Risk-based framework for Compliance Assessment and CO_2 Geological Storage Monitoring: Application in the Getica CCS Study

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Abstract

Geological CO_2 storage is one of the key solutions for reducing greenhouse gas emissions, but its successful implementation depends on developing effective monitoring strategies and compliance assessment frameworks. This paper presents a risk-based monitoring methodology for CO_2 storage, based on the experience gained from the feasibility study of the Getica CCS project, which aims to store CO_2 in saline aquifers. The monitoring plan developed within Getica CCS ensures compliance with European and international regulations while demonstrating the safety and efficiency of the storage process. It integrates a comprehensive set of monitoring technologies, including geophysical, geochemical, and reservoir engineering methods. Geophysical monitoring is a core component of the plan, utilizing advanced technologies such as 4D seismic based on distributed acoustic sensing (DAS) and seismic nodes. These methods allow for detecting any changes in the geological structure of the saline aquifer and identifying potential risks associated with CO_2 migration. Additionally, gravimetric and ground deformation measurements are employed to assess the behavior of the geological formation and detect any variations in pressure and mechanical stresses. Geochemical monitoring plays a crucial role in verifying CO_2 storage safety and identifying possible chemical interactions between CO_2 and the host formation. The monitoring plan includes isotopic analyses and CO_2 concentration sensors in groundwater to detect potential leaks and assess the system's chemical stability. These methods are complemented by analyses of dissolved gas composition and measurements of pH and alkalinity, providing essential data on the geochemical balance of the site. Furthermore, the monitoring plan incorporates an advanced pressure and temperature monitoring system within the reservoirs, using dedicated probes and numerical modeling to predict the long-term evolution of the CO_2 storage site. This approach enables the adjustment of operational strategies to ensure long-term storage security. Another important aspect analyzed in this study is the integration of risk perspectives and monitoring strategies from different European countries. The Getica CCS project serves as a concrete example of how these methods can be applied in the specific context of saline aquifers, contributing to the development of best practices for future CO_2 storage projects. This paper highlights the importance of integrated and risk-based monitoring for ensuring compliance and operational safety in CO_2 storage projects. The lessons learned from Getica CCS demonstrate the necessity of using advanced technologies and a multidisciplinary approach to guarantee efficient and sustainable CO_2 storage, offering a replicable model for future carbon capture and storage initiatives.

Keywords: *monitoring, reservoirs, storage, aquifer, pressure*

1. Introduction

The investigated area was chosen as a circle with a radius of 50 km around the Turceni Energy Complex. This zone covers a small part of the western sector of the Moesian Platform and the Getic Depression.

In this area, only the saline aquifers within the Tertiary formations are considered suitable to serve as CO_2 storage reservoirs.

These formations are located at depths (greater than 800 m and less than 3000 m) that are suitable for serving as storage reservoirs in a CCS (Carbon Capture and Storage) project. A reservoir must be located at depths greater than 800 m for the CO_2 to be in a supercritical state, but not too deep in order to avoid increased well construction costs and, consequently, higher capital investment.

The Tertiary formations have been more thoroughly studied over the years due to oil and gas exploration and exploitation activities.

Based on the criteria described in the previous chapter, 7 potential storage zones have been selected within the investigated area (fig. 1). Following the previous analysis conducted for each site, we selected two zones (Zones 1 and 5-fig.1) that meet the best conditions for geological CO_2 storage.

This selection was made based on the following criteria:

- The total volume of the reservoir rock, which is approximately 860 x 10^9 m³ (for Site 5) and 72.55 x 10^9 m³ (for Site 1-fig.1);
- The sedimentary sequences have created stacked structural-stratigraphic traps with varying extents in the case of Site 5, and only one trap in Site 1;
- The closure of the traps is well-defined for sequences S3–S5 (Site 5-fig.2) and S5 (Site 1);
- The caprock is well-developed, thick, and continuous in both sites;
- The reservoir's permeability and porosity are favorable.

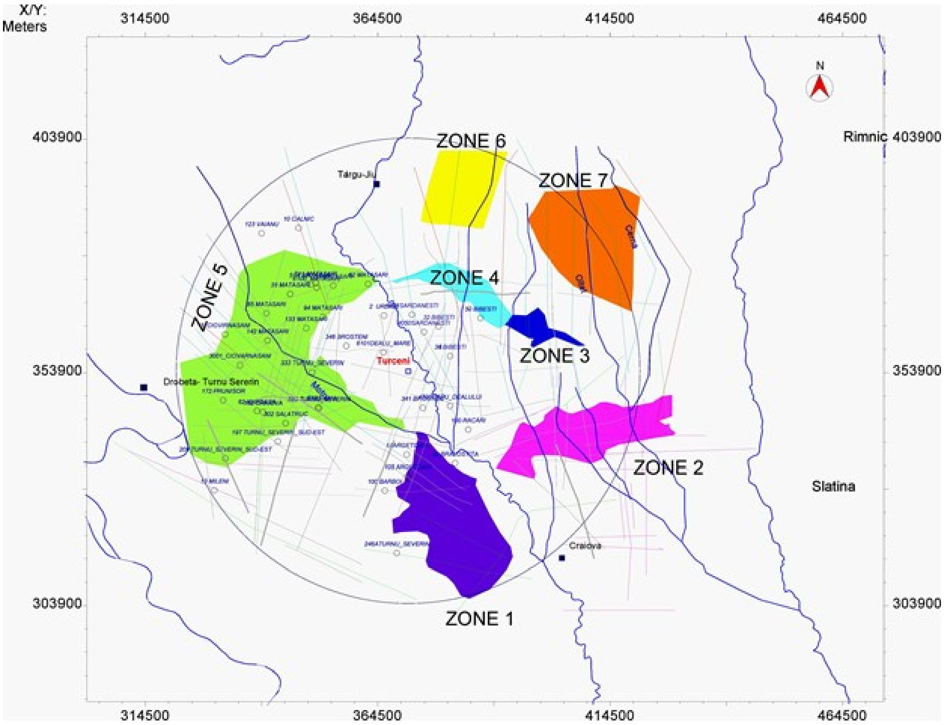

Fig. 1. Location of potential CO_2 storage sites

Monitoring activities will be performed on the selected storage sites with the aim of managing the performance of the injection operations and controlling the risk inherent to storage, pursuant to the obligations laid in Annex II of the EU Directive 2009/31/EC and its implementation Guidelines .

The aim of this report is to define which monitoring technologies are required, and for which goal. Most of the objectives of a monitoring plan are straightforward to achieve, and technologies need to be selected among possible technologies listed in Table 2, as described in paragraph 1.1. Technology selection to monitor "CO2 displacement and fate" and for "detection of leaks/migration" is more complicated to address because the applicability of available technologies to the geological environment considered for injection must be evaluated first.

For Zone 5, to monitor "CO2 displacement and fate", we find that time-lapse seismic, time-lapse surface deformation measurements (InSAR) and time-lapse gravity are applicable. These are global technologies and will acquire information for the entire field in one acquisition. Some local technologies, which will acquire information within a few hundred meters from one monitoring well are also applicable: time-lapse cross-well seismic, time-lapse cross-well electro-magnetic and time-lapse Vertical Seismic Profile. Time-lapse well logging will acquire very accurate measurement at the well, and is applicable in this case as well: sonic logging, cased-hole neutron porosity, cased-Hole resistivity logging, pulsed neutron logging[1]. Finally, point measurements, consisting in pressure and temperature measurements work in any geological environment, and are applicable as well. To fulfill the objective "detection of leaks/migration", only time-lapse seismic and pressure and temperature measurements seem appropriate measurement in this geological context.

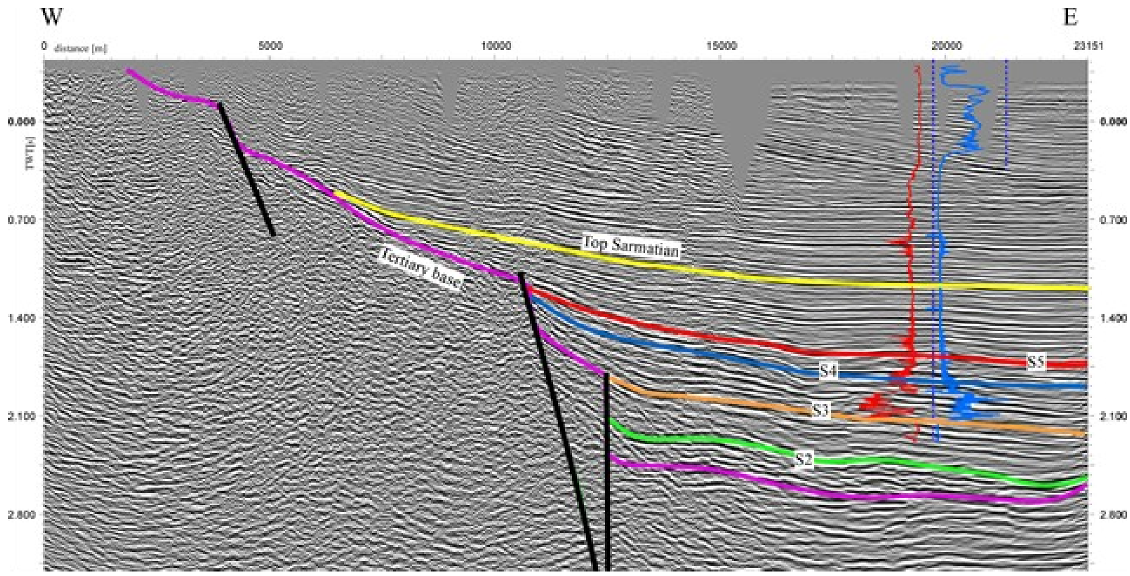

Fig. 2. Interpreted seismic profile no. R05Z01

For Zone 1, the main difference is that seismic/sonic technologies might not reach detectability level for all expected CO2 plumes, which include time-lapse 3D (2D seismic), time-lapse cross-well seismic, time-lapse Vertical Seismic Profile, and time-lapse sonic logging. Of course, additional seismic forward modeling should be run to assess this conclusion, once more data becomes available to better constrain the geological environment. We also find that time-lapse gravity will be below detectability level.

For both Zone 5 and Zone 1, we find that two main strategies could be followed, that would answer both monitoring objectives simultaneously, monitor "CO2 displacement and fate" and "detection of leaks/migration". The first strategy relies on repeat 3D seismic surveys. These repeat surveys could be spaced through time if alternative cheaper technologies, such as surface deformation measurements (InSAR), are used to fill the gap. The second strategy relies on using a number of monitoring wells, equipped with pressure and temperature gauges[2]. This second strategy would make it possible to use additional well log measurements that would provide accurate distributions of CO2 saturation at the monitoring wells.

2. Methodology

Preliminary monitoring plan for Zone 1

In order to comply with the requirements of the European Directive 2009/31/EC on Carbon Capture and Storage, a number of objectives must be considered and addressed as part of three components: operation, verification, and ensuring the proposed monitoring plan. These objectives include: Control of the injection operation, Quantification of injected CO_2, Integrity of the fault/protective formation system, Integrity of the wells, CO_2 displacement and behavior, Impact: monitoring of environmental factors (HSE), Detection of migration/leakage pathways and Quantification of reservoir leakage.

The portfolio of applicable monitoring measures includes: monitoring of injection operations (control of injection operations), verification monitoring (integrity of the fault/caprock system), and safety monitoring (impact: HSE monitoring). Injection operation control refers to monitoring the injection wellhead pressure as well as the pressure and temperature at the bottom of the well. The integrity of the fault/seal system refers to microseismic activity and pressure influence, while well integrity focuses on monitoring downhole pressure and temperature profiles. For monitoring CO_2 displacement and behavior, both pressure and temperature will be evaluated using global and local geophysical techniques. Within injection operation monitoring, the quantification of injected CO_2 involves data on mass and volumetric flow rates, as well as CO_2 flow characteristics: composition, pressure, temperature, and phase. Safety monitoring measures include: HSE impact monitoring (drinking water quality, atmospheric concentration, and R&D-based approaches), detection of migration pathways (pressure, temperature, caprock testing, soil gas measurements, and geophysical methods—global, local, and logging), and quantification of reservoir leakages (addressed solely from a research and development perspective).

In Zone 1, several monitoring technologies are considered for inclusion in the monitoring plan, each with varying applicability for CO_2 plume tracking and leak detection[3].

3D Seismic is included in the monitoring plan and is applicable for both monitoring the CO_2 plume and detecting leaks. Gravimetry is not included in the plan and is not considered suitable for either CO_2 plume monitoring or leak detection. InSAR (Interferometric Synthetic Aperture Radar) is included and is applicable for both plume monitoring and leak detection.

Soil and gas measurements are useful for detecting leaks and offer delayed detection of the CO_2 plume. Cross-well Electromagnetic (EM) and Cross-well Seismic are not included in the monitoring plan. Vertical Seismic Profiling (VSP) is marked as possibly applicable, depending on conditions.

Sonic logging, cased-hole neutron porosity logging, cased-hole resistivity logging, and pulsed neutron logging are all marked as possibly applicable, depending on site-specific factors.

Temperature and pressure measurements in wells are included in the plan and are essential for both plume monitoring and leak detection. Fluid sampling is also included in the monitoring plan and helps analyze injected CO_2 characteristics.

Sonic/ultrasonic logging for cement bonding and casing integrity verification is included to ensure wellbore integrity. Borehole microseismicity monitoring is used as an indirect method, focusing on pressure front movement rather than direct plume visualization, and is included in the plan. Finally, flowmeters are included and are necessary to quantify the injected CO_2, by providing information on mass and volumetric flow, as well as CO_2 composition, pressure, temperature, and phase. The five presented technologies have been identified as potentially acceptable for monitoring the CO_2 plume in deep monitoring wells where the presence of CO_2 is expected.It is estimated that an optimal combination of some of these five technologies could be used to achieve the objective, and that it will not be necessary to implement all five.

At this stage, no specific selection has been made for the purpose of cost estimation. The uncertainty in the estimate refers to the overall amount required for the proposed well logging monitoring, as reflected in the preliminary cost model, which also includes in-well fluid sampling.

Permanent Sensors and Periodic Measurements – Monitoring Plan Overview

Permanent Sensors:

- Flow Meters: Installed on each injector, these will operate continuously throughout the entire injection period to monitor injection flow rates.
- Pipeline Flow Meters for Custody Transfer: Used for monitoring flow during the transfer of custody of the storage site.
- Wellbore Microseismicity Sensors: Installed on one injector or monitoring well. The current budget allows for microseismicity monitoring in only one well.
- Distributed Temperature Sensing (DTS): Implemented in several injectors to monitor distributed temperature profiles along the wellbore.
- Well Pressure Monitoring: Pressure will be measured at the wellhead for all monitoring and injection wells. Bottomhole pressure will also be measured in selected wells.
- Soil Monitoring: Conducted near injectors and legacy wells to detect any surface anomalies or potential leaks.
- Air Monitoring: Performed across the entire area, with a focus on regions around injectors and known fault lines[9].

Periodic Measurements:

- Sonic/Ultrasonic Logging in Cased Wells: Carried out in injection wells to monitor casing and cement integrity, every 2–3 years. In deep monitoring wells, these logs will also be performed 2–3 times during CO_2 plume migration and every 4–5 years post-injection, including cement and casing monitoring.
- Fluid Sampling: Performed in monitoring wells where CO_2 is expected. Each well will be sampled 2–3 times during the CO_2 plume's migration. In shallower wells (for potential leak detection), the frequency will be determined during ACT-3-ST-1 in coordination with authorities.

- Pulsed Neutron, Cased-Hole Resistivity, Neutron Porosity[4], Sonic Logging, and Vertical Seismic Profiling (VSP): These logs will be conducted only in wells where CO_2 is anticipated. Each well will undergo 2–3 measurements during the plume migration.
- 3D (or 2D) Seismic Surveys: One baseline measurement will be taken before injection (Phase 2). Subsequent surveys will combine 2D and 3D acquisitions focused around the injectors, approximately every 7 years post-injection.
- InSAR (Interferometric Synthetic Aperture Radar): Performed every 5 years to detect surface deformation associated with subsurface CO_2 migration.

Data from the permanent sensors will be collected as part of the monitoring management program. This program will enable instant access to key injection parameters and support decision-making related to the site. For example, if a discrepancy is observed between the planned and actual injection parameters, the supervision team will implement a corrective action plan to resolve the issue.

The monitoring management program[5] will allow access to the full dataset from the start of the monitoring phase, enabling continuous risk and efficiency assessments. This ongoing evaluation may lead to necessary adjustments to the injection strategy and operational plan.

Preliminary monitoring plan for Zone 5

The general observations made regarding the monitoring plan for Zone 1 also apply to Zone 5. Regarding Zone 5, the results are largely similar to those for Zone 1, except for those related to 3D seismic, which appear more promising for Zone 5. However, the preliminary decision to include 3D seismic in the monitoring plan is positive in both cases.

The monitoring technologies for Zone 5 and their applicability in the preliminary monitoring plan include the following:

3D Seismic – This technology is included in the plan as it is applicable for both monitoring CO2 plumes and detecting leaks[8].

Gravimetry – This technology is not included in the plan, as it is not applicable for monitoring CO2 plumes or detecting leaks in this specific geological environment.

InSAR (Interferometric Synthetic Aperture Radar) – This technology is applicable for monitoring CO2 plumes and detecting leaks, and is therefore included in the plan.

Soil & Gas Measurements – These are suitable for detecting late-stage leaks and are included in the plan for leak detection.

Electromagnetic (EM) Between Wells – This technology is not included in the monitoring plan due to its lack of applicability in detecting CO2 migration or leakage.

Seismic Between Wells – This technology is not included, as it does not provide the necessary data for monitoring CO2 plumes or leak detection in this environment.

Vertical Seismic Profiling (VSP) – This technology is possible for use in the monitoring plan, as it can help in detecting CO2 plumes in certain conditions, but it is not fully confirmed.

Sonic Logging[7] – This technology is also possible for use in the monitoring plan. It can be used to measure conditions within the wellbore, though it may not be universally applicable in all conditions.

Neutron Porosity Logging in Cased Hole – This technology is possible for monitoring CO2 plumes in wells, though its applicability will depend on specific site conditions.

Resistivity Logging in Cased Hole – Similar to neutron porosity logging, this technology is possible for inclusion, depending on specific conditions and its ability to provide data on CO2 migration.

Pulsed Neutron Logging[6] – This is another possible technology for use in monitoring CO2 plumes, though its applicability will depend on the geological setting.

Temperature and Pressure Measurements in Wells – These are confirmed as applicable for monitoring CO2 plumes and are included in the monitoring plan.

Fluid Testing – This technology is applicable for wells expected to have CO2 presence and is included in the monitoring plan.

Sonic/Ultrasonic Logging for Casing and Tubing Integrity – This technology is applicable and included in the plan to monitor the integrity of the well casing and tubing over time.

Microseismicity in the Wellbore – Monitoring only the pressure front is considered an indirect measurement method, and this is included in the plan for monitoring potential CO2 migration or leakage.

In conclusion, the preliminary monitoring plan for Zone 5 includes a combination of technologies, some of which are more universally applicable than others, but all are aimed at addressing the primary objectives of CO2 plume monitoring and leak detection.

The five technologies presented have been identified as potentially acceptable for monitoring CO2 plumes in deep monitoring wells where the presence of CO2 is expected. It is estimated that an optimal combination of some of these five technologies could be used to achieve the goal, and that all five will not be necessary.

Given that the lack of data prevents us from distinguishing between the two zones and that the results of the monitoring technology evaluation are similar, the proposed preliminary monitoring plan is the same for both zones. As a result, the recommendations presented for the use of permanent and periodic sensors also apply to Zone 5.

3. Conclusions and recommendations

Table 1 summarizes the conclusion of the feasibility studies reported to CO_2 plume tracking:

- time-lapse seismic and sonic technologies (3D seismic, cross-well seismic, VSP, sonic logging): an appropriate log suite needs to be acquired in order to be able to make clear conclusions. Once this appropriate log suite is acquired, this study should be repeated, and then forward modeling should be run. Such a log suite will allow us to check whether assumptions made in this work are correct. At this stage, if we assume that our assumptions are correct, detectability should be reached, butonly in regions of the plume where porosity and CO2 saturations are sufficiently high.

- time-lapse gravity from surface: here, 5 injection wells are expected to be needed. Thus, total CO2 mass is split into five spots. In these conditions, detectability will be reached only after 13 years of injection, and only for two injection wells (INJ1N and INJ3N). This makes gravity an appropriate tool for late monitoring of the CO2 plumes coming out of INJ1N and INJ3N, but not in the early stages of injection.

- time-lapse surface deformation (InSAR): we would like to point out here that this is the only technology sensitive to the pressure front and not the fluid front. Again, the appropriate log suite needs to be acquired so as to check that our assumptions are in agreement with actual overburden deformation. If this is the case, surface deformation will reach detectability levels after only one year of injection, and will be above detectability during the entire injection and monitoring phases.

- time-lapse electro-magnetic technologies (cross-well EM, resistivity logging): one key unknown here is salinity. This quantity should be carefully measured before any decision is made to use electro-magnetic technologies for monitoring. If all our assumptions are correct, these technologies should be very interesting to monitoring the CO2 front for each of the five plumes. An additional consideration for wellbore resistivity measurements is the actual well design of the monitoring well.

- time-lapse neutron: large uncertainty exists for porosity. They should be acquired during the characterization phase of the study and forward modeling repeated. However, if all the assumptions are correct, these technologies would be worth to consider for CO2 plume tracking. Also due to the small plume movement around the injectors, as of to date, monitoring wells would have to be drilled very close the injectors, less than 500m in order to monitor the CO2 plume movement. Based on the performed computations the CO2 plume could not be detected for the first 4-5 years after the start of injection.

- pressure and temperature gauges are deployable in any type of environment, and are added in the table for the sake of completeness (see Table 2)[10].

Tab. 1. Summary of technologies reviewed and their applicability

Global methods			**Advantages**	**Drawbacks**
	Proven result	Expected result		
3D (2D) time-lapse seimic			High vertical and lateral resolution in comparison to other methods No monitoring well needed	Need for baseline before injection starts Expensive (3D)
gravity			Cheap Complementary to seismic methods No monitoring well needed	Need for baseline before injection starts No vertical resolution/poor lateral resolution
InSAR			Cheap Complementary to seismic methods No monitoring well needed	Need for baseline before injection starts no vertical resolution/poor lateral resolution
Local methods				
cross-well EM			Complementary to seismic methods	Need for baseline before injection starts small area imaged Monitoring well to be drilled cannot be run in injecting well No tubing possible in the two wells
cross-well seismic			High vertical and lateral resolution, small level of noise	Need for baseline before injection starts small area imaged Monitoring well to be drilled cannot be run in injecting well No tubing possible in the two wells
VSP			High vertical resolution, small level of noise	Need for baseline before injection starts small area imaged cannot be run in injecting well
Well logging methods				
Sonic log			High vertical resolution, small level of noise	Information at the well only, higher frequency than for seismic
Cased-Hole Neutron porosity			Neutron porosity decrease with increasing CO_2 saturation	Tool limitation (4 5/8" casing); Change in Sw needs to be present
Cased-Hole resistivity logging			Medium resolution CO_2 plume detection and tracking	Tool limitations (e.g. casing, cement bond and resistivity) need to be considered first; 100 ohm-m resistivity limit.
Pulsed Neutron Logging			High resolution quantitative plume saturation measurement	Has limitations in low salinity and low porosity environments
Point measurements				
Pressure, Temperature			Direct measurements, quantities that have a wide footprint	Information at one point only

Based on the above results, some initial considerations can be made to determine whether a leakage will be detectable for each technology:

- Gravity is not highly sensitive to vertical CO2 displacement (it is more sensitive to lateral displacement), and since detectability appears to be achieved only after 13 years for CO2 plume tracking around well INJ1N and INJ3N, we do not consider it as a valid technology for CO2 leakage detection.

- InSAR is sensitive to pressure changes. As such, only a massive leak of CO2 should affect surface deformation, which, a priori, does not make it a very appropriate tool for leakage detection.

- EM technologies should be able to detect CO2 leakage and a specific study could be made to assess this detectability in the overburden. Cross-well EM has the drawback to require two monitoring wells, on the leakage path, which is very constraining. EM logging can be used, only if placed on the leakage path[11].

Tab. 2. Conclusion of the feasibility studies

Global methods			Advantages	Drawbacks
	Proven result	Expected result		
3D (2D) time-lapse seimic			High vertical and lateral resolution in comparison to other methods No monitoring well needed	Need for baseline before injection starts Expensive (3D)
gravity			Cheap Complementary to seismic methods No monitoring well needed	Need for baseline before injection starts No vertical resolution/poor lateral resolution
InSAR			Cheap Complementary to seismic methods No monitoring well needed	Need for baseline before injection starts no vertical resolution/poor lateral resolution
Soil gas survey			Cheap No monitoring well needed	Need for baseline before injection starts Detection after CO_2 has reached the surface
Local methods				
cross-well EM			Complementary to seismic methods	Need for baseline before injection starts small area imaged Monitoring well to be drilled cannot be run in injecting well No tubing possible in the two wells
cross-well seismic			High vertical and lateral resolution, small level of noise	Need for baseline before injection starts small area imaged Monitoring well to be drilled cannot be run in injecting well No tubing possible in the two wells
VSP			High vertical resolution, small level of noise	Need for baseline before injection starts small area imaged cannot be run in injecting well
Well logging methods				
Sonic log			High vertical resolution, small level of noise	Information at the well only, higher frequency than for seismic
Cased-Hole Neutron porosity			High vertical resolution	Information at the well only Need for baseline Monitoring well to be drilled
Cased-Hole resistivity logging			Medium resolution CO_2 plume detection and tracking	Information at the well only Need for baseline Monitoring well to be drilled
Pulsed Neutron Logging			High resolution quantitative plume saturation measurement	Information at the well only Need for baseline Can be run through tubing
Point measurements				
Pressure, Temperature			Direct measurements, quantities that have a wide footprint	Information at one point only
Fluid sampling			Direct measurement	Information at one point only

- time-lapse seismic technologies: cross-well seismic will require two monitoring wells, located on the leakage path, which is a strong constraint. VSP images can be acquired if the leakage path is sufficiently well known so as to place the sources and receivers correctly. 3D time-lapse seismic has strong advantages for this purpose because it maps the entire overburden, and does not require a priori knowledge of the leakage path, provided this leakage path is located above the reservoir. 3D time-lapse seismic will detect CO2 accumulation. Once the appropriate log suite becomes available, a specific study can be done, that will determine how much CO2 needs to accumulate to become detectable.

- time-lapse neutron: Due to the small CO2 plume movement around the injectors, a change in properties (Neutron porosity, sigma, resistivity) will not be detected during the first few years of injection in case the monitoring well is spaced 500m away and all our assumptions on the petrophysical properties are correct. However, due to the relative high resolution of the tools, leakage close to the wellbore could be detected after the CO2 plume has reached the monitoring well.

- pressure and temperature monitoring: this type of monitoring will be sensitive to CO2 leakage. A sensitivity study, based on the ECLIPSE model should be lead so as to determine how much CO2 needs to leak in order to become detectable, depending on the location of selected monitoring wells.

The optimal study in case more data becomes available would include the following.

- A fluid substitution study and forward seismic modeling should be run in the reservoir (based on the reservoir model) and in the overburden (caprock and above, based on available logs)

- Plume detectability through time should also be looked at based on the results of this fluid substitution study
- Considerations on leakage detectability in seismic data should be made, based on the fluid substitution study
- A sensitivity study should be run to assess seismic signal variability due to imperfect knowledge of the underground
- 2D or 3D finite difference modeling should be run to assess cross-well EM detectability
- An appropriate log suite should be used to derive a fit for purpose 1D Mechanical Earth Model that should be applied for surface deformation prediction

The monitoring program will have to be adapted and revised regularly to take into account all new data available and as new regulations become available. Comparison between predicted and actual measurements will allow calibrating and refining simulation models, for improved predictions and risk reduction.

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