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Digital monitoring of CO2 storage projects (DigiMon)

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Abstract

With an overall objective to "accelerate the implementation of CCS by developing and demonstrating an affordable, flexible, societally embedded and smart Digital Monitoring early-warning system", the DigiMon project aims to combine different technologies for monitoring CO_2 storage into a uniform system. The project includes qualification of critical system components, integration of the components and embedding the system in a societal context.

Keywords: CO_2 monitoring, MMV, containment, conformance, contingency, geophysics, DxS, DAS, DCS, seismic, gravimetry, sensors, societal embeddedness

1. Introduction

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.

Technical verification of integrated systems and determination of the effect on (the quality of) measurements is challenging, especially when combining legacy and new technologies. Furthermore, the societal embeddedness of CCS is also important for the deployment of new technologies and is closely linked to perception of technological quality and reliability by societal stakeholders, and that of environmental impact in case of failure. Commercially, market introduction of any new system approach is challenging, both technology optimization and market needs must be addressed, to maximize cost/benefit ratios for customers and the CCS value chain.

The DigiMon monitoring system will be developed having both technical and societal requirements in-mind. A well-designed co-creation process with (local) stakeholders, using the novel tool of "Societal Embeddedness Level methodology" (SEL), will ensure that the developed monitoring system will both be technically feasible and fulfill societal requirements.

2. The DigiMon project

To accelerate the implementation of CCS, by cost effective monitoring of any CO_2 storage reservoir and subsurface barrier system, receiving CO_2 from process plants and other industries, the DigiMon concept combines distributed fibre-optic sensing technology (DxS), seismic point sensors, seafloor deformation monitoring and micro-gravimetry with proven ethernet-based digital communication and real-time, web-based smart data processing software.

The DigiMon project involves development and integration of system components that are available at intermediate to high Technology Readiness Levels (TRLs). It will develop the system components to a uniformly high TRL, prior to integration of components into the DigiMon early-warning system.

Sub-objectives for the project are to:

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 with the public and policy makers.

2.1. Monitoring system layout

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 focus of the DigiMon concept is on geophysical monitoring (Figure 1).

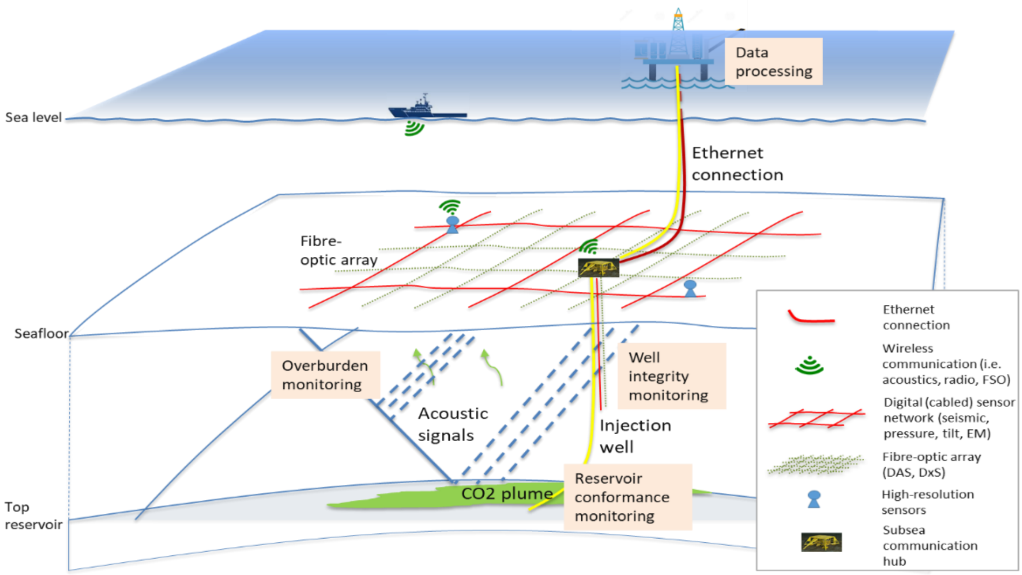

Figure 1: The DigiMon Digital Monitoring System

Referring to the overall objective of the DigiMon project to "materially accelerate the implementation of CCS by developing and demonstrating an affordable, flexible, smart and societally embedded Digital Monitoring early-warning system", the project will address:

- Monitoring the plume movement in the reservoir mainly using remote passive geophysical measurements of changes in saturation and pressure (Conformance monitoring).
- Monitoring well integrity, mainly with downhole sensing (Containment and Contingency monitoring).
- Monitoring the overburden, including monitoring of above-zone CO_2 migration and early detection of CO_2 leakage anomalies (Containment and Contingency monitoring).
- Integration of societal requirements for monitoring CO2 storage

The critical technology elements in DigiMon project include instrumentation and data acquisition and processing techniques for both active and passive seismic surveys; 4D gravity; seafloor deformation; and chemical sensing of CO_2. The project aims to raise the TRL of individual technologies for application to CCS monitoring and the progress made on the development of individual monitoring system components will be accounted for in the design and recommendations for the DigiMon monitoring system. Furthermore, participative research with various stakeholders and citizens both at national and local level will give insight in the main societal requirements and how they could be included in the development and implementation of the DigiMon monitoring system. Besides high TRLs this also contributes to a socially embedded DigiMon system.

3. Results

The DigiMon project is proceeding according to plan and below we highlight current results from the project.

3.1. Critical technology elements

The work on passive and active seismic monitoring consists of several strands. Fibre-optic Distributed Acoustic Sensing (DAS) is a relatively new tool for seismic data acquisition and the research in this area involves small-scale laboratory tests to understand the response of fibre-optic cables to seismic waves (Figure 2). Additionally, active and passive seismic field data collected as part of the project and provided by project partners are being used to develop processing workflows for DAS data. The aim is to determine if and when DAS technology can complement, enhance, or even replace traditional seismic instruments. There is also advancement in seismic data collection with the development of a new SV seismic source, to be field tested in 2021.

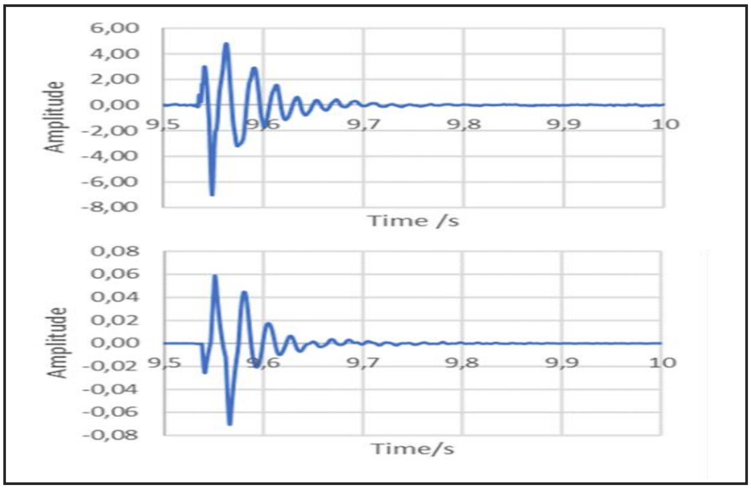

Figure 2. Example results from laboratory experiments comparing the response of a fibre-optic cable and geophones to seismic signals.

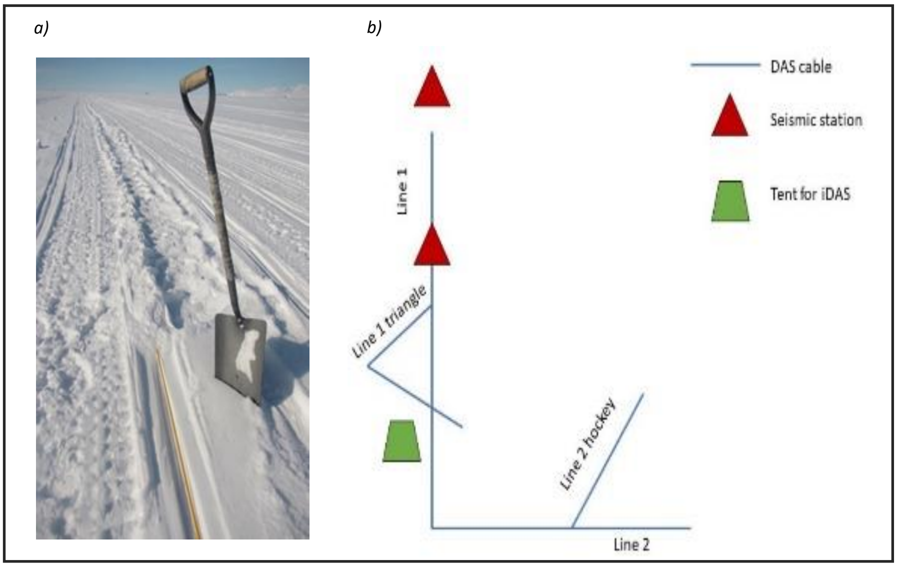

Figure 3. a) DAS surface cable deployment in Antarctica (Photo: Mike Kendall, University of Oxford) b) DAS array set-ups for active and passive seismic data collection. Data were collected with different array configurations: linear, triangular (Line 1 triangle) and a "hockey stick" (Line 2 hockey). Reftek seismic instruments were also deployed to record data.

To date modelling techniques have been developed to produce synthetic DAS data [1] and workflows have been advanced to detect and locate microseismicity recorded on fibre-optic cables [2]. Passive and active seismic DAS and geophone data collected in Antarctica, where the fibre-optic cable is well coupled to the ice (Figure 3), show that DAS provides data with good signal to noise ratio (SNR). The dense spatial sampling of DAS facilitates techniques such as data stacking to improve the SNR and hence seismic event detection [3]. Array configurations have been tested to analyse the effect on recorded signal quality and also on seismic event location capabilities. Non-linear arrays provide extra constraints on microseismic event locations to help overcome the one-component nature of DAS recordings.

3.2. Integrating the components

To combine distributed fibre-optic sensing technology (DxS), seismic point sensors, seafloor deformation monitoring and micro-gravimetry we propose a stochastic inversion method. This workflow to monitor CO2 saturation and pressure distributions is illustrated in Figure 4. Input to the method is a prior ensemble of model parameters that are generated from fluid flow simulations utilizing different permeability and porosity distribution representing the geological uncertainty in the reservoir models. The outcome of the analysis is the most likely solution and an estimate of the uncertainty in the estimated model parameters. The proposed workflow is tested on the Johansen formation which is a deep saline aquifer in the North Sea [4]. The simulated time-lapse geophysical data (here time-lapse seismic and gravity data) are computed covering 75 years of CO2 injection for each realization. The obtained results illustrate how efficiently the CO2 plume distribution can be monitored by combining time-lapse seismic and gravity data while integrating fluid flow information as constraints in the stochastic inversion algorithm.

As part of the project, a field test will be conducted to assess the use of DAS data in wells for cross-well tomography. In addition, we will investigate into the value of expanding the conventional seismic data sets with both the horizontal and vertical shear wave components through the incorporation of a novel shear wave source. To find the most reliable field test measurement setup, we have modelled travel times on an unstructured mesh and their inversion for the underlying slowness distribution for a tomographic cross-hole scenario (Figure 5). In this cross-hole experiment fibre-optic sensors will be utilized that will allow higher resolution with higher sensitivity to smaller inhomogeneities.

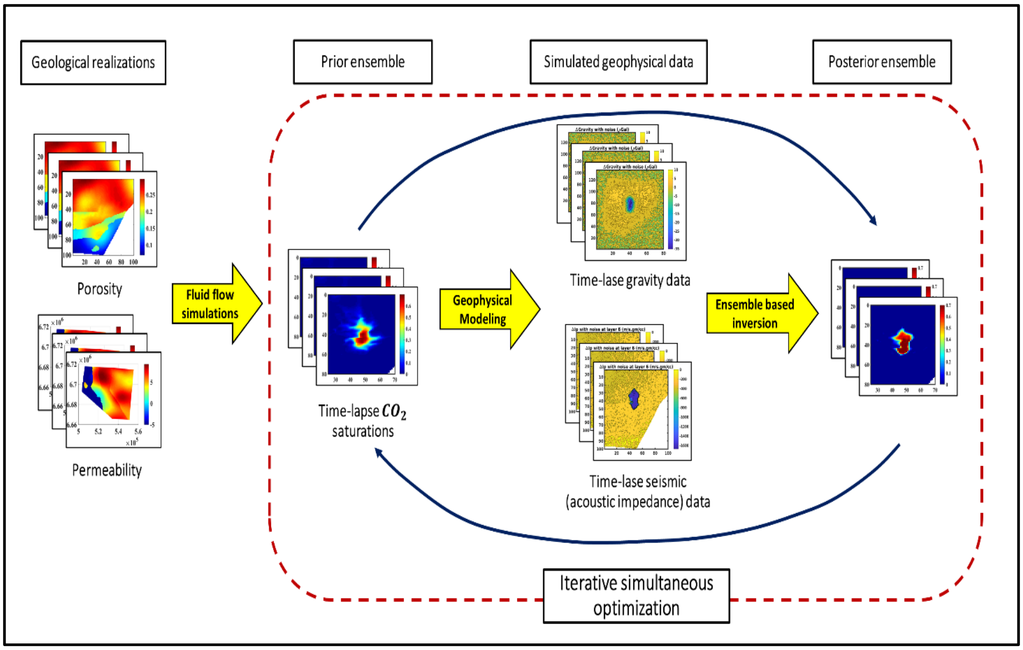

Figure 4: Workflow of ensemble-based inversion algorithm. Here, time-lapse gravity and seismic (acoustic impedance) data are used to estimate time-lapse CO2 saturations.

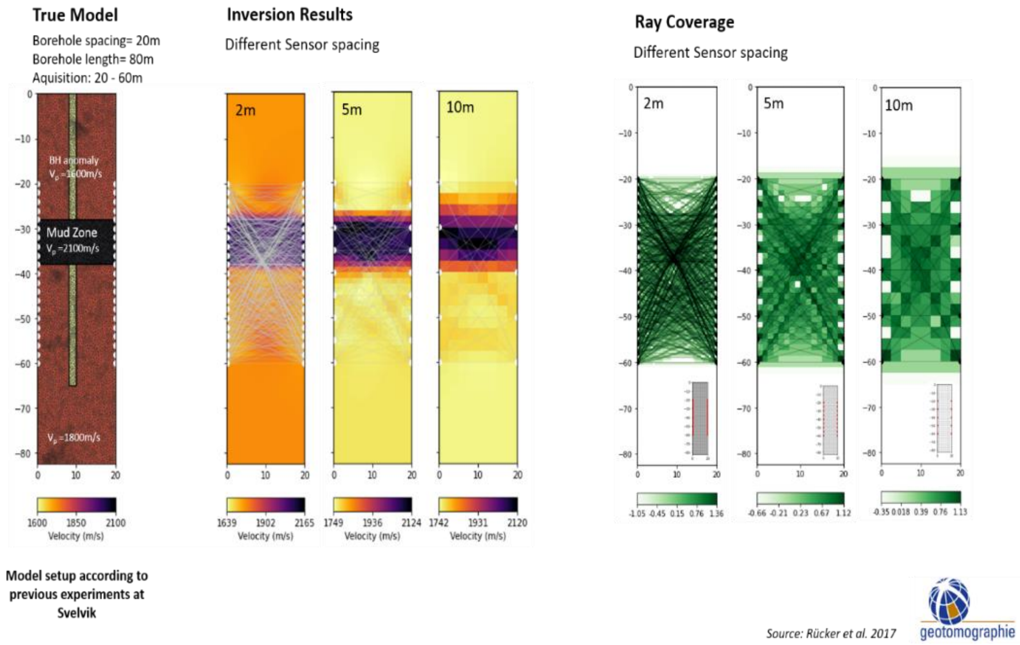

Figure 5: Tomography cross-hole workflow

3.3. A human centered monitoring system

Both technical factors and non-technical factors influence the readiness of a technology for implementation and should be part of the development process. Many studies show that societal aspects influence the development of an innovation and can delay or hamper the implementation process. In practice, we see a strong focus on the technical readiness of an innovation (TRL method), which is not sufficient for deployment of a technology in its societal context. Therefore, the Societal Embeddedness Level (SEL) Methodology developed by TNO has been adapted in DigiMon as a vehicle to pay better attention to the societal aspects in technology development.

The SEL methodology builds upon the Technology Readiness Level (TRL), which assesses the maturity of technologies. The SEL is related to the TRL: for a low TRL a low SEL is sufficient, but the closer to deployment (high TRL), the higher the SEL of a technological innovation should be, taking into account all relevant societal requirements. If there is a discrepancy between the TRL and SEL– e.g. a high TRL and a low SEL – not all societal requirements are met, and the existing societal challenges need to be dealt with to reach societal embeddedness at the corresponding TRL level. Figure 6 shows the relation between the TRL and SEL [5].

The SEL methodology distinguishes four levels of societal embeddedness and four societal dimensions, see figure 7. The four societal embeddedness levels – which correspond to the TRL levels - are: SEL 1 Exploration, SEL 2 Development, SEL 3 Demonstration and SEL 4 Deployment. In each level four societal dimensions are taken into account: (1) Environment, (2) Stakeholder involvement, (3) Policy and Regulations and (4) Market and Financial Resources. These four dimensions influence the societal embeddedness of a technological innovation. [5].

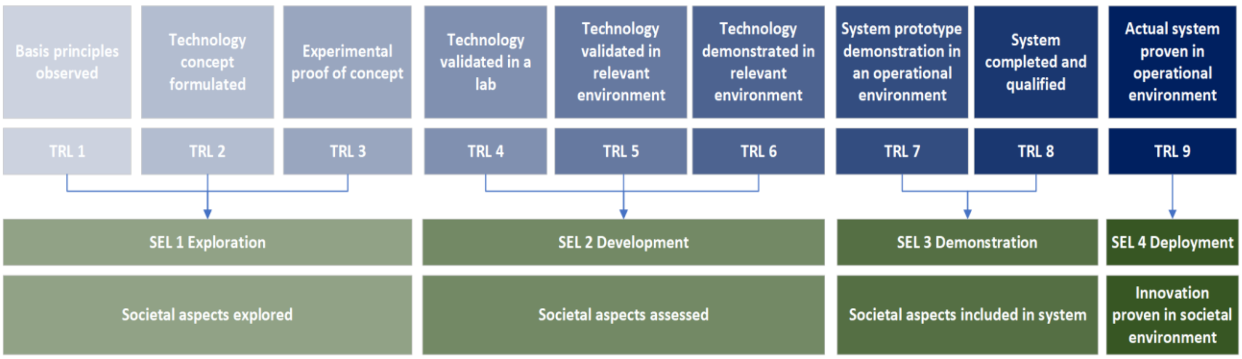

Figure 6: Correspondence between TRL and SEL

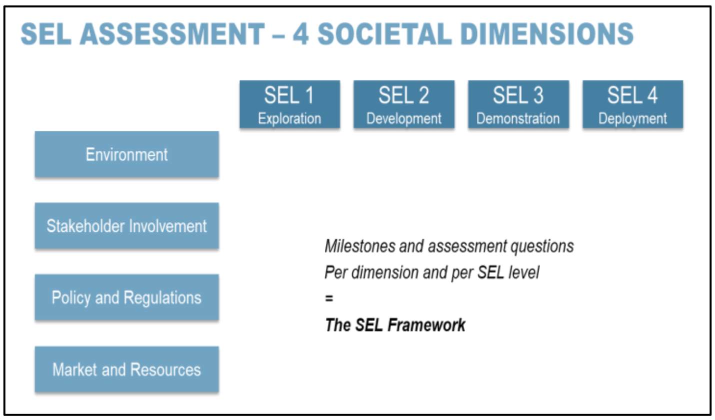

Figure 7: The SEL framework

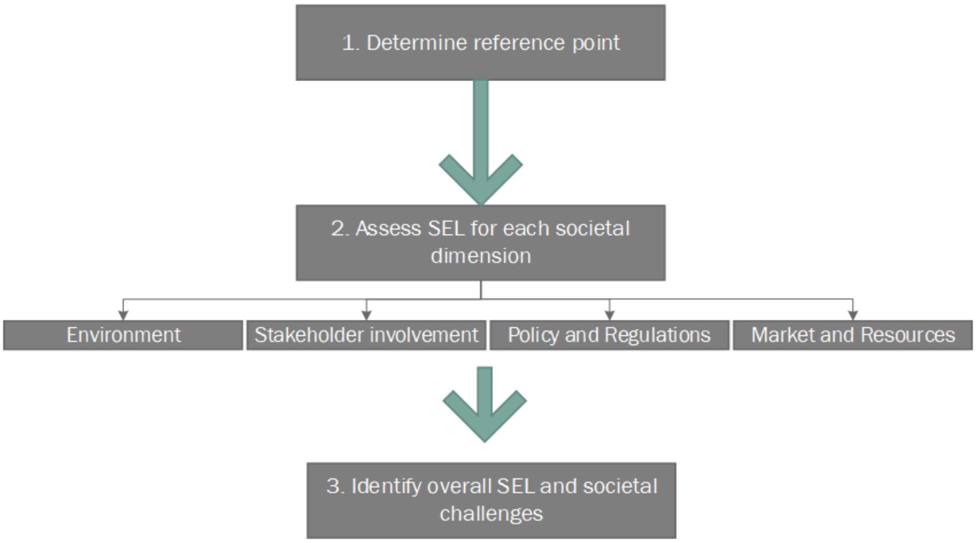

Figure 8: Stepwise process to assess the SEL of a technological innovation.

In the DigiMon project, the SEL assessment will be applied on CCS in four national case studies [6] as well as on the DigiMon monitoring system in four local case studies. These case studies give insight in the main societal requirements for monitoring activities regarding CCS and for the deployment of the DigiMon system more specific. Furthermore, the case studies provide insight in the value and applicability of the novel methodology Societal Embeddedness Level (see figure 8). By organizing a participative research process, perspectives of different stakeholders on both national and local level can be identified. The interdisciplinary process as a leading principle within the DigiMon project ensures that the outcomes of the SEL research will be connected with the technical research for developing the DigiMon monitoring system.

4. Conclusions

By integrating various technologies and system components and developing methods for uncertainty quantification at both component and system level, the DigiMon project demonstrates how a holistic and flexible monitoring system for CO_2 storage can be assembled. The combined technical and societal approach enables appropriate communication of monitoring strategies to accommodate concerns and risk of stakeholders and the public.

Acknowledgements

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