D1.11- Project report on WP1 outcomes relevant to other WPs

DigiMon

Digital monitoring of CO_2 storage projects

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- LLC Lawrence Livermore National Security
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1 Introduction

1.1 Purpose of document

This report summaries some of the key technologies that have been studied and developed through WP1 with the purpose of transferring these finding to other WPs in the DigiMon project. The objective of the DigiMon project is to develop an early-warning system for Carbon Capture and Storage (CCS) which utilises a broad range of sensor technologies including Distributed Acoustic Sensing (DAS). While the system is primarily focused on the CCS projects located in the shallow offshore environment of the North Sea, it is also intended to be adaptable to onshore settings.

Some of the key areas that the systems will monitor include the movement of the plume within the reservoir, well integrity and CO_2 leakage into the overburden. A combination of different methods will be adopted to monitor these key areas, which include active and passive seismics, gravimetry, temperature and chemical sensing. This report focuses on technology and methods which have been developed by the DigiMon project and is not intended as a technology review, which is instead the focus of the DigiMon deliverable 2.3 Technology Readiness Assessment.

1.2 Overview of document structure

This report is split between outcomes that are relevant to WP2 (Section 2), which is the integration of the DigiMon components, and WP3 which is focussed on the societal acceptance aspects of the project (Section 3). Section 2 is sub-divided in the key monitoring areas covered by the DigiMon system, then further sub-divided between surface/ seafloor and borehole technologies. Within these sub-sections a summary of the outcomes relating to different relevant technologies are detailed. A general overview is:

- Conformance - Plume imaging
  - Surface /seabed surveys
  - Borehole/in-well seismic surveys
    - 4D Vertical Seismic Profiles
    - Crosswell surveys
- Containment - Caprock integrity
  - Surface /seabed surveys – Passive microseismic
  - Borehole/in-well seismic surveys
- Well integrity
  - In-well sensing surveys

Within Section 3, the societal acceptance aspects of the Digimon system are discussed and the relevance of the key technologies that will contribute to the system.

2 Technology outcomes from WP1

2.1 Summary

This section provides an overview of the technologies studied and/or developed as part of WP1 which mainly contribute to the WP2. WP2 aims to integrate monitoring technologies to form the DigiMon system. Therefore, the technology developments in WP1 are very relevant to WP2 to facilitate it through the following outcomes;

- An integrated interpretation and uncertainty quantification,
- Optimization of the monitoring solution,
- The development of an informatic SCADA system that integrates all the DigiMon technologies.

2.1.1 Conformance - Plume imaging

Monitoring the CO_2 plume movement in the reservoir through the use of remote geophysical measurements of changes in saturation and pressure have been improved by using the following applications and methods

2.1.1.1 Surface /seabed surveys

Technology	WP1 outputs & conclusions	Improvements in capabilities including accuracy & precision	Improvements in practicalities/ deployments including reliability & life-time	Cost reductions (if any)	References
2/3D seismic - Streamer	Towed 1C streamer to provide reference image of the subsurface to compare it to the seismic image acquired by horizontal DAS array at the ocean bottom.	Provides standard baseline to which other methods can be compared			Taweesintananon et al., 2021 DigiMon D1.14 – PRM Report

2/3D seismic - Ocean-bottom nodes & ocean-bottom	OBN at Oseberg oilfield. Ocean-bottom cable in the Trondheimsfjord	Clear observation of earthquakes as low as M_L=2. Ongoing work on estimating the velocity model and Q-values of the area.			Taweesintananon et al., 2021 DigiMon D1.14 – PRM Report
2/3D seismic - DAS	Seismic image of the near-surface of Trondheimsfjord acquired with a submarine cable (active seismic survey) compared to streamer image.	Demonstration of the image capability of DAS data from a horizontal cable in a marine environment.	Permanent deployment of fibre enables repeatable surveys and reductions in survey times.	Survey time reductions = Cost reduction	Taweesintananon et al., 2021 DigiMon D1.14 – PRM Report
Ambient noise - Ocean-bottom nodes & ocean-bottom cables / surface geophones	Noise comparison of ocean-bottom cables and hydrophone streamer.	The DAS image has lower dominant frequency and more low-frequency content than the streamer image.			Taweesintananon et al., 2021 DigiMon D1.14 – PRM Report
Ambient noise - DAS	Ambient Noise Interferometry (ANI) applied to Antarctica dataset Velocity profile produced to a depth of ~100m	SNR significantly enhanced by using a geophone node as virtual ‘source’.	Selective stacking of cross-correlations would reduce passive recording time		Hudson et al., 2021 DigiMon report D1.1 Zhou et al., 2022 (in prep)

Gravimetry	Improvements in 4D gravity accuracy and cost reduction for CCS applications have been implemented and successfully field tested during 2020 4D gravity campaign at Ormen Lange	A world record low uncertainty of 0.61 µGal for gravity was achieved during the operation at Ormen Lange in 2020	Reduction of thermal disturbances and new functionalities for image recognition for faster and improved repeatability placement reduce time to deploy and measurement time enabling more autonomous operation	A 15% reduced measurement time per datapoint and 13% reduced numbers of measurements versus previous campaign at the same field reduce overall data acquisition time and cost accordingly	DigiMon report D1.9 Ruiz et al., 2020
Surface deformation monitoring	Improvements in surface deformation accuracy and cost reduction for CCS applications have been implemented and successfully field tested during 2020 4D gravity campaign at Ormen Lange	Stand-alone subsidence measurements has enabled autonomous operation which is a game changer for low-cost CCS seabed deformation monitoring. Today this method is regarded as the gold standard for seabed deformation monitoring with a 2mm accuracy with a 5seconds measurement time	New version of the software, DepthWatch, for stand alone seafloor deformations has enabled a very low-cost seabed deformation monitoring.	The use of small vessels with observation ROV or USV operated ROVs, or even AUV operation, has reduced the overall costs with a factor 3-5 depending on application and area of operation	DigiMon report D1.9 Hatchell et al., 2019

Table 1: Surface/ seafloor surveys for CO_2 plume imaging

2.1.1.2 Borehole/in-well seismic surveys

4D Vertical Seismic Profiles

Technology	WP1 outputs & conclusions	Improvements in capabilities including accuracy & precision	Improvements in practicalities/deployments including reliability & life-time	Cost reductions (if any)	References
Active source - DAS	Seismic profiles at Skytrain Ice Rise, West Antarctica. Direct and reflected P- and S-wave energy observed at a range of different offsets. Significant noise resulted from the fibre hanging untethered in borehole. Velocities and attenuation (*Q*) measured.	When well coupled to the borehole, the mean vertical interval velocity measured was 3984m/s with an uncertainty (1 standard deviation) of 218m/s. A mean interval *Q* of 75±12	Optical technology allows long term deployments and improves the repeatability of monitoring surveys.	Low cost technology and enables logistically light experiment	Brisbourne et al., 2021 DigiMon Report D1.1
Ambient noise - Geophones / hydrophones	Dataset available but not yet processed: Digimon FRS survey, borehole geophones are recorded continuously and will be processed				
Ambient noise - DAS	Dataset available but not yet processed: Digimon FRS survey, 2 boreholes with linear and helical wounded cables				

Table 2: 4D borehole surveys for CO_2 plume imaging

Crosswell surveys

Technology	WP1 outputs & conclusions	Improvements in capabilities including accuracy & precision	Improvements in practicalities/deployments including reliability & life-time	Cost reductions (if any)	References
Active source - Geophones / hydrophones	Monitoring CO_2 injection by seismic tomography with P-, SH- and SV- waves Using multi-station borehole system and hydrophones to record P-, SH-, SV- waves Successful test of the novel SV- source Successful generation of a full tomographic dataset with high quality P-, SH- and SV- data All seismic sources provide sufficient energy for DAS monitoring	First time cross-hole tomographic experiment with DAS and conventional seismic receivers using 3 different seismic sources to monitor CO_2 injection Rapid and detailed monitoring of the effects caused by CO_2 injection 3 seismic sources produce highly repeatable signals also for DAS Possibility of joint inversion using P-, SH- and SV- waves and assessing anisotropy effects	All seismic sources are powered by same HV impulse generator Multi-station borehole system allows a rapid shear wave tomography SV- source improves practicability of s-wave tomography by faster handling	Reduced costs due to usage of one impulse generator for all sources Multi-station borehole system allows an economic field survey in shorter time	D1.1 addendum 3 – Svelvik dataset Conference abstract & publication in prep.

Active source - DAS	Linear and helically-wound (HWC) cable performed well in P-wave surveys. S-wave surveys possible but weaker signal due to weaker source. HWC performs better the linear at near broadside (perpendicular) P-wave incidence.	First time demonstration of capabilities of DAS in crosswell tomography (analysis of full capabilities ongoing).	Permanent deployment of fibre and full wellbore coverage enable repeatable surveys and reductions in survey times.	Survey time reductions = Cost reduction	D1.1 addendum 3 – Svelvik dataset Conference abstract & paper in prep.
Ambient noise - DAS	Dataset available but not yet processed				

Table 3: Crosswell surveys for CO_2 plume imaging

2.1.2 Containment - Caprock integrity

Monitoring the overburden, including monitoring of above-zone CO_2 migration and early detection of CO_2 leakage anomalies.

Surface /seabed surveys – Passive microseismic

Technology	WP1 outputs & conclusions	Improvements in capabilities including accuracy & precision	Improvements in practicalities/deployments including reliability & life-time	Cost reductions (if any)	References
DAS	Antarctica dataset acquired using three different DAS array configurations and 3C seismic geophones. Dataset recorded 10,000's of microseismic events relating to icequakes.	Resolution on DAS array improved through array based processing methods. DAS outperforms conventional geophones for source spectra and full-waveform source mechanism inversion 2D DAS array geometries can be used as a multi-component sensor capable of measuring shear-wave splitting			Hudson et al., 2021 Butcher et al., 2021 DigiMon report D1.1
	A comprehensive field dataset at Field Research Station (FRS) in Canada has been successfully acquired in September 2021. This dataset consists of both surface stations (1C, 3C) and trenched fibre-optic at the surface, as well as borehole fibres. Alongside the measurements CO_2 injection tests have been done as well. This dataset can be used to study if	At the FRS site both straight and helical fibres are present. The helical fibres are expected to give an improved response compared to straight fibres. More efficient data processing and event detection workflow based on slant stacks	Permanent deployment of trenched fibre enable repeatable surveys and reductions in survey times. Detection of weaker seismic events.		

	caprock properties can be determined from surface measurements. Processing workflow and application to field data				
Geophones	Advantage over DAS thanks to multiple components and broadband response. Geophones prove to be useful, at least to complement/calibrate DAS records and constrain event characterization				
Ocean bottom nodes/cables	No direct comparison of OBNs and cables				

Table 4: Surface/ seafloor surveys for assessing caprock integrity

2.1.2.1 *Borehole/in-well surveys*

Technology	WP1 outputs & conclusions	Improvements in capabilities including accuracy & precision	Improvements in practicalities/deployments including reliability & life-time	Cost reductions (if any)	References
DAS	Two datasets serve this goal; the FRS dataset collected in September 2021, and the vintage FORGE dataset. A comprehensive field dataset at Field Research Station (FRS) in Canada has been successfully acquired in September 2021. This dataset consists of both surface stations (1C, 3C) and trenched fibre-optic at the surface, as well as borehole fibres. Alongside the measurements CO_2 injection tests have been done as well. This dataset will be used to study how caprock properties (and changes) can be inferred from borehole measurements. The pre-existing FORGE dataset was used to quantify the DAS transfer function.	Fibre-optic sensing provides a much denser spatial sampling and allows acquisition of data near and through the reservoir itself. Capability to turn DAS measurement into ground velocity measurement.	Permanent deployment of fibre and full wellbore coverage enable repeatable surveys and reductions in survey times. Use knowledge on transfer function in processing workflow and to quantify magnitude of seismic events.	Provides much more point measurements at lower cost. Reduction of survey time results in cost reduction.	DigiMon report D1.1 addendum 2

DTS	Temperature measurements in boreholes appear to be consistent with expected potential depths for CO_2 accumulation.	Validation/calibration/alternative to seismic measurements	Permanently deployed fibre cables in boreholes can give a low cost indication of where CO_2 accumulates	DTS can potentially reduce the need for costly survey methods.	Publications in progress
DCS	Demonstrated CO_2 detection by Raman spectroscopy in hollow core fibre demonstrated. Tactics to provide hybrid integration with solid core fibre for effective deployment were also evaluated	Determine limit of detection and demonstrate operation with integrated solid core fibres and FBGs	Evaluate armouring for deployment of fibre in wellbore and operation with repeatable surveys.	Direct detection would improve safety margins all along the bore and thus management cost	DigiMon report D1.8 Paper accepted at SPIE Photonics West Jan 22 - paper in prep.

Table 5: Borehole surveys for assessing caprock integrity

2.1.3 Well integrity

Monitoring well integrity, mainly with downhole sensing.

2.1.3.1 In-well sensing surveys

Technology	WP1 outputs & conclusions	Improvements in capabilities including accuracy & precision	Improvements in practicalities/deployments including reliability & life-time	Cost reductions (if any)	References
DAS	Until now no knowledge has been developed within DIGIMON on this topic. However, with behind the casing fibre optic sensing you can evaluate real-time well integrity changes. With this you can avoid well intervention programs.			Avoid costly well intervention programs.	Rabb et al., 2019

Table 6: In-well sensing surveys for well integrity

2.2 Other technologies

It is important to note that there are some technologies not considered in WP1 and therefore no associated results or recommendations are given. These include electromagnetic methods, downhole pressure and temperature measurements, geophysical logging, fluid sampling and chemical sensing techniques other than DCS.

3 Societal acceptance aspects

3.1 Introduction

To optimise results and outputs from WP3, WP1 must disseminate any aspects of individual monitoring technologies impacting on the societal acceptance of CCS. The work in WP3 takes account of political, economic and societal aspects of CCS technologies in general, as these are of paramount importance in the wider adoption of CCS.

WP3 has conducted national Society Embeddedness Level (SEL) assessments for CCS showing that monitoring currently is a regulatory requirement as part of permitting procedures, which may alleviate community concerns on safety. In order to effectively contribute to trust-building among stakeholders, a CCS monitoring system should

- be low cost, efficient and easy to maintain over a long timeframe,
- measure and predict leakages and plume movement,
- be transparent, allowing real-time access to monitoring data,
- provide continuously reliable access to experts for questions on the data,
- be externally supervised by unbiased institutions, and
- be connected to a safety concept that states what happens when the data divert from normality.

Insights from the local assessments (Task 3.2), which were ongoing during the preparation of this report, indicate that monitoring is perceived as useful towards ensuring site safety, protecting groundwater resources, safeguarding the environment, minimising the possibility of induced seismicity, identifying possible leakage, and providing information on CO_2 emissions reductions.

The outcomes of the local societal assessment will provide monitoring criteria and indicators for further development and improvement of the DigiMon monitoring system, as well as requirements and design specifications for best practice monitoring systems.

Relevant monitoring system aspects to societal acceptance include the monitoring system contribution to:

- reducing or preventing CCS environmental impact;
- engaging organizations or individuals involved or affected by CCS;
- developing and complying with CCS policies and regulations;
- mobilizing market and financial resources for CCS projects.

A summary WP1 work relevant to each of these aspects is given below.

3.2 Relevance to DigiMon technologies

3.2.1 Overview

The relevance of developed DigiMon CCS monitoring technology components to societal aspects are graphically summarized in Figure 1 and are analysed in detail below.

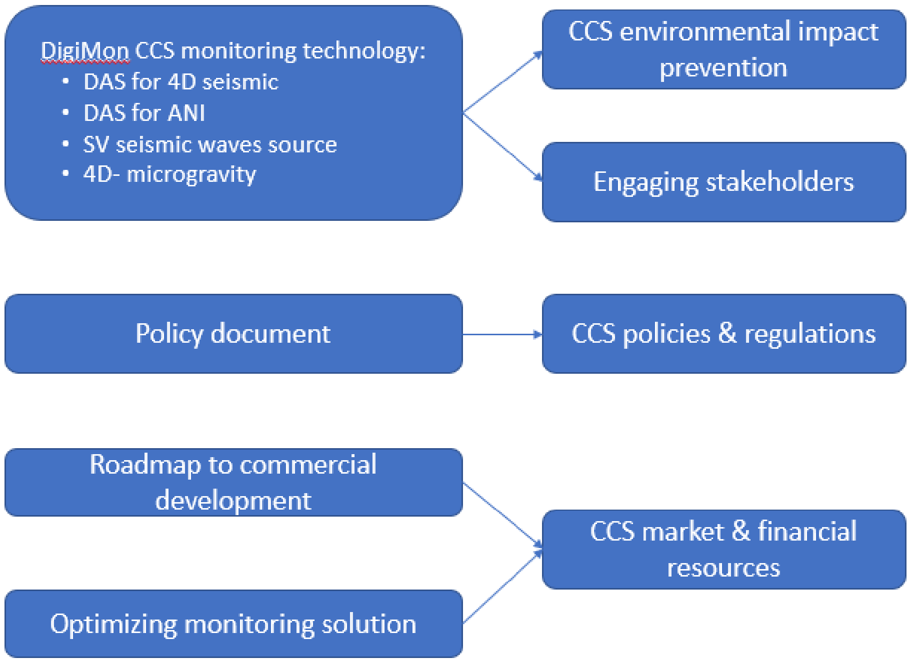

Figure 1. Relationship of DigiMon technological developments (left) with requirements for a societally embedded monitoring system (right).

3.2.2 Contribution to reducing or preventing environmental impact of CCS

Technological developments during WP1 are all directly related to the environmental dimension of the societal embeddedness, by providing cost efficient methods to monitor and reduce the impact to the environment of CO_2 geological storage.

Fibre-optic monitoring can provide long-term monitoring solutions and reduce the mobilisation required for monitoring surveys, hence reducing the environmental impact. Work in WP1 has focussed on developing processing methods for fibre-optic Distributed Acoustic Sensing (DAS) data to raise the Technology Readiness Level (TRL) and improve the applicability of the technology. The instrument response and site response determination (Task 1.2) of DAS systems allows recordings to be converted to velocity in a similar way to the conventional methods used for geophones. This permits a DAS fibre-optic system to map the subsurface seismic velocity field in a geological storage site. The evolution of the seismic velocity field over time can provide an image of CO_2 plume location and expansion, as well as an early warning of potential CO_2 migration into the water table or potential leakages at the sea floor or ground surface. The development of processing techniques for microseismic DAS data, i.e., the detection of very small seismic events, (Task 1.3) enables the data to be used for microseismic monitoring. This type of monitoring can highlight faults that contribute to induced seismicity risk. Understanding the size and orientation of these faults helps form a more complete understanding of the risk of induced seismicity and CO_2 leakage. DAS is now often deployed in-well for onshore CCS projects. The technology is yet to be deployed for an offshore project.

4D seismic can provide qualitative information on the outline of the CO_2 plume. The advantage of DAS advantage is the low cost, the ability to cover a wide area with continuous measurement sampling (e.g. every metre) and time lapse (4-D) recordings, while the corresponding equipment (fibre and electronics) can be installed on permanent basis within wells or at surface. Work to understand suitable deployment scenarios for DAS for this purpose is ongoing.

The application of DAS fibre-optic in ambient noise interferometry (ANI) surveys further expands available options in this aspect. For the purposes of monitoring CO_2 storage sites using DAS, ANI has the potential to provide cost-effective, repeatable measurements for early warning of leakage. Potentially fibre-optics combined with ANI could offer wire-line operation free permanent CO_2 storage monitoring capability. This is yet to be fully tested at a CCS site.

The development of instrumentation, data processing, modelling and visualization tools of a novel SV seismic waves generating source (Task 1.4), provides the full suite of seismic sources for crosswell surveys to image CO_2 in the subsurface. The use of DAS fibre-optics for cross well seismic velocity tomography has also been tested. Cross well seismic velocity tomography in essence provides direct calibration to depth of seismic surveys, making CO_2 plume mapping possible. Crosswell surveys are possible in onshore and offshore but logistically they are difficult and expensive offshore. Crosswell surveys can be particularly useful where it is possible to do surveys at depths greater than 400 m, where seismic velocity calculations accuracy from surface recordings alone drops below the level required to identify velocity changes related to CO_2 movement. Cross-well seismic experiments could be enhanced or made more cost effective by a distributed acoustic sensing (DAS) fibre.

The development of a new fibre for CO_2 detection and testing it via laboratory experiments coupled to modelling CO_2 diffusion in fibre (Task 1.5), will allow direct detection of CO_2 leakages in the environment. This is particularly important for monitoring well integrity, which can provide early warning for an incoming well failure and potential CO_2 leaking through it. This technology is still at the laboratory testing phase.

The development of data acquisition techniques and processing software for a time lapse microgravity survey (Task 1.6) will provide another accurate and cost-efficient method for subsurface CO_2 plume mapping and evolution, by defining the subsurface density distribution. Coupling with a distributed strain sensing (DSS) fibre-optic system will provide a cost-efficient mapping of seafloor or ground surface deformation and the necessary calibration to the density data. 4D gravity is valuable to quantify the mass changes within the reservoir, the density of the CO_2 plume and thereby the fraction of dissolved CO_2 in brine.

3.2.3 Contribution to and meeting CCS policies and regulations

The policy document that will be prepared and delivered to policy makers (Task 1.9), describing the aspects of the WP1 technologies that could and should influence CCS policy, will provide valuable insights on how a monitoring system can contribute to developing suitable policies and regulations and how to meet those policies and regulations.

3.2.4 Contribution towards mobilizing the market and financial resources of CCS projects

The roadmap towards commercial delivery and implementation of WP1 technologies (Task 1.7) that will be prepared will be a key aspect of defining the CCS projects market offer. The testing of monitoring set-ups for permanent seismic reservoir monitoring (PRM) of Task 1.11, will optimize monitoring costs by fine tuning the subsurface imaging resolution. Efficiencies in data collection and processing of gravity and seafloor deformation (Task 1.6) have been made to reduce costs. The further development of distributed fibre-optic technology has the potential to reduce monitoring costs (Tasks 1.2 and 1.3).

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DigiMon Deliverable 1.1 add2: DAS field dataset to compare technologies and deployment scenarios – CaMi, FRS, Canada Dataset

DigiMon Deliverable 1.1 add3: DAS field dataset to compare technologies and deployment scenarios – Svelvik, Norway

DigiMon Deliverable 1.8: Feasibility of using distributed chemical sensing for CO_2 leakage monitoring

DigiMon Deliverable 1.9: Improved algorithms to acquire and process gravity and deformation data Digital monitoring of CO_2 storage projects

DigiMon Deliverable 1.14: Report on optimisation of seafloor deployments for PRM

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