State-of-the-Art of Monitoring Methods to evaluate CO_2 Storage Site Performance

• July 2013 •

CGS Europe
FP7 Pan-European Coordination
Action on CO_2 Geological Storage

CO_2GeoNet
The European Network of Excellence
on the Geological Storage of CO_2

CGS Europe Key Report Executive Summary

This report was prepared in the framework of the FP7 EU-funded project CGS Europe "Pan-European Coordination Action on CO_2 Geological Storage" (Project no. 256725) as Deliverable D3.3 under the coordination of Heike Rütters (BGR) and with the contribution of the following authors:

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The report has been edited by Anna Korre, Rowena Stead and Niels Bo Jensen and should be cited in literature as follows:

Rütters, H., Möller, I., May, F., Flornes, K., Hladik, V., Arvanitis, A., Gülec, N., Bakiler, C., Dudu, A., Kucharic, L., Juhojuntti, N., Shogenova, A., Georgiev, G., 2013. State-of-the-art of monitoring methods to evaluate CO_2 storage site performance. *CGS Europe report No. D3.3,* Korre, A., Stead, R., Jensen, N.B. (Eds.), July 2013, 109 p.

EXECUTIVE SUMMARY

The basic idea of the "Carbon dioxide Capture and Storage (CCS)" technology is to store CO_2 produced by fossil fuel combustion and industrial processes in the deep geological underground, rather than releasing it into the atmosphere. To have a beneficial effect on climate and to prevent interaction between the surplus CO_2 and the biosphere, the CO_2 needs to remain safely underground for a sufficiently long time, of the order of at least 10,000 years, although it is expected to remain contained for much longer time periods in properly selected reservoirs. To ensure and verify the safe geological containment of CO_2 underground, monitoring of CO_2 storage site performance is mandatory. This includes, among other things, monitoring the injection process, tracking the CO_2 plume migration in the reservoir and installing monitoring systems to give (early) warning in the case of CO_2 leakage, i.e. CO_2 leaving the storage complex. Not only do the impacts of the CO_2 itself need to be considered, but also potential associated impacts due to co-injected incidental substances ("impurities"), mobilised substances, displaced migrating saline formation water and pressure increase following CO_2 injection.

The main objective of this report is to identify and review monitoring methods for a performance assessment of geological CO_2 storage sites. This report discusses state-of-the-art monitoring techniques, introduces general concepts and gives recommendations for procedures to set up site-specific monitoring plans. This is complemented by an overview of monitoring applications employed at demo or pilot CO_2 storage sites or in field tests. There is a special focus on establishing site-specific monitoring plans, with two examples selected to represent the two major storage options in Europe and worldwide, namely saline aquifers (Romanian example) and depleted gas fields (Slovakian example). Finally, recommendations for future research and development activities are derived.

Monitoring - general considerations and definitions (Chapter 1)

The monitoring of CO_2 storage sites provides data on the state of and processes within the storage complex and the surrounding environment for the durable, safe, efficient and environmentally friendly management of storage operations. As such, monitoring must provide all the information needed for planning, performing and supervising actions in all stages of storage, during normal operations, incidents and after site closure. Thus, monitoring is laid out as a continuous task allowing basic target-performance comparisons (progress against plan) and it provides a basis for decision-making, e.g. on corrective measures, if the state of a process is not as foreseen.

Various monitoring purposes have to be integrated in monitoring concepts: i) health, safety and environmental (HSE) provisions, ii) injection management and site operation, iii) verification of CO_2 storage and quantification of CO_2 leakage according to the European Emission Trading Scheme (ETS, Directive 2003/87/EG) and iv) satisfying the public interest on environmental information, especially in the case of deviations from the predicted storage behaviour.

Site-specific monitoring plans include various levels of monitoring scale, intensity and precision and must be flexible to allow adaptations to the actually observed processes and migration of fluids in the subsurface. Different technologies need to be employed for surveying larger areas, for detecting unexpected leakage and for local, detailed observations of potential or actual leakage pathways in high resolution.

Risk-based monitoring, as required according to the EU CCS Directive (2009/31/EC), must pay special attention to potential pathways and subjects of protection. The main potential leakage pathways of concern are: spill points, fractures and faults, weak points or gaps in the cap rocks and (abandoned) wellbores. The prime subjects of protection are human life, health and safety; other protected subjects include climate, landscape, cultural heritage, quality of life and socio-economic stability, soils, groundwater, natural resources, surface water bodies, ambient air, flora and fauna (including farm animals, agricultural crops or forests). Apart from CO_2, associated incidental substances in the CO_2 stream, displaced formation fluids like saline brines or crude oil and substances released from rocks and soils can be a matter of concern and require appropriate monitoring.

A comprehensive monitoring concept is needed to integrate requirements by the different monitoring purposes and to address potential risks for various subjects of protection during the individual phases of a CO_2 storage project. Such a comprehensive monitoring concept is summarised in the overview table given below. This table may also be used to set up and check site-specific monitoring concepts for completeness.

Comprehensive, generic monitoring framework: Monitoring purposes with regard to different compartments and project phases (May *et al*., 2011). Symbols in brackets indicate the need of case-specific considerations.

Compartment \ Phase	Pre-Injection, Baseline	Operation: normal	Operation: significant irregularities	Post-Closure: before transfer of responsibility	Post-Closure: after transfer of responsibility
Injection facilities, incl. wells		⚒ ⊘ 📄 ☺	⚒ ⊘ 📄 ☺	⊘ ☺	
Near-surface environment, incl. local communities and biosphere	⚒ ⊘ 📄 ☺	⚒ ⊘ ☺	⊘ 📄 ☺	⊘ ☺	⊘ ☺
Marine environment and/or	⚒ ⊘ ☺	⚒ ☺	⚒ ⊘ 📄 ☺	⊘	
Freshwater aquifers (potable water)	⊘ (📄) ☺	⊘ ☺	⊘ (📄) ☺	⊘	⊘
Hydraulic unit (area beyond storage complex)	⚒ ⊘	⚒ ⊘	⚒ ⊘ ☺	⊘	(⊘)
Storage complex: Overburden, incl. faults	⚒ ⊘	⚒ ⊘	⚒ ⊘ ☺	⊘	
Storage complex: Secondary containment formation	⚒	⚒	⚒ ⊘ ☺	⊘	(⊘)
Storage complex: Storage formation, incl. caprock	⚒	⚒ ☺	⚒ ⊘ ☺	⚒ ⊘	⊘

Monitoring purposes:

⚒ Storage operation
📄 Accounting for emission certification
⊘ Health, safety and environmental protection
☺ Communication with local communities

Monitoring techniques for different compartments (Chapter 2)

The report discusses various monitoring techniques and concepts in a practical context of monitoring specific compartments and/or processes, such as monitoring CO_2 plume migration in the storage reservoir or potential CO_2 leakage out of the storage complex. In addition to the storage reservoir itself, the considered compartments comprise the overburden (mechanical reaction of overburden, surface uplift, induced seismicity and faults), abandoned wells, overlying and adjacent aquifers, freshwater aquifers and the near-surface eco-compartments flora and fauna, soils, the shallow atmosphere and surface water bodies.

Monitoring concepts – status quo (Chapter 3)

General monitoring concepts provide a framework for setting up site-specific monitoring programmes and give general recommendations for potentially suitable techniques. The general monitoring concepts suggested in pertinent publications are briefly introduced. The monitoring requirements by the EU CCS Directive, the respective Guidance Documents and those of the EU ETS Monitoring and Reporting Guidelines are described in this chapter. In addition, other high-level regulations in place are presented, including the OSPAR and London protocol for a protection of the marine environment and the Clean Development Mechanisms of the United Nations Framework Convention on Climate Change. On a national level, many different directives, regulations and laws concerning CO_2 storage site monitoring are in place, implemented or being developed in different parts of the world, in particular in the USA, Canada, Australia and member states of the European Union. In Europe, there is one common EU CCS Directive that builds the frame for national CCS legislation in all 28 Member States and countries of the European economic area. In the US, Australia and Canada, the monitoring requirements are defined at state and provincial level. An overview of the current state of transposition of the EU CCS Directive to national laws is also given in Chapter 3.

Extensive monitoring programmes have been deployed in current CO_2 storage projects in order to fulfil the requirements by the regulations in place and to test the applicability of diverse geophysical, geochemical and biological monitoring methods. These are introduced for the full-scale industrial projects at Sleipner, Weyburn-Midale, In Salah and the smaller scale research and pilot projects K12-B and Ketzin. Monitoring programmes implemented at demo and industrial-scale projects are primarily oriented towards the most technically effective and cost-effective monitoring methods to comply with legal and safety requirements. In contrast, a wide variety of monitoring tools is developed, adapted, tested and validated at the pilot sites. Some of the demo and industrial-scale projects have been involved in research projects to gain additional information beyond the monitoring data required by the regulators and to advance new monitoring approaches.

Setting up a site-specific monitoring plan (Chapter 4)

To establish site-specific monitoring plans, location-specific features and risks must be identified and adequately addressed. After an introduction of the monitoring requirements in the EU CCS Directive, the procedure of transferring a general monitoring concept to a site-specific monitoring programme is exemplified for two sites.

The first example site is a deep saline aquifer in the south of Romania. The results of a site-specific risk assessment are presented and techniques to monitor the identified risks are listed. The target compartments for monitoring are ground surface, groundwater, soil, wells, possible faults and air. Suggested methods include logs, seismic surveys, cross-well techniques and microseismic surveys.

The second example is a depleted gas field in Slovakia at the border with Austria. The present irregular network of 35 old production wells and the existing geological fault system need particular attention in setting up a monitoring plan. Geochemical and geophysical baseline monitoring as well as monitoring during the injection phase and for the post injection period is suggested for this field. The methodology proposed follows those developed and applied for other storage projects in depleted natural gas reservoirs currently in operation, in particular the Otway Project in Australia.

Conclusions and Recommendations (Chapter 5)

Monitoring must form an integral part of the overall risk management of geological CO_2 storage sites. A number of established, reliable methods and tools exist for near-surface monitoring at CO_2 storage sites as well as for monitoring reservoir performance. The different suites of techniques are useful for i) tracking the extension and migration of the CO_2 plume, ii) large-scale surveys to detect eventual leakage pathways on a regional level, iii) detailed small-scale verification and characterisation procedures for selected, confined areas of CO_2 release.

All CO_2 storage sites need a comprehensive, integrative, dynamic monitoring strategy that addresses identified site-specific risks. A flexible multi-level approach must comprise the elements detection, verification, characterisation and long-term monitoring. Baseline monitoring will reveal natural (e.g. seasonal) variations for relevant parameters and unravel controlling factors of these variations. The interpretation of monitoring data needs to relate the results to local baselines and local knowledge on topography and geology, for example. For an overall assessment of site performance, the monitoring data need to be related to dynamic storage simulations. Monitoring data are further needed for updating geological models of the storage site.

The EU CCS Directive does not specify which methods or monitoring technologies should be used, but requires that the choice is based on best practice available at the time of design. Consequently, it is very important to test and evaluate the applicability of emerging monitoring tools that may provide new insights and additional information.

Based upon experience from existing CO_2 storage projects, other underground activities and research on natural analogues and at test sites, the following recommendations are derived:

- Monitoring plans must be site-specific, comprehensive, and flexible in order to satisfy various monitoring needs during normal operation and for contingency monitoring.
- Monitoring must form an integral part of the overall site management and needs to be continuously improved along with any associated activities.
- New, efficient, durable, precise and inexpensive monitoring tools and concepts should be tested at ongoing and future demo and industrial-scale storage projects under *in situ* conditions.
- Criteria and threshold values are needed for the evaluation of differences between monitoring results and model predictions.
- All stakeholders should be involved in the definition of i) acceptable conditions, ii) significant irregularities, iii) site-specific thresholds and iv) corrective measures and remediation plans.
- The systematic connection of near-surface and subsurface monitoring results is essential for the detection of irregularities.

- Thorough baseline monitoring and an understanding of natural processes is vital for the verification of anomalies and the quantification of deviations from model predictions.
- CO_2 injected into a storage formation should be regarded as contained within the storage complex, provided that no indication of a deviation has been observed by a reasonably extensive, sensitive and appropriate monitoring programme.
- Planning, operation, performance, and updating of monitoring activities, as storage operation in general, should be under independent supervision.

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