated the interdisciplinary research process by interviewing project members, analyzing questionnaires that evaluated the interdisciplinary events and having evaluative discussions within the WP3 team. The results of this evaluation are presented in D3.5 Best practices for developing a human centered monitoring system for CO2 storage projects through a collaborative and interdisciplinary research approach (Sprenkeling et al., 2022). The report elaborates on how the interdisciplinary process was embedded in each task, best practices and lessons learned and recommendations for future research.

Deviations from proposal/work plan

Alternative planning research activities WP3

During two in-person meetings with the WP3 researchers (November 2019 and March 2020) the WP3 team explored the most suitable research approach for achieving the WP3 objectives. Due to new insights since the submission of the proposal in 2019, the WP3 team decided to update the research design for WP3, as a better way to reach the milestones and deliverables.

In general, the revision concerned a different planning of described research methodologies in time and tasks. The revision concerned the postponement of the surveys with the population (second out of three elements for the identification of the societal embeddedness of CCS on a national level, see page 59 of the proposal). In the submitted proposal these surveys were planned as part of Task 3.1 'Framing - Societal Embeddedness Level for CCS.' In the updated research design, the surveys were applied within Task 3.2 'Researching the SEL at local level.'

The surveys are mentioned on page 59 of the submitted proposal (see Table 4.5: WP3 task description) as one of the research methodologies for assessing the SEL for CCS at a national level:

"Surveys with general population to identify effects of monitoring on trust. The necessary infrastructure for performing survey experiments is readily available in Norway (i.e., the Norwegian Citizen Panel), and comparable infrastructures exist in several of DigiMon's member countries. We aim to conduct surveys in Norway, the Netherlands, Germany, and Greece."

In the updated research design the WP3 team proposed to:

- Collect the content for assessing the SEL at national level via desk research and interviews with key stakeholders at national level (part of task 3.1.2), resulting in deliverable D3.2
- Make use of surveys among the general public in Greece, Germany, Norway, and the Netherlands as one of the research methodologies to assess the SEL at *local* level (part of task 3.1.2), resulting in deliverable D3.3

4.4 WP4: Project Management

Coordination of the DigiMon project was led by host institution NORCE, assisted by the Work Package Management Team comprising each of the WP 1-4 leaders.

The overall objective of this work package was to carry out a sound overall management and coordination of the Project activities and reporting. Specific objectives included:

- To manage efficiently the resources of DigiMon to allow DigiMon to perform on time and on budget.
- To establish an effective organisation, planning and efficient communications channels to avoid duplication of efforts, pin-point potential synergies, and ensure efficient communication within DigiMon.
- To ensure impact dissemination of DigiMon both internally and externally. The latter is in order to ensure the desired scientific, industrial, and societal impact. The relevant project results are to be presented attractively to project partners, to a wider scientific community, to end users, stakeholders / decision makers, and to the general public.
- To manage seamless communication with the ACT coordinators and the national contacts to optimize project understanding and control by the ACT administration.
- To design and facilitate an interdisciplinary research process in which all Digimon partners collaborate.

Activities

Four milestones were defined for WP4 (Table 4.6).

Number	***Milestone***
M4.1	Project established (kick-off)
M4.2	Main project plan ready
M4.3	Subordinate project plans ready (Quality assurance, internal communication, data management, dissemination, implementation)
M4.4	Final project meeting

Table 4.6: WP4 milestones and associated milestone number

The work in WP4 were organized into three tasks:

- Task 4.1 - Project management
- Task 4.2 - Interdisciplinary research process
- Task 4.3 - Dissemination

WP4 activities were managed according to a set of managing documents: Project plan, Quality assurance plan, Internal communication plan, Data management plan and Dissemination plan.

Altogether six partner meetings and workshops were faciiltated:

- Kick-off meeting Bergen, September 2019
- Workshop, November 2020
- Project update meeting TAC, QAC and SC, June 2020
- Partner meeting, June 2021
- Partner meeting, December 2021
- Final project meeting, September 2022

Kick-off meeting Bergen, September 2019

A two-day project kick-off meeting was held in Bergen, September 2019, with participants from all project partners (Figure 4.11). The agenda included plenary presentations of institutional partners and individual researchers, and review of the DigiMon proposal scope and objectives. Ample time was spent in WP break-out sessions discussing milestones and deliverables, collaboration and linkages between WPs and identifying critical factors for achieving project objectives. Moreover, the concept of disciplinary working methodology was introduced to all project participants (see Section 5).

Figure 4.11: DigiMon kick-off meeting in Bergen, September 2019.

Final project meeting, September 2022

A 3-days final project meeting for the DigiMon project was held in Bristol, September 2022 (Figure 4.12). The University of Bristol hosted the event, which was conducted as a hybrid in-person and Teams meeting. The two first days summarized the results of the DigiMon project. During the last day the DigiMon team discussed opportunities for extending the collaboration.

Figure 4.12: DigiMon Final meeting in Bristol, Engineers' House, September 2022.

Overall progress

Project reports have been submitted according to schedule and the project came to a close with all green marks in the final ACT traffic light report (Table 4.7).

Progress in:			
WP1: Critical Technology Elements			x
WP2 Integrating the components			x
WP3: Designing a human centered monitoring system			x
WP4: Project management			x
Critical path			x
Financial progress			x
HSE issues			x

Table 4.7: DigiMon final traffic light report.

Nine out of eleven milestones were met, whereas two milestones related to system integration have only been partially met (Table 2.8, 2.9). For M2.3: "A system communication platform available for data collection and communication at standardized formats", a review of available solutions and formats were performed, but we did not develop a standardized platform for system communication. For M2.4: "Overall system design", system components were developed and tested on an individual basis, but we did not integrate and test the components in a full system set-up.

Number	*Milestone*	*Key target*
M1.1	Raising of DAS TRL for passive seismic monitoring	1
M1.2	Assessment of DCS feasibility for CO2 detection	1
M1.3	Reduction in cost of 4D gravity and seafloor deformation measurements	4
M1.4	Availability of a new SV-wave source for active seismic surveys	1
M2.1	Technology Readiness Assessment (TRA) of different system components	1
M2.2	Framework for integrated inversion and uncertainty quantification	2,3,4
M2.3	A system communication platform available for data collection and communication at standardized formats	4,5
M2.4	Overall system design	4
M3.1	All partners instructed on how to apply the SEL concept to CCS	6
M3.2	Jointly identification of main focus areas for a societally embedded CCS monitoring system for the selected field sites with input from WP's 1, 2 and 3 (Norway, UK, Netherlands),	6
M3.3	Requirements & design specifications_identified for the technical development of the CO2 monitoring system.	4,6

Table 4.8: DigiMon milestones with reference to key targets. Key targets green color indicate milestones and targets accomplished, yellow color indicate milestone and target partially accomplished. See figure 2.1 for description of targets.

Deviations from proposal/work plan

Due to the Covid-19 pandemic and the following travel restrictions, most project meetings and workshops following project kick-off had to be arranged as digital events. DigMon succesfully used Teams as our preferred communication platform., although digital meetings do not allow for the same good dialogue as in-person meetings. In summary, execution of the DigiMon project went well with few and limited negative consequences of the pandemic, the most noticeable being delays in the planned field campaigns at Cami FRA and Svelvik.

Delays in field tests were mitigated primarily by ensuring access to a combination of existing data, especially the Antarctica field data set, collecting laboratory scale data and modify the delayed field tests so that the project all together gets access to all necessary data to fulfil the project scope and deliverables by the final delivery date.

In addition, several other milestones and deliverables experienced minor delays, however, without noticeable effects on the overall progress of the project.

4.5 Mid-term review

The mid-term review pointed to key several challenges in the DigiMon project:

- The WP-1 team is commended for maximizing opportunities to gather important and relevant data to assess a range of technology elements (some fiber optic technologies, gravimetry and strain measurements). The connection to WP1 and the flow to WP2, the purpose of which is to identify those features that are necessary for WP3, can and should be emphasized much more strongly. Operators will need Original Equipment Manufacturers and a research and innovation community that focuses on those data required for decision making.
- The WP2-team is commended for having developed a process to identify system components, having identified a conceptual test site, and for focusing on control of a specific barrier (identification of CO2 plume) and one specific escalation factor (fault stability). WP2 should highlight truly innovative aspects of its work program; the modeling framework (e.g. ensemble-based methods for forecasting reservoir behavior), the integration of DAS data and analysis into static and dynamic reservoir modeling, fault stability modeling, and addressing the need and value of seismic tomography to constrain CO2 plume mapping and tracking is state-of-the-art. We recommend that you clearly specify that you focus on some aspects of fiber optic technologies and major improvement in accuracy and precision of gravimetry and strain measurements.
- The WP3-team is commended for development of the SEL methodology and framework, which is exceptionally innovative and an important contribution to CCS and other societal projects that integrate technology and social systems. There are some concerns regarding the scale and scope of the SEL implementation and bringing national level surveys to the local level deployment. Certainly, the WP3 team will gain insights at both levels, but there needs to be a clear connection (or reconnection) of how this specifically relates to DIGIMON as a system.

To meet with the recommendations from the mid-term review panel a set of mitigative actions were put in place. To secure a better integration between work packages, it was decided to run joint WP1 and 2 meetings to secure transfer of knowledge and incorporation of WP1 results in the inversion modelling framework which was developed in WP2. We are also decided to host regular meetings between WP2 and 3 to explore how they could benefit from each other and make optimal use of intermediate research results. Prolongation of travel restrictions and other pandemic related limitations called for extended and expanded use of digital internal communication as well as external dissemination.

4.6 Financial results

DigiMon financial results are presented in Tables 4.9 and 4.10 below.

Country	ACT funding	Other public funding	Private funding R&D inst	Private funding, industry	In kind R&D institution	In-kind industry	Other funds	Total after 3 years per partner	Total after 3 years per country
Norway (€)									2112016
NORCE	702459			88000	437673			1228132	
MonViro AS (Reachsubsea)	323241					174053		497294	
NTNU[1]	258805			64051	63734			386590	
UK									1255166
University of Bristol	891571							891571	
University of Oxford	101209							101209	
Silixa LTD	240295					22091		262386	
Germany									612191
Geotomographie	177484	0	0	0	0	122570	0	300054	
UFZ	312137	0	0	0	0	0	0	312137	
The Netherlands									1625000
TNO	1625000				0			1625000	
Greece									164116
CRES [2]	164116	0	0	0	0	0	0	164116	
Romania									200000
Sedona Development SRL	200000							200000	
USA									450000
LLNL	450000							450000	
Total pr funding	5446317	0	0	152051	501407	318714	0	6418489	6418489

[1] NTNU will continue until December 31.2023 [2] CRES will continue until August 6, 2023

Table 4.9 Actual costs per country / per organisation.

Partner	WP1	WP2	WP3	WP4	Not specified on WP	Total project costs	Total partner budget	% of Total grant
NORCE	124837	359545	145163	598587		1228132	1078000	114%
MonViro	146763	350531	0	0		497294	500000	99%
NTNU	0	386590	0	0		386590	477000	81%
Univ of Bristol	822527	46421	600	22023		891571	1040841	95%
Univ of Oxford	93909	0	0	7300		101209		
Silixa	217849	0	0	44537		262386	240295	109%
Geotomo.	286625	13429	0	0		300054	295807	101%
UFZ	0	0	312137	0		312137	347700	90%
TNO	558438	302612	473659	150812	139479	1625000	1625000	100%
CRES	10110	13939	128013	12054		164116	197000	83%
SEDONA	69590	69261	35864	25285		200000	200000	100%
LLNL	300000	150000	0	0		450000	450000	100%
TOTAL	2630648	1692328	1095436	860598		6418489	6451643	99%
Total Budget	**2,642,723**	**1,468,820**	**1,322,400**	**1,031,533**			**6,465,476**	
% of Total grant	100%	115%	83%	83%				

Table 4.10 *Total accumulated costs pr. partner and WP 2019 - 2023*

5. Project impact

5.1 Contribution to the facilitation of the emergence of CCUS

The DigiMon project addressed the condition of the ACT Call to develop and demonstrate more effective CCS technologies. Secondly, DigiMon has integrated technical and social science research, contributing to better communication of CCS technologies to policy makers and the public and allowing them to make better informed decisions and establish economic arguments for CCS.

WP1 and 2 addressed the ACT objective to aim for high TRL levels. The project included development of technologies to higher TRLs and has demonstrated their abilities in an integrated system. The project has combined proven and less mature sensors and system components, with intermediate to high current and targeted TRLs. The DigiMon consortium has performed field tests at the ECCSEL Svelvik site and the operational FRS site in Canada and used these data for modelling and integrating various system components of the Digimon system. By developing algorithms and workflows to expand existing software solutions to include tools that will help service providers and operators of CCS to introduce gravity and subsidence results in their history matching workflows, DigiMon has facilitated the adaption of the technology by new clients and for OCTIO Environmental to expand upwards in the value chain and provide commercially data interpretation services.

WP3 of the DigiMon project addresses Objective 1 of the ACT call with a human centred monitoring system. In the most recent interdisciplinary Digimon event in March 2021, in which participants address various new insights they gained during the meeting, many contributions mention the value of better understanding the societal requirements for technological developments. Another example of the intermediate impact of WP3 research comes from the feedback from one of the reviewers of deliverable D3.2 who emphasizes the value of the SEL methodology for meeting societal requirements while developing new innovative technological solutions for urgent societal challenges; not only in the energy domain, but also in other policy domains. Our expectation is that the next planned WP3 research activities could contribute to improve the design and implementation strategies of the Digimon system as promised in the proposal. The collaborative research approach within WP3, the frequent meetings between WP1, WP2, WP3 and WP4 and continuous attention for interlinkages between WPs, as well as the interdisciplinary events all contribute to designing a human centered CO2 storage monitoring system.

The DigiMon project presents a solution for MMV of CO_2 storage that is applicable to a wide range of CO_2 reservoirs and storage sites, onshore and offshore. The technology will be demonstrated in relevant environments in 2021-22.

The ambition is that the DigiMon technology will be piloted and offered commercially within 2025. This will be done primarily through the industry partners Octio Environmental and SIlixa, as technology providers.

5.2 Strengthening the competitiveness and growth of European companies

Table 5.1 below lists key results of the DigiMon project and their impact. DigiMon results have contributed to strengthening the competitiveness of the SME partners Octio environmental and Silixa in the European and global market. They also contribute to strengthening operator's ability to design and plan credible storage projects.

WP	*Key result*	*Impact*
1	Develop individual components of the system to a common, high TRL.	Improved TRL system components implemented in the product lines of Octio Env. and Silixa and offered to the market.
2	Optimise and validate processing software for system components.	Implementation in Octio Env. and Silixa product portfolios. Technological readiness Assessment (TRA) of system components.
1,2	Develop an effective DAS data interpretation workflow.	Implementation in the DAS system offered to the market by industry partners Octio Env. and Silixa. Implementation in end users Equinor and Repsol interpretation workflows.
2	Development of forward modelling and inversion frameworks.	Implementation in research partners and industry partner workflows.
3	Develop societal embeddedness methodology (SEL) for CCS.	Implementation by industry supplier partners, regulatory bodies, authorities.

Table 5.1: Key results and impact

5.3 Other environmental or socially important impacts

Development of the SEL methodology for monitoring societal embeddedness of CCS technology and projects has received much attention and will contribute to increase public acceptance of CCS in general.

5.4 Chances for commercializing the technology further

No current plans exist for further commercializing the technologies developed in DigiMon. However, the inversion framework developed in WP2 and the SEL-methodology developed in WP3 have been carried over in a new research proposal, "Risk-based framework for assessing CO_2 storage monitoring (RamonCO)", under the *CETP –2022-00032* call, submitted March, 2023. The overall objective of the RamonCO project is "*to develop multi-dimensional robust conformance assessment methodology and advance risk-based monitoring and societal implementation strategies*", and thereby contribute to acceleration of the CO_2 storage project permitting phase and secure containment and conformance during the project execution phase.

Several of the DigiMon partners are part of the RamonCO consortium, in addition to several new partners, both research and industry.

a. Gender issues

The DigiMon project had a good gender mix in managerial and governing body positions. Interestingly, all WP leaders were females.

6. Implementation

The SET Plan Implementation Action 9 states that CCS needs to become a cost-competitive technology and gain public acceptance, so that it could start to be commercially deployed and thus contribute to the low-carbon transition of the European economy. The DigiMon project has provided research that addresses SET plan Implementation Action 9 as follows:

By developing cost effective technologies for CO_2 storage monitoring, DigiMon has contributed directly to *R&I Activity 5*: Unlocking European Storage Capacity, i.e particularly demonstration or evaluation of monitoring and verification techniques, and/or techniques for improving the storage performance (e.g. pressure management) for CO2 storage or CO2 EOR (onshore or offshore)

By developing the SEL-methodology for assessing societal embeddedness of CCS, DigiMon has contributed to *R&I Activity 8*: Understanding and communicating the role of CCS in meeting European and national energy and climate change goals, i.e particularly understanding and communicating the socio-economic case for investing in CCS and CCU.

The DigMon project has provided research that addresses also the Mission Innovation Priority Research Directions (PRDs):

By developing multi-physics cost effective and flexible technologies for CO_2 storage monitoring, DigiMon has contributed in particular to MI *S-4*: Developing Smart Convergence Monitoring to Demonstrate Containment and Enable Storage Site Closure; and *S-5*: Realizing Smart Monitoring to Assess Anomalies and Provide Assurance, as well as *CC-1*: Incorporating Social Aspects into Decision-Making; and *CC-4*: Developing Tools to Integrate Life Cycle Technoeconomic, Environmental, and Social Considerations to Guide Technology Portfolio Optimization.

7. Collaboration and coordination within the Consortium

7.1 Governance and management structures

The DigiMon project was governed by the following set of agreements:

1) Intellectual Property Rights (IPR) Agreement. This agreement regulates ownership of results and property rights in the project, as well as principles for commercialization. It has been signed by all parties in the DigiMon consortium.
2) Consortium Agreement (CA). This agreement describes governance structures and operational procedures, based on the principles of DESCA. It has been signed by all European parties in the DigiMon consortium.

The DigiMon project was governed by a simple and a flexible management structure to accomplish the project objectives (Figure 7.1). The project structure contributed to efficient project execution and communication between the consortium partners. End users and industry had the majority in the steering and advisory committees to ensure relevant industrial impact and high TRL level.

The General Assembly (GA) was the project's highest authority and met annually. All partners were represented. The GA was responsible for the following tasks: (a) Approve major changes in budgets and plans as defined in CA; (b) Approve amendments in the CA; (c) Appointment of the Steering Committee (SC) and Technical Advisory Committee (TAC) as defined in the CA.

The SC counted 7 members, including NORCE, TNO, UoB, Equinor, Octio Environmental, Repsol and Silixa, with industry representatives in majority. The SC made final decisions related to execution of activities, including following up deviations from plan and re-allocation of funding. The SC provided strategic guidance to the project activities and ensured the relevance and delivery of the planned and approved deliverables according to CA. The SC met on a quarterly basis. Due to the COVID-19 pandemic, meetings have been on Teams.

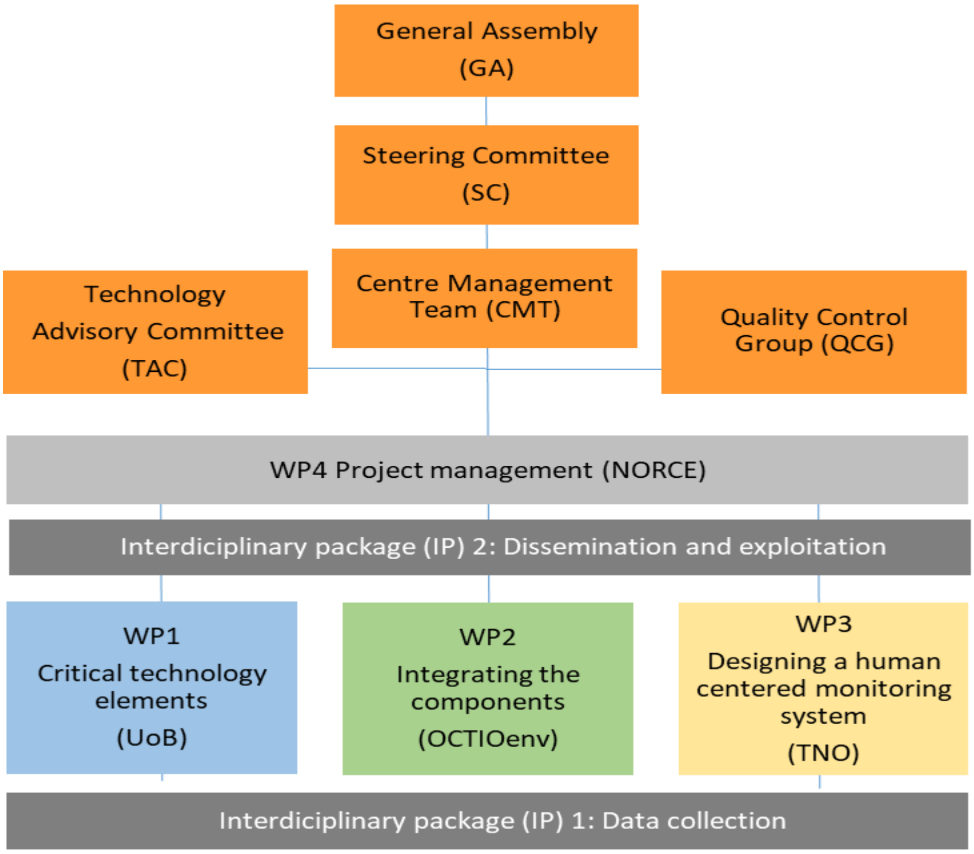

Figure 7.1: DigiMon project structure and organization

Two of the WPs were led by industry (WP1 and 2; Silixa and OCTIOenv) and two by research partners (WP3 and 4; TNO and NORCE). This ensured a good balance of industry and academic interests in the project.

A Technical Advisory Committee (TAC) was established to evaluate research performance and collaboration of the DigiMon project. The TAC independently gave advise on project objectives, research results and the interaction between research partners and user partners according to CA. The TAC reported to the SC. Members to the TAC were recruited primarily from institutions outside of the DigiMon project but included one member from DigiMon industry partner Equinor.

Steering Committee (SC)

Anne-Kari Furre Equinor, leader
Øyvind Aasarød, Repsol Norge
Athena Chalari, Silixa
Bjarte Fagerås, MonViro AS
Sarah Eileen Gasda, NORCE
Mike Kendall, University of Oxford
Pim Piek, TNO

Technical Advisory Committee (TAC)

Marcella Dean, Shell
Poppy Kalesi, Environmental Defense Fund
Olav Barkved, Petoro
Kjetil Johannessen, Equinor

Quality Control Group (QCG)

Nick Riley, BGS
Emma ter Mors, Leiden University

7.2 Management Team

The DigiMon Management Team (WPMT) consisted of the Project manager (PM), the PM team and WP leaders. The WPMT counted 6 females and 1 male and met monthly, monitoring project progress and quality according to the CA. The WP leaders were responsible for daily, running operations and management of individual WPs. The WPs also met monthly and industry sponsors Equinor and Repsol were invited to the meetings.

Arvid Nøttveit
Project manager

Kirsti Midttømme
Project coordinator & WP 4 Lead

Marie B. Holstad
WP administrative support

Anna Stork
WP1 Lead

Martha Lien
WP2 Lead

Hanneke Puts
WP3 Lead

Figure 7.2: DigiMon Management team

7.3 Role of industry participation

Industry partners participated in the DigiMon project at two levels. First, Octio Environmental and Silixa were project leads and participated actively in the scientific work in WP 1 and 2, respectively, whereas Geotomographie developed a new source for cross-well tomography. Second, Equinor and Repsol, in addition to Octio Environmental and Silixa, were at the Steering Committee of the project. They also participated actively at WP meetings and workshops, ensuring continuous transfer of knowledge and results from the project. Third, Equinor granted access to critical datasets for the project.

7.4 Interdisciplinary approach

The DigiMon project approach included a process for interdisciplinary knowledge development as part of the project management (See Chapter 4, WP4). TNO supported NORCE in designing and implementing this approach by preparing and organizing specific moments for interdisciplinary collaboration and exchange between work packages, partners, and disciplines during all crucial phases and progress meetings of the project; starting with the DigiMon kick off meeting in Bergen in 2019 and identifying how to create mutual beneficial interrelationships between the main discipline lines and work packages in the project. Based on this first exercise, the project participants putted effort in creating a shared knowledge basis for the planned DigiMon developments: understanding each other's backgrounds, expertise and perspectives; creating a 'common language' by planning boundary spanning activities and working on boundary spanning objects. Follow up activities were organized during project meetings and innovative participatory methods and tools were introduced to also facilitate the interdisciplinary process during the online meetings. During the project even more linkages between the work packages were found and effectuated. In the final stage, working towards the key deliverables of the integrating work package (WP 2), experts from all disciplines were involved to secure the integration of insights from all disciplines cooperating in the project and in the three work packages.

Four Interdisciplinary events have been organized during execution of the project:

<u>Kick off meeting in Bergen, September 2019</u>

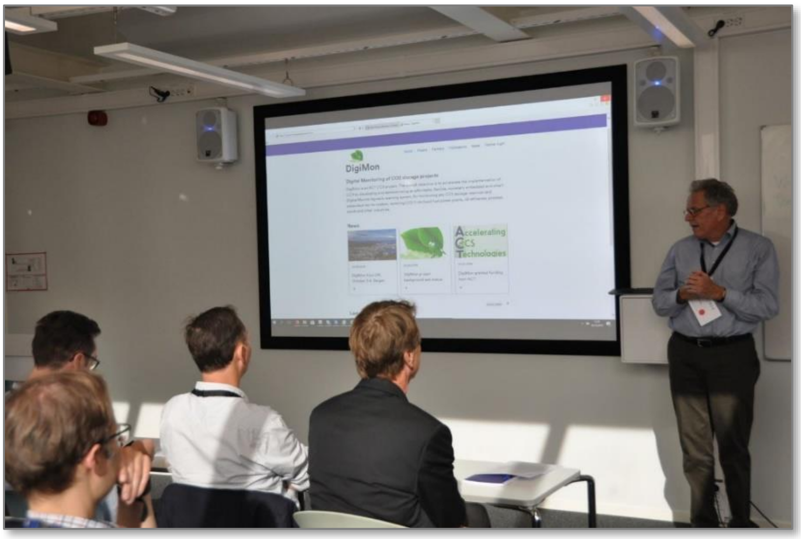

Figure 7.3: DigiMon interdisciplinary event, Bergen, September 2019.

During the Kick off meeting in Bergen the concepts of interdisciplinarity and interdisciplinary reserach processes have been introduced by TNO to the Digimon community. And first exercises have been done on developing a common understanding of the Digimon objectives and the interrelationships between WPs as well as on creating a common language.

Interdisciplinary training event, March 2020 – in March 2020 the WP3 team organized the so-called Interdisciplinary Training even on the Societal Embeddedness Level Methodology for all Digimon partners. The aim of the meeting was to

- Inform all partners about the SEL methodology and how to apply it in Digimon.
- Create common understanding of the SEL methodology within the Digimon consortium.
- Enrich the guideline for applying the SEL methodology with the inputs from all partners.
- Gain insight in how the various disciplines frame the SEL-methodology and how each can contribute to its further development and implementation.

The outcomes of and insights from of the Training Event have been of great value for finalizing the development of the SEL Assessment Framework and composing the SEL Guideline D3.1. Furthermore, the event contributed to a better and common understanding of how all Digimon research activities are related and which interlinkages are key for the research process of all work packages.

Figure 7.4: DigiMon interdisciplinary event, Amsterdam, February 2020.

Interdisciplinary event, March 2021, on outcomes of national assessments – in March 2021, the WP3 team organized a second interdisciplinary event among all Digimon partners. In contrast to the meeting in March 2020, this second event had to be organized online. The team succeeded in offering an interactive and collaborative event in which the outcomes of the SEL national assessments have been introduced and perspectives were shared on how to design the local SEL assessments (key research activity for WP3 team 2021). The objectives of the event were:

- Creating a common understanding of the main societal challenges per country towards CCS deployment.
- Sharing insights on the applicability of the SEL methodology for CCS

- Exchanging perspectives on how the development of the Digimon system (WP1 and WP2) could best benefit from the outcomes of the local case studies (WP3)
- Strengthening crosslinks between disciplines and WPs within Digimon.

The evaluation of the event showed that all Digimon partners appreciated the interactive design of the online meeting and that they had gained new insights on the value of WP3 research for the technical design of the monitoring system (Figure 7.5).

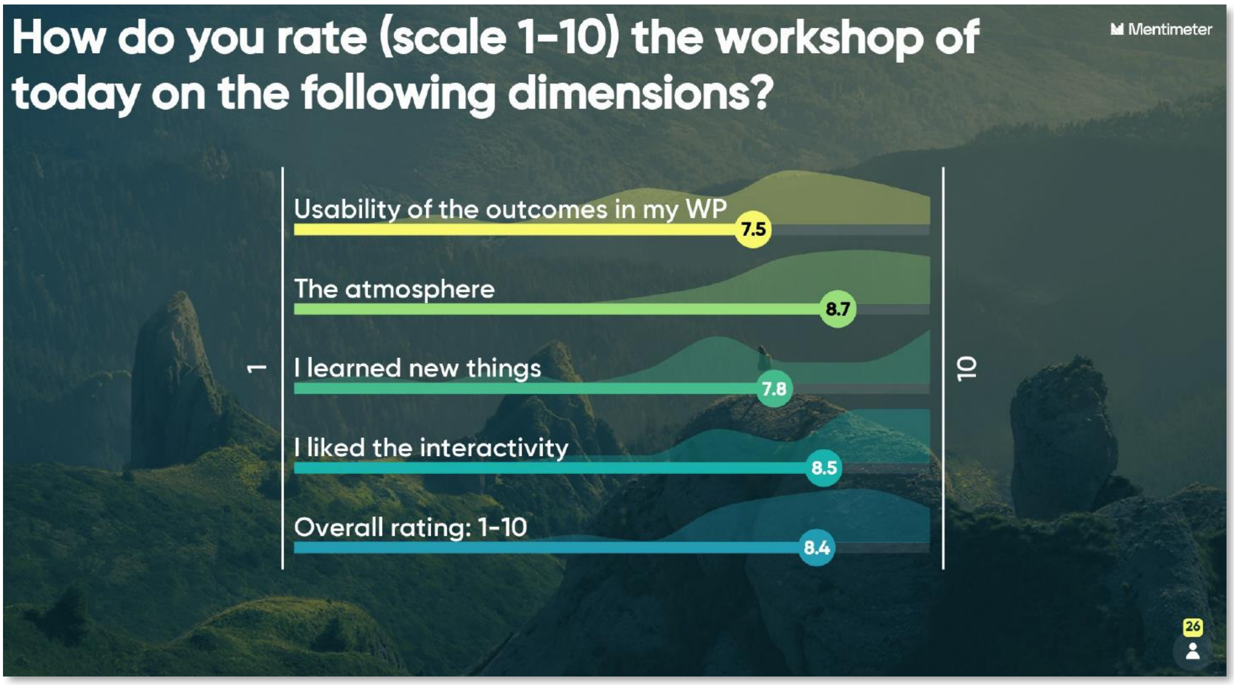

Figure 7.5. Outcomes evaluation of the Interdisciplinary event March 2021 among participants.

Interdisciplinary event, March 2022, on design-options, trade-offs and narratives of the DigiMon system - In this online event we jointly explored and discussed design-options, trade-offs and narratives of the DigiMon system. The results and the discussions of this meeting helped the WP3 team to develop workshops with stakeholders in order to validate configurations and requirements of the Digimon system. For all partners it was a chance to learn about the societal requirements and narratives for a substantial contribution of the Digimon system to the societal embeddedness of CCS. The objectives of the event were:

- Inform and discuss with all partners on societal requirements influencing design options and trade-offs for the DigiMon system.
- Share understanding of how the DigiMon system contributes to the societal embeddedness of CCS.
- Discuss how learnings from the societal research influence the narrative of DigiMon.

7.5 Added value of transnational collaboration

The DigiMon consortium included renowned partners from many European countries and the USA, and the project had access to top-class research infrastructure, such as the Cami FRS and Svelvik field sites. The transnational collaboration enabled compilation of cross-disciplinary expertise and methodologies that none of the collaborating partners had access to on their own.

In WP1 and 2 top-class knowledge on fibre-optics, multi-physis forward modelling and inversion were shared between UK, Dutch, German, Norwegian and US partners. In WP3, development of the SEL methodology as well as the integrated technical – social science approach proved very unique and rested heavily upon the transnational dimension.

8. Project dissemination

8.1 Project deliverables

Number	Deliverable	Authors	Partners	Year
D1.1	DAS field dataset to compare technologies and deployment scenarios - Antarctica Dataset	Kendall, J-M., Kufner, S., Brisbourne, A., Butcher, A	Univ. of Oxford, Univ. of Bristol, British Antarctica Survey	2020
D1.1_add 2	DAS field dataset to compare technologies and deployment scenarios CaMI Field Research Station, Canada	Butcher, A., Vandeweijer, V., Kendall, J-M., Zhou, W., Stork, A.	Univ. of Bristol, TNO, Univ. of Oxford, Silixa Ltd	2021
D1.1 _add 3	Cross hole seismic experiment with DAS/DTS data - Svelvik CO2 field lab	Thomas, P.J. Stork, A.,Fechner, T., Koedel, U., Butcher, A.	NORCE, Silixa Ltd, Geotomographie GmbH, Univ. of Bristol	2021
D1.1_add 4	Data from lab-scale experiments of fibre optic vibration measurement	Thomas, P.J., Heggelund, Y., Paap, B.,Mellors, R., Pitarka, A., Matzel, E., Butcher, A.	NORCE, TNO, LLNL, University of Bristol	2021
D1.2	DAS dataset suitable for microseismic and ANI analysis	Paap, B., Mellors, R., Stork, A., Butcher, A., Kendall, J-M	TNO, LLNL, Silixa Ltd., Univ of Bristol, Univ. of Oxford	2020
D1.3	DAS synthetic dataset	Baird, A.F., Mellors, R., Paap, B., Vanderweijer, V., Verdal, A., Butcher, A., Stork A.	Univ. of Bristol, LLNL, TNO, Silixa Ltd	2020
D1.4	DAS preprocessing workflow	Butcher, A., Hudson, T., Baird, A., Mellors, R., Stork, A.	Univ. of Bristol, Univ. of Oxford, LLNL, Silixa Ltd	2020
D1.5	DAS Processing Algorithms	Butcher, A., Hudson, T., Zhou, W., Lapin S., Kendall, J-M., Baird, A.	Univ. of Bristol, Univ. of Oxford	2021
D1.6	DAS Processing Workflow	Butcher, A., Zhou, W., Baird, A., Boullenger, B., Paap, B., Vanderweijer, V., Hudson, T., Kendall, J-M., Stork, A.	Univ. of Bristol, TNO, Univ. of Oxford, Silixa Ltd	2021
D1.7	Project report on capabilities of new SV-wave source	Ködel, U., Fechner, T.	Geotomographie GmbH	2021
D1.8	Feasibility of using distributed chemical sensing for CO2 leakage monitoring	Bond, T.	LLNL	2021
D1.9	Improved algorithms to aquire and process gravity and deformation data	Fageraas, B., Lien., M., Ruiz	MonViro AS, OCTIO AS	2021
D1.10	A Roadmap for Commercial Delivery and Implementation of WP1 outcomes	Butcher, A., Lapins, S., Stork, A., Kendall, J.-M., Vandeweijer, V., Lien, M., Thomas, P.J., Ködel, U., Theim, L., Bond, T., Mendrinos, D.	Univ of Bristol, Silixa Ltd., Univ. of Oxford, TNO, MonViro AS, NORCE, Geotomographie, NTNU, LLNL, CRES	2022

D1.11	Project report on WP1 outcomes relevant to other WP	Stork, A.,Butcher, A., Zhou, W., Kendall, J.-M., Hudson, T., Paap, B., Boullenger, B., Vandeweijer, V., Lien, M., Fageraas, B., Thomas, P.J., Ködel, U., Theim, L., Landrø, M., Bond, T., Mendrinos, D.	Silixa Ltd.,Univ of Bristol, Univ. of Oxford, TNO, MonViro AS, NORCE, Geotomographie, NTNU, LLNL, CRES	2021
D1.12	WP1 results summary report suitable for policy makers.	Butcher, A., Lapins, S., Stork, A., Kendall, J.-M., Vandeweijer, V., Lien, M., Thomas, P., Ködel, U., Theim, L., Bond, T., Mendrinos, D.	Univ of Bristol, Silixa Ltd., Univ. of Oxford, TNO, MonViro AS, NORCE, Geotomographie, NTNU, LLNL, CRES	2023
D1.13	Critical technology elements (WP1) Final report	Stork, A.,Butcher, A., Zhou, W., Lapins, S., Kendall, J.-M., Hudson, T., Paap, B., Boullenger, B., Vandeweijer, V., Lien, M., Fageraas, B., Thomas, P.J., Ködel, U., Fechner, T., Theim, L., Landrø, M., Bond, T., Mendrinos, D.	Silixa Ltd.,Univ of Bristol, Univ. of Oxford, TNO, MonViro AS, NORCE, Geotomographie, NTNU, LLNL, CRES	2023
D1.14	Report on Optimization of Seafloor Deployments for Permanent Reservoir Monitoring	Landrø, M., Theim, L.	NTNU	2023
D2.1	Framework for forward modelling of the DigiMon data	Vanderweijer, V., Paap, B., Candela, T., Bhakta, T., Lien, M.	TNO, NORCE, MonViro	2021
D2.2	Concept description for the use of fibre-optic measurements for seismic tomography	Thomas, P.J., Heggelund, Y., Ködel, U., Fechner, T., Butcher, A.	NORCE, Geotomographie GmbH, Univ. of Bristol	2021
D2.3	TRA of DigiMon components	Vanderweijer, V., Ködel, U., Lien, M., Bond, T., Candela, T., Zhou, W., Butcher, A., Kendall, J.-M., Stork, A., Mellors, R.	TNO, Geotomographie GmbH, MonViro AS, LLNL, Univ. of Bristol, Univ. of Oxford, Silixa, Univ of California	2022
D2.4	Examination & interpretation of the seismic tomography data in respect to "up-lift" phenomena and stress induced anisotropy.	Ködel, U., Fechner, T.	Geotomographie GmbH,	2022
D2.5	Project report and algorithms for integrated inversion of individual DigiMon data components.	Bhakta, T., Mannseth, T., Lien., M., Paap, B., Vandeweijer, V.	NORCE, MonViro AS, TNO	2022
D2.6	Recommendations on communication platform and data standards to facilitate autonomous operations, high performance computing and the integration of large data sets	Løvheim, L., Åsgard, K.	MonViro AS, OCTIO AS	2021
D2.7	Project report and algorithms for optimizing acquisition layout and frequency	Mellors, R., Pitarka, A., White, J., Lien, M.	Univ. of California, San Diego, LLNL, MonViro AS	2022

D2.8	Project report with guidelines and recommendations for monitoring system to be applied at a set of planned or active CCS sites	Heggelund, Y., Lien, M.	NORCE, MonViro AS	2022
D2.9	Project report on seismic tomography data interpretation and conceptual model for integrating DAS into borehole seismic tomography surveying	Ködel, U., Fechner, T. Stork, A.,	Geotomographie GmbH, Silixa Ltd.	2022
D2.10	WP2 final report	Paap, B., Candela, T., Vandeweijer, V., Mendrinos, D., Vladut, G., Thiem, L., Landrø, L., Mellors, R., Mannseth, T., Bhakta, T., Thomas, P.J., Heggelund, Y., Stork, A., Lien, M., Fageraas, B., Løvheim, L., Åsgard, K., Ködel, U.	TNO, CRES, SEDONA, NTNU, Univ. of California, San Diego, NORCE, Silixa Ltd, MonViro AS, OCTIO AS, Geotomographie GmbH	2023
D3.1	Guideline Societal Embeddedness Assessment	Geerdlink, T., Sprenkeling, M., Slob, A., Puts, H.	TNO	2020
D3.2	Report on the outcome of the Societal Embeddness Level Assessment in four countries: Norway, the Netherlands, Greece and Germany	Mendrinos, D., Polyzou, O., Nordø, Å., Sprenkeling, M., Peuchen, R., Geerdink, T., Puts, H., Otto, D.	CRES, NORCE, TNO, UFZ	2021
D3.3	Stakeholder perceptions and preferences regarding monitoring CO_2 storage and its contribution to optimizing the societal embeddedness of CO_2 storage projects	Sprenkeling, M., Peuchen, R., Langefeld, A., Bijvoet, J., Otto, D. Nordø, A., Veland, S., Karytsas, S., Mendrinos, D., Polyzou, O.,	TNO, UFZ, NORCE, CRES	2022
D3.4	On the Organisation of Translation - Am Inter- and Transdisciplinary Approach to Developing Design Options for CO2 Storage Monitoring Systems	Otto, D., Sprenkeling, M., Peuchen, R., Nordø, Å.D., Mendrinos, D., Karytsas, S., Veland, S., Polyzou, O., Lien, M., Heggelund, Y., Gross, M., Piek, P., Puts, H.	UFZ, TNO, NORCE, CRES	2022
D3.5	Best practices for developing a human centered monitoring system for CO_2 storage projects through a collaborative and interdisiplinary research approach	Sprenkeling, M., Otto, D., Nordø, Å.D., Mendrinos, D., Polyzou, O.,	TNO, UFZ, NORCE, CRES	2022
D4.1	Project plan	Midttømme, K., Nøttveit, A., Holstad, M. B.	NORCE	2020
D4.2	Quality assurance plan	Nøttveit, A., Midttømme, K., Holstad, M. B	NORCE	2020
D4.3	Internal communication plan	Nøttveit, A., Midttømme, K., Holstad, M. B	NORCE	2020
D4.4	Data management plan	Holstad, M.B., Nøttveit, A., Midttømme, K.	NORCE	2020
D4.5	Dissemination plan	Nøttveit, A., Midttømme, K., Holstad, M. B	NORCE	2020
D4.6	Quarterly progress reports and mid term report	Midttømme, K., Nøttveit, A., Holstad, M. B., Stork, A., Lien, M., Puts, H	NORCE, Silixa Ltd, MonViro AS, TNO	2020-23
D4.7	Project web-site	Midttømme, K., Holstad M.B.	NORCE	2019

D4.8	Scientific publications	All	All partners	2019-23
D4.9	DigiMon Final Report	Nøttveit, A., Midttømme, K. and all partners	NORCE and all partners	2023

Table 8.1 Project deliverables

8.2 DigiMon scientific publications

Author(s)	Title	Journal	Year	Project partners involved	Other involved
Hudson, T., Baird,A., Kendall, J.-M., Kufner, S., Brisbourne, A., Smith, A., Butcher, A., Chalari, A., Clarke, A.	Distributed Acoustic Sensing (DAS) for natural microseismicity studies: A case study from Antarctica,	Journal of Geophysical Research: Solid Earth, 126, e2020JB021493	2021	Univ. of Bristol , Univ. of Oxford, Silixa	British Antarctic Survey
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,	2021	NTNU	Alcatel Submarine Networks
Brisbourne, A.,Kendall, J.-M., Kufner,S., Hudson,T., Smith, S	Downhole distributed acoustic seismic profiling at Skytrain Ice Rise, West Antarctica,	The Cryosphere Discuss, 15, 3443–3458,	2021	University of Oxford	British Antarctic Survey
Otto, D., Gross, M.	Stuck on coal and persuasion? A critical review of carbon capture and storage communication,	Energy Research & Social Science,	2021	UFZ	
Otto, D., Thoni, T., Wittstock, F., Beck, S.	Exploring Narratives on Negative Emissions Technologies in the Post-Paris Era,	Frontiers in Climate	2021	UFZ	
Zhou, W., Butcher, A., Brisbourne, A.M., Kufner, S-K., Kendall, J.-M. Stork, A.	Seismic Noise Interferometry and Distributed Acoustic Sensing (DAS): Inverting for the Firn Layer S-Velocity Structure on Rutford Ice Stream, Antarctica,	Journal of Geophysical Research: Earth Surface, 127, e2022JF006917.	2022	Univ. of Bristol , Univ. of Oxford, Silixa	British Antarctic Survey

Otto, D., Pfeiffer, M., de Brito, M. M., Gross, M.	Fixed Amidst Change: 20 Years of Media Coverage on Carbon Capture and Storage in Germany	Sustainability, 14 (12), 7342	2022	UFZ	
Otto, D.,Sprenkeling, M., Peuchen, R., Nordø, Å.D., , Mendrinos, D., Karytsas, S., Veland, S., Polyzou, O., Lien, M., Heggelund, Y., Piek, P., Gross,M., Puts, H.	On the Organisation of Translation—An Inter- and Transdisciplinary Approach to Developing Design Options for CO2 Storage Monitoring Systems.	Energies, 15 (15), 5678.	2022	UFZ, TNO, NORCE, CRES, MonViro	
Mendrinos, D., Karytsas, D., Polyzou, O., Karytsas, C., Nordø, Å.D., Midttømme, K., Otto, D., Gross, M., Sprenkeling, M., Peuchen, R., Geerdink, T., Puts, H.	Understanding societal requirements of CCS projects: Application of the Societal Embeddedness Level assessment methodology in 4 national case studies	Clean Technologies 4(4):893-907,	2022	CRES, TNO, NORCE, UFZ	
Boullenger B., Paap, B., Vandeweijer, V., Butcher, A.	Turning distributed acoustic sensing measurements into calibrated ground motion responses using co-located geophones: application to a downhole seismic experiment.	in prep.	2023	TNO, Univ. of Bristo	
Lapins, S., Butcher, A., Kendall, J. M., Hudson, T. S., Stork, A. L., Werner, M. J.	DAS-N2N: Fully automated end-to-end denoising of Distributed Acoustic Sensing (DAS) data using weakly supervised machine learning and spliced fibers.	in prep	2023	Univ. of Bristol , Univ. of Oxford, Silixa	
Bhakta, T., Paap, B., Vandeweijer, V., Lien, M., Mannseth, T.	Assessment of various geophysical data types for cost-efficient monitoring of CO2 sequestration	International Journal of Greenhouse Gas Control (In review)	2023	NORCE, TNO, MonViro AS	

Table 8.2 DigiMon scientific publications

8.3 DigiMon outreach

Hosted events, participation at conferences, other

Author(s) or speaker(s)	**Title with link if available**	**References**	**Year, month**	**Project partners involved**	**Other involved**
DigiMon Webinars (open events)					
Nøttveit, A., Puts, H.Kendall, J.-M., Fageraas, B., Midttømme, K.,	DigiMon Webinar (open)		2020, November	NORCE, TNO, Univ,. of Oxford, MonViro AS,	

Otto, D., Koedel, U.,	Stakeholder Workshop Germany: Design Options for Carbon Storage Monitoring Systems	Online Meeting	2022 April	UFZ	
Stork, A., Landrø. M., Meckel, T., Midttømme, K.	DigiMon webinar on digital monitoring of CO2 storage	DigiMon webinar	2021 June	NORCE, Silixa NTNU	Univ of Texas
Butcher, A., Zhou, W. Boullenger, B., Lapins S., Bond T., Nøttveit, A., Midttømme, K	Advancing fibre optic technologies for CO2-storage monitoring	DigiMon Webinar	2022 October	UoB, TNO, LLNL, NORCE	
Lien, M., Ködel, U., Candela, T., Mellors, R., Pitarka, A., White, J., Bhakta, T., Mannseth, T., Heggelund, Y., Midttømme., K	New Developments Within Fiberoptic and Gravimetric Monitoring of Geological CO2 Storage	DigiMon Webinar	2022 October	MonViro, Geotomograpie,TNO, LLNL, NORCE	Univ of California
Spenkling, M., Mendrinos, D., Karytsas, S., Otto, D., Nøttveit, A., Midttømme, K.	Towards Large-scale Deployment of CO2 Storage with Innovative and Societal Embedded Monitoring Techniques	DigiMon Webinar	2022 November	TNO, CRES, UFZ, NORCE,	
Piek, Puts, Vandeweijer, Paap, Boullenger, Candela, Sprenkeling, Zhou, Nøttveit	Dutch Stakeholder Workshop Towards large-scale deployment of CO2 storage with innovative and societal embedded monitoring techniques	Utrecht, Stakeholder workshop	2022 October	TNO, NORCE	TU Delft
S. Oikonomou, L. Pyrgiotis, M. Kotsias, A. Tsikouras, C. Karytsas, D. Mendrinos, S. Karytsas, A. Chalari	Greek Stakeholders Workshop "Capture, Transport, Geological Storage and Use of CO2" (in Greek)	Athens, Greece	2023 March	CRES, SILIXA	Industry, CERTH
Presentations with abstract (or video)					
Poletto,F., Bellezza, C., Corubolo, P., Goertz, A., Bergfjord, E.V., Lindgård, J.E.	Seismic While Drilling Using a Large-Aperture Ocean Bottom Array	SEG International Exposition 89th Annual meeting	2019, September	Octio EM,	OGS, Italy
Midttømme, K., Nøttveit, A., Holstad, M. B., Stork, A., Lien, M., Puts, H.	Digital monitoring of CO2 storage projects (DigiMon)	Nordic Geological Winter Meeting 2020, Oslo	2020, January	NORCE, Silixa, Octio EM, TNO	
Baird, Alan	Modelling the Response of Helically Wound DAS Cables to Microseismic Arrivals	First EAGE Workshop on Fibre Optic Sensing, Amsterdam	2020, March	Univ of Bristol	
Koedel U., Fechner,T., Gross, M.	DigiMon- Digital Monitoring of CO2 storage projects	80. Annual Meeting of the German Geophysical Society	2020, March	Geotomographie, UFZ	
Otto, D., Gross M	Pushed, Opposed, Cancelled!? – The Fates of Carbon Capture and Storage (CCS) Projects across Europe	EASST/4S 2020 conference	2020, August	UFZ	

Kendall, J.-M., Brisbourne, A., Hudson, T., Kufner,S. K., Butcher, A., Smith, A., Chalari, A., Clarke, A.	Interrogating the cryosphere using distributed acoustic sensing (DAS): examples of active and passive surveys in West Antarctica	AGU Annual Fall Meeting	2020, December	UoO, UoB, Silixa	British Antarctic Survey
Nøttvedt, A., Midttømme, K., Stork, A., Lien, M., Puts, H.	Digital monitoring of CO2 storage projects (DigiMon)	Climit 2021 Digits	2021, February	NORCE, Silixa, Octio EM, TNO	
Butcher, A., Hudson, T., Kendall, J.-M., Kufner, S., Brisbourne, A., Stork, A.	Radon transform-based detection of microseismicity on DAS networks: A case study from Antarctica.	Second EAGE Workshop on Distributed Fibre Optic Sensing	2021 March	Univ of Bristol, Univ.of Oxford, Silixa	British Antarctic Survey
Hudson, T., Baird, A., Kendall, J.-M. Kufner, S., Brisbourne, A., Smith, A., Butcher, A., Chalari, A., Clarke, A.	Distributed Acoustic Sensing in Antarctica: What we can learn for studying microseismicity elsewhere	Second EAGE Workshop on Distributed Fibre Optic Sensing	2021 March	Univ. of Oxford, Univ of Bristol, Silixa	British Antarctic Survey
Kendall,J. -M., Brisbourne, A., Hudson,T., Kufner,S., Butcher,A., Baird, A., Smith, A., Chalari, A., Clarke, A.	Listening to Ice Sheets - Fibre Optic Cables as Seismic Sensors in the Antarctic (Keynote)	Second EAGE Workshop on Distributed Fibre Optic Sensing	2021 March	Univ of Oxford, Univ of Bristol, Silixa	British Antarctic Survey
Vandeweijer, V., Paap,B., Verdel, A., Mellors, R., Baird, A., Stork, A., Butcher, A.	Modelling the DAS response for offshore CO2 storage sites,	GHGT, Greenhouse Gas Control Technologies	2021 March	TNO,LLNL, Univ of Bristol, Silixa Ltd	
Nøttvedt, Lien, Midttømme, Puts, Stork,	Digital monitoring of CO2 storage projects (DigiMon)	GHGT, Greenhouse Gas Control Technologies	2021 March	NORCE, Silixa, Octio EM, TNO	
Pitarka, A., Thomas, P. J., Paap, B., Heggelund, Y., Butcher, A., Matzel, E., Mellors, R.	Understanding Fiber Response With Lab-Scale Tests and Modeling	SSA Seismological Society of America Annual Meeting 2021,	2021, April	LLNL, NORCE , TNO, Univ. Of Bristol	
Hudson, T., Butcher, A., Baird, A., Kendall, J.-M., Kufner, S.K., Brisbourne, A., Smith, A., Stork, A., Chalari, A., Clarke, A.	Antarctic icequakes shed light on the applicability of DAS for microseismic monitoring	SSA Seismological Society of America Annual Meeting 2021,	2021, April	Univ. of Oxford, Univ of Bristol, Silixa	British Antarctic Survey
Nøttvedt, Lien, Midttømme, Puts, Stork,	DigiMon	SPE Virtual Workshop: Offshore CCUS - The Size of the Prize and the Way Forward	2021 April	NORCE, OCTIO EM, TNO, SIlixa	
Otto, D., Gross M.	DigiMon – Digital Monitoring of CO2 Storage Projects	Energy Working Group, Helmholtz-Centre for Environmental Research	2021, May	UFZ	

Bhakta, T., Mannseth.T, Lien, M.	Monitoring of CO2 saturation plume movement from time-lapse inverted-seismic and gravity data using an ensemble-based method	82nd EAGE Annual Conference and Exhibition, Amsterdam	2021, June	NORCE, OCTIO EM	
Otto, D., Gross, M.	Beyond Leakage and Communication -Reconsidering Trust in Carbon Capture and Storage (CCS)	Congress of the European Sociological Association, Barcelona	2021 September	UFZ	
Stork, A., Butcher, A., Hudson,T., Kendall, J.-M., Lapins, S., Zhou, W., Paap, B., Boullenger B.	Advances in Distributed Acoustic Sensing (DAS) monitoring for CCS projects: The DigiMon project,	SPE CCUS Conference 2022	2022, February	Silixa, Univ of Bristol, Univ. of Oxford , TNO	
Paap, B., Bhakta, T., Vanderweijer, V. Mannseth, T	Modeling approach for evaluating time-lapse effects of CO2 storage on particle velocity and strain rate data	EAGE Geotech- Third EAGE Workshop on Distributed Fibre Optic	2022 April	TNO, NORCE	
Zhou W., Butcher A., Kendall J.-M., Stork A.	Enhancing Ambient Noise Interferometry for Das: Selective Stacking and Hybrid Seismic Receivers.	EAGE Geotech- Third EAGE Workshop on Distributed Fibre Optic	2022 April	Univ. of Bristol, Univ. of Oxford, Silixa Ltd	
Otto, Danny; Pfeiffer, Maria; Madruga de Brito, Mariana; Gross, Matthias	Flashbacks and Framing Loops. 20 years of media coverage on carbon capture and storage in Germany	3rd International Conference on Energy Research & Social Science in Manchester,	2022 June	UFZ	
Otto, D., Sprenkeling, M., Peuchen,R., Nordø, Å. D., , Mendrinos, D., Karytsas, D., Langefeld, A., Bijvoeta, J., Veland, S., Polyzou, O., Gross, M., Puts, H.	How to study societal requirements for little know technologies? Insights from an international research project on the perception of carbon capture and storage in Germany, Greece, Norway and the Netherlands	3rd International Conference on Energy Research & Social Science in Manchester, June 20-23 2022	2022 June	UFZ, TNO, NORCE, CRES	
Zhou, W., Butcher, A., Kendall, J.-M., Kufner, S.-K., Brisbourne, A.	S-wave velocity profile of an Antarctic ice stream firn layer with ambient seismic recording using Distributed Acoustic Sensing	EGU General Assembly 2022	2022 May	Univ. of Bristol, Univ. of Oxford	British Antarctic Survey
Otto, D., Sprenkeling, M., Peuchen, R., Nordø, Å. D., Mendrinos, D., Karytsas, S., Langefeld, A., Bijvoeta, J., Veland, S., Polyzou, O., Gross, M., Puts, H.	Does monitoring matter? Understanding the perception and societal requirements for carbon capture and storage (CCS) in Germany, Greece, Norway and the Netherlands.	EASST – European Association for the Study of Science and Technology, Conference "Politics of technoscientific futures", Madrid July 6-9, 2022	2022 July	UFZ, TNO, NORCE, CRES	
Bhakta, T., Paap, B., Vanderweijer, V. Mannseth, T	Modeling approach for evaluating time-lapse effects of CO2 storage on particle velocity and strain rate data	SEG/AAPG International Meeting for Applied Geoscience & Energy	2022 August	NORCE, TNO, MonViro AS	

Butcher, A., Zhou, W., Kendall, J.-M., Stork, A., Vandeweijer, V., Macquet, M., Lawton, D.	Near-surface monitoring of CO2 storage sites: Case study from CaMI FRS	EAGE Asia Pacific Workshop on CO2 Geological Storage, Perth, Australia, 22-25 August 2022	2022 August	Univ of Bristol, TNO, Silixa	CaMI
Mendrinos, D., Polyzou, O., Karytsas, S., Nordø, Å. D., Midttømme, K., Sprenkeling, M., Peuchen, R., Geerdink, T., Puts, H., Otto, D.	Understanding societal requirements of subsurface resources exploitation projects: Societal Embeddedness Level assessment methodology, its application in 4 CCS National case studies and implications for the geothermal industry.	European Geothermal Congress 2022, Berlin, Germany, 17-21 October	2022 October	CRES, TNO, NORCE, UFZ	
Bond T., Chang, A., Sahota, S., Arteag, J., Heyrich, M., . Delmas, W.,. Tumkur, T., Khitrov, V	Distributed chemical sensing for CO2 leakage monitoring,	16th International Conference on Greenhouse Gas Control Technologies GHGT-16	2022 October	LLNL	Univ of Colorado
Koedel, U., Stork, A., Thomas, P. J., Zhou,W., David, A., Maurer, H., Soeding, H., Fechner, T.	Seismic Cross-hole Surveying to Monitor a CO2 Injection at the Svelvik Test-site in Norway	16th International Conference on Greenhouse Gas Control Technologies GHGT-16	2022 October	Geotomographie, UFZ, Silixa, NORCE, Univ of Bristol	ETH Zurich
Sprenkeling, M., Otto, D., Nordø, Å., D., Mendrinos, D., Peuchen, R., Langefeld, A., Bijvoet, J., Gross, M., Veland, S., Karytsas, S., Polyzou, O., Puts, H.,	Stakeholder perceptions and preferences regarding monitoring CO2 storage and its contribution to optimizing the societal embeddedness of CO2 storage projects	16th International Conference on Greenhouse Gas Control Technologies GHGT-16	2022 October	TNO, UFZ, NORCE, CRES	
Vandeweijer, V., Candelaa T., , Lien, M., Koedel, U., Fechner, T., Bond, T., Zhou, W., Butcher, A., Kendall, J.-M. Stork, A., Mellors, R.	A Technology Readiness Assessment for CCS site monitoring systems	16th International Conference on Greenhouse Gas Control Technologies GHGT-16	2022 October	TNO, Monviro, Geotomographie, LLNL, Univ. of Bristol, Univ of Oxford , Silixa	Univ of California , San Diego
Butcher, A., Zhou, W., Vandeweijer, V., Lapins, S., Kendall, J.-M., Boullenger, B., Paap, B., Broman, B., Stork, A., Macquete, M., Lawton, D.	Monitoring CO2 injection at CAMI FRS using Distributed Acoustic Sensing networks.	16th International Conference on Greenhouse Gas Control Technologies GHGT-16	2022 October	UoB, UoO, Silixa. TNO	CaMI
Lien, M., Goertz, A., Vassvåg, S. C., Ward, C., Ackers, M., Pujol, T., Fletcher, A.	Feasibility of 4D microgravimetric monitoring of a CO2 flood in a depleted gas reservoir	Submitted to the Energy Geoscience Conference (EGC)	2023, May	OCTIO (ReachSubsea)	Spririt Energy
Presentations without abstract					

Midttømme, K.	DigiMon - Digital monitoring of CO2 storage projects	Safe and Cost-efficient CO2 Storage for Europ. Indust., seminar. SINTEF/ PreAct, Brussel	2019, October	NORCE	
Nøttvedt, A., Midttømme, K., Stork, A., Lien, M., Puts, H.	Presentation of new ACT-2 projects: DigiMon	4th ACT Knowledge Sharing Workshop. Athene Greece,	2019 November	NORCE	
Midttømme, K., Nøttvedt, A., Holstad, M.B.	Digital monitoring of CO2 storage projects	Bergen CCUS seminar,	2019, December	NORCE	
Nøttvedt, A., Midttømme, K., Stork, A., Lien, M., Puts, H.	DigiMon- Digital Monitoring of CO2 storage projects	ACT projects and international activities, Pre meeting STEM-CCS workshop, Bergen	2020, February	NORCE	
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	2020, March	Octio EM	
Otto, D., Gross, M	Policy Interaction, Governmental Commitment and Public Perception – The Case of Carbon Capture and Storage (CCS)	ECPR General Conference 2020	2020, August	UFZ	
Otto, D.	Building Trust in Technologies for a Zero Carbon Future	UK-Germany Energy Symposium (Royal Academy of Engineering) 2020 (virtual)	2020, October	UFZ	
Nøttvedt, A.	DigiMon - Digital monitoring of CO2 storage projects	ACT knowledge sharing workshop (digital)	2020, November	NORCE	
Otto, D., Gross, M	National SEL Assessment CCS Germany	WP3 - DigiMon-National Assessment Workshop	2020, December	UFZ	
Otto, D., Gross, M	“Unwanted but Unavoidable”. Revisiting Stakeholder Perception towards CCS Technology in Germany	5th Energy and Society conference	2021, February	UFZ	
Kendall, J.-M	Passive seismic monitoring and the geomechanical response to CO2 storage (Invited)	Recent progress with CO2 storage monitoring and development of integrated methods Webinar Univ of Oslo	2021, March	Univ. Of Oxford	
Nøttvedt, A.	DigiMon - Digital monitoring of CO2 storage projects	CCUS Event, Rotterdam	2022, June	NORCE	

Nøttveit, A., Midttømme, K.,	DigiMon Digital Monitoring of CO2 Storage Projects	Northern Lights seminar	2022, August	NORCE	
Otto, D., Sprenkeling, M., Peuchen, R., Nordø, Å.D., , Mendrinos, D., Karytsas, S., Veland, S., Polyzou, O., Piek, P., Gross, M., Puts, H.	DigiMon - Digital monitoring of CO2 storage projects	UFZ Science Days	2022, October	UFZ, TNO, NORCE, CRES	
Midttømme	DigiMon: Digitalt tidlig varslingssystem for CO2 lagringsfelt,	Havlunsj , GCE Ocean Technology, Bergen	2022, October	NORCE	
Nøttveit & Midttømme	DigiMon – an ACT project	Bergen CCUS seminar,	2022, November	NORCE	
Butcher, A., Stork., Thiem, L., Thomas, P.J., Midttømme., K.	Workshop on fiber optics ,	Equinor, ACT SENSE, DigiMon workshop	2023 April	NORCE, Equinor	
Technical publications					
Landrø, M., Amundsen, L.	From Arrhenius to CO2 storage Part III: A Simple Greenhouse Model	GeoExpro Recent Advances in Technology May 2019	2019, September	NTNU	
Landrø, M., Amundsen, Ringrose, P.	From Arrhenius to CO2 storage Part IV: Challenges and Some Practical Issues	GeoExpro Recent Advances in Technology May 2019	2019, October	NTNU, Equinor	
Halland, E., Landrø, M., Amundsen, L.	From Arrhenius to CO2 storage , Part V: Underground Storage of CO2	GeoExpro Recent Advances in Technology Dec 2019	2019, December	NTNU	Norwegian Petroleum Directorate

Table 8.3 DigiMon outreach

9. References

Bond T., A. Chang, S. Sahota, J. Arteag, M. Heyrich, W. Delmas, T. Tumkur, and V. Khitrov (2022). Distributed chemical sensing for CO2 leakage monitoring, 16th International Conference on Greenhouse Gas Control Technologies, GHGT-16, http://dx.doi.org/10.2139/ssrn.4284049

Boullenger B., B. Paap, V. Vandeweijer, A. Butcher (in prep). Turning distributed acoustic sensing measurements into calibrated ground motion responses using co-located geophones: application to a downhole seismic experiment.

Brisbourne A., J-M. Kendall, S. Kufner, T. Hudson, A. Smith (2021). Downhole distributed acoustic seismic profiling at Skytrain Ice Rise, West Antarctica, The Cryosphere, 15, 3443–3458, https://doi.org/10.5194/tc-15-3443-2021

Butcher A., T. Hudson, J.-M. Kendall, S. Kufner, A. Brisbourne, A. Stork (2021). Radon transform-based detection of microseismicity on DAS networks: A case study from Antarctica, Second EAGE Workshop on Distributed Fibre Optic Sensing, https://doi.org/10.3997/2214-4609.202131039

Butcher A., W. Zhou, J-M. Kendall, A. Stork, V. Vandeweijer, M. Macquet and D. Lawton (2022a). Near-surface monitoring of CO2 storage sites: Case study from CaMI FRS, EAGE Asia Pacific Workshop on CO2 Geological Storage, https://doi.org/10.3997/2214-4609.202275038

Butcher A., W. Zhou, V. Vandeweijer, S. Lapins, J-M. Kendall, B. Boullenger, B. Paap, B. Broman, A. Stork, M. Macquet and D. Lawton (2022b). Monitoring CO2 injection at CAMI FRS using Distributed Acoustic Sensing networks, 16th International Conference on Greenhouse Gas Control Technologies, GHGT-16, http://dx.doi.org/10.2139/ssrn.4286315

Hudson, T. S., Baird, A. F., Kendall, J. M., Kufner, S. K., Brisbourne, A. M., Smith, A. M., Chalari, A. And Clarke, A. (2021a). Distributed Acoustic Sensing (DAS) for natural microseismicity studies: A case study from Antarctica. Journal of Geophysical Research: Solid Earth, 126, e2020JB021493. https://doi.org/10.1029/2020JB021493.

Hudson, T. S., Baird, A. F., Kendall, J. M., Kufner, S. K., Brisbourne, A. M., Smith, A. Chalari and A. Clarke (2021b). Distributed Acoustic Sensing in Antarctica: What we can learn for studying microseismicity elsewhere, Second EAGE Workshop on Distributed Fibre Optic Sensing, doi: https://doi.org/10.3997/2214-4609.202131037

Kendall J-M., A. Brisbourne, T. Hudson, S. Kufner, A. Butcher, A. Smith, A. Chalari and A. Clarke (2020). Interrogating the cryosphere using distributed acoustic sensing (DAS): examples of active and passive surveys in West Antarctica, AGU Fall Meeting.

Kendall J-M., A. Brisbourne, T. Hudson, S. Kufner, A. Butcher, A. Baird, A. Smith, A. Chalari and A. Clarke Listening to Ice Sheets - Fibre Optic Cables as Seismic Sensors in the Antarctic (Keynote) (2021). Second EAGE Workshop on Distributed Fibre Optic Sensing, doi: https://doi.org/10.3997/2214-4609.202131076

Koedel, U. A. Stork, P. Thomas, W. Zhou, A. David, H. Maurer, Soeding and T. Fechner (2022). Seismic Cross-hole Surveying to Monitor a CO2 Injection at the Svelvik Test-site in Norway, 16th International Conference on Greenhouse Gas Control Technologies, GHGT-16, http://dx.doi.org/10.2139/ssrn.4274670

Lapins, S., Butcher, A., Kendall, J. M., Hudson, T. S., Stork, A. L., Werner, M. J. (in prep). DAS-N2N: Fully automated end-to-end denoising of Distributed Acoustic Sensing (DAS) data using weakly supervised machine learning and spliced fibers.

Lien, M., A. Goertz, S.C. Vassvåg, C. Ward, M. Ackers, T. Pujol and A. Fletcher (2023). Feasibility of 4D microgravimetric monitoring of a CO2 flood in a depleted gas reservoir, Energy Geoscience Conference (EGC) Aberdeen.

Ruiz, H., M. Lien, M. Vatshelle, H. Alnes, M. Haverl, and H. Sørensen (2020). Monitoring the Snøhvit gas field using seabed gravimetry and subsidence. SEG Technical Program Expanded Abstracts, 3768-3772. https://doi.org/10.1190/segam2020-3413983.1

Taweesintananon K., M. Landrø, J.K. Brenne and A. Haukanes (2021). Distributed acoustic sensing for near-surface imaging using submarine telecommunication cable: A case study in the Trondheimsfjord, Norway, Geophysics, 86(5), https://doi.org/10.1190/geo2020-0834.1

Zhou, W., Butcher, A., Kendall, J.-M, & Stork, A. L. (2022a). Enhancing Ambient Noise Interferometry for DAS: Selective Stacking and Hybrid Seismic Receivers, EAGE GeoTech 2022 Third EAGE Workshop on Distributed Fibre Optic Sensing, https://doi.org/10.3997/2214-4609.20224027

Zhou, W., Butcher, A., Brisbourne, A. M., Kufner, S.-K., Kendall, J.-M, & Stork, A. L. (2022b). Seismic noise interferometry and distributed acoustic sensing (DAS): Inverting for the firn layer S-velocity structure on Rutford Ice Stream, Antarctica. Journal of Geophysical Research: Earth Surface, 127, e2022JF006917. https://doi.org/10.1029/2022JF006917