

MONITORING REQUIREMENTS FOR CO<sub>2</sub> STORAGE SITES ON THE  
DUTCH CONTINENTAL SHELF

# TASK 1 & 2 - Technical Review of Monitoring Solutions & Recommendations for Monitoring Plans (Executive Summary)

Ministerie van Economische Zaken en Klimaat

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## EXECUTIVE SUMMARY

This report, prepared by DNV, presents results stemming from the 'Monitoring requirements for CO<sub>2</sub> storage sites on the Dutch Continental Shelf' (KEM-27) study commissioned by the Ministerie van Economische Zaken en Klimaat (Ministry of Economic Affairs and Climate Policy, EZK). The monitoring, measurement, and verification (MMV) of injected carbon-dioxide (CO<sub>2</sub>) into the subsurface is essential for assuring conformance to its expected behaviour or detecting irregularities over time so that leakage and environmental impacts are avoided. Furthermore, MMV and MMV plans are a requirement of the EU CCS Directive. Several notable projects, such as the K12-B project in the Netherlands, have followed comprehensive, yet varied MMV programs using an assortment of methods. However, a robust set of recommended monitoring solutions is lacking and best practices for developing MMV plans are not specified within the EU CCS Directive or by Dutch regulation at present, where such resources would provide support in the design and assessment of MMV plans associated with potential megatonne-scale projects located within the Dutch North Sea (e.g., Aramis). The KEM-27 study addresses these gaps via two tasks. Task 1 is to review established and innovative CO<sub>2</sub> storage monitoring tools, technologies, and techniques, whereas Task 2 is to provide guidance toward developing and assessing MMV plans. The scope of the two tasks is relevant for both saline aquifers and depleted hydrocarbon fields, as either may be suitable for CO<sub>2</sub> storage in the Dutch North Sea.

To complete the objectives of the KEM-27 study, DNV assembled a team of subsurface experts with direct CCS and petroleum industry experience, and whose technical specialties include drilling and well engineering, geophysics, geomechanics, and geology. The team relied on public information from academic, regulatory, and commercial sources, but also utilised first-hand knowledge to complete the study. This is particularly true for the CO<sub>2</sub> monitoring tool, technology, and technique review of Task 1. For Task 2, the team leveraged DNV's Recommended Practice for Geological Storage of Carbon Dioxide (DNV-RP-J203) to provide best-practice recommendations MMV plan development. By design, the results and research from this study are specific to CO<sub>2</sub> storage in neither saline aquifer nor depleted hydrocarbon field environments, but rather, are intended to be applicable for both.

The report first provides background information related to the study and describes key concepts to orient the reader on the subject matter. This includes the development of CO<sub>2</sub> storage sites, the goals of MMV and MMV plans, the basic principles in MMV plan development, the importance of risk assessment and site characterisation, and the significance of operational planning. Throughout the various project stages, the purpose of MMV activities is to demonstrate site performance, containment, and conformance, while managing health, safety, and environmental risks as well as demonstrating the long-term security and stability of the storage site. This must be done meeting regulatory compliance while remaining site-specific, fit-for-purpose, risk-based, flexible, and adaptive. Additional MMV principles ensure that timely warning of performance anomalies is made, each monitoring domain is monitorable, transparency is practiced, and the work is conducted based on sound science and engineering, as well as the best available technologies economically achievable. Ultimately, MMV plans are dependent on the identified risks unique to the storage project and its location, meaning that risk assessment and site characterisation will impact the robustness and success of the corresponding MMV plan. In the Dutch North Sea, the MMV plan must also consider the other possible surface or subsurface users during storage operations.

Personnel responsible for screening the tools, technologies, and techniques used for offshore CO<sub>2</sub> storage monitoring must have an overview of the options available to make informed selection decisions and meet MMV objectives, thus driving the motivation behind Task 1 of the KEM-27 study. To help address this need, a comprehensive array of monitoring solutions was compiled for this report, and are divided into 6 categories, including geophysical, well, petrophysical, CO<sub>2</sub> release, geochemical, and marine biosphere, as well as a seventh category for innovative solutions. A total of 80 tools, technologies, and techniques were identified, researched, and described. Of these, half from the total list fall under the geophysical (20) or well and petrophysical (20) categories, whereas the remaining 40 solutions are associated with the other 5 categories, including 7 innovative solutions. Technical, operational, environmental,



economic, and other relevant characteristics of individual CO<sub>2</sub> storage monitoring solutions are described in the report, giving insight towards their capability and suitability to meet MMV objectives. Case examples are provided in instances where use of a solution has been well documented, and specific considerations relevant for monitoring offshore in the Netherlands are also made where possible. As an additional step, the full list of monitoring tools, technologies, and techniques have been curated into a set of informative tables. The tables include concise, yet practical details about an item's application, acquisition, scope, spatial coverage, advantages and challenges, costs, maturity, as well as other helpful pieces of information. Overall, the tables can be utilised during the monitoring tool, technology, and technique screening process before making selections for project MMV plans.

Those developing or assessing MMV plans require a sense of how they should be designed and structured. The results from Task 2 provide an organized approach to MMV plan development and review based on the details of DNV-RP-J203. The approach has 8 steps: defining objectives, describing context, specifying monitoring targets, screening monitoring techniques, selecting monitoring techniques, planning monitoring activities, evaluating completeness, and updating the plan. The report also provides guidance and examples to illustrate the process for each step, and includes descriptions related to the main tasks, inputs, outputs, and considerations. For instance, when specifying monitoring targets, it is important to be explicit about the physical properties to be measured, their variability, the location of measurement, frequency, and detection thresholds. A variety of challenges and limitations, such as the uncertainty and variability of the subsurface conditions, the trade-offs between different monitoring techniques, the need for adaptive and flexible planning, and the importance of stakeholder engagement and communication are also discussed. Lastly, a connection between Task 1 and 2 is made in relation to screening and selecting monitoring solutions, where the list and description of monitoring solutions discussed earlier can be leveraged. The primary goal of the MMV plan guidance is to help stakeholders make sure that MMV plans are fit-for-purpose, risk-based, and cost-effective, while ensuring the long-term safety and security of CO<sub>2</sub> storage.

Appended to the report are additional considerations for MMV in the Dutch Continental Shelf. First, the differences and similarities between CO<sub>2</sub> storage in depleted hydrocarbon fields and saline aquifers, and how they affect the MMV plans are discussed. The report identifies key risks and factors that vary between these settings, such as injection pressure, legacy wells, seal integrity, and reservoir heterogeneity. However, the principles and goals of MMV and developing MMV plans in either environment are the same. Even more specific to the Dutch North Sea, the report highlights some of the challenges and opportunities for data collection and MMV deployment. For example, there are multiple surface and subsurface activities in the region which will need to be accounted for throughout the life of a CO<sub>2</sub> storage project, including wind farm and other operations. In some cases, the report suggests alternative monitoring techniques and deployment options that can overcome these challenges, such as ocean-bottom nodes. As a final contribution, a few simplified hypothetical examples are put forth to help demonstrate and strengthen key MMV concepts, such as the use of bowtie analysis, risk assessment, solution screening and selection, and MMV plan evaluation. These examples are based on realistic scenarios of CO<sub>2</sub> storage in the Dutch North Sea, and include legacy wellbore leakage, seismicity during injection, and other topics.

Overall, monitoring is a cornerstone activity in the successful execution of a geological CO<sub>2</sub> storage project. MMV plans are required under the EU CCS Directive and must implement the best prevailing practices and technical solutions available, but neither the document nor Dutch regulation specifies such details at this time. The results of the KEM-27 study produced by DNV for EZK broadly, however, address some of the deficiencies of the EU CCS Directive regarding MMV by contributing a formal catalogue of suitable monitoring tools, technologies, or techniques, as well as a guidance for site-specific and risk-based MMV plan development. Going forward, this report provides support and recommendations for competent authorities, storage operators, or supervisory bodies to assess whether a given MMV plan is fit-for-purpose or otherwise inadequate in the context of offshore CO<sub>2</sub> storage projects, particularly those located along the Dutch Continental Shelf.