International Journal of Greenhouse Gas Control 113 (2022) 103553

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

Introduction to the STEMM-CCS special issue

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This special issue brings together a selection of papers resulting from the STEMM-CCS (Strategies for Environmental Monitoring of Marine Carbon Capture and Storage) project. STEMM-CCS was an ambitious, four-year, project on offshore geologic carbon dioxide storage funded under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 654,462). The aim was to deliver new insights, guidelines, and tools for the monitoring of CO_2 storage at putative offshore Carbon dioxide Capture and Storage (CCS) sites. CCS is an important potential mitigation strategy to reduce anthropogenic CO_2 emissions.

Although CO_2 leakage from geological reservoirs is considered unlikely, there is a regulatory need and societal expectation to undertake appropriate monitoring to provide assurance that leakage is not occurring. Should leakage be suspected, the capacity to detect, attribute, monitor, and quantify potential CO_2 leaks from sub-seafloor CCS reservoirs will be critical. In addition, it is important to predict and understand potential environmental impact from a range of leak scenarios, such that mitigation can be enacted if necessary. Regulatory and legislative bodies need assurance that potential storage leaks can be rapidly detected and quantified. Operators need to be able to detect and quantify, but also must have the ability to attribute leaks to a specific reservoir, potentially within a field of different storage systems and operators. Additionally, quantification techniques will be vital for storage operators if a carbon tax credit system were to be implemented. STEMM-CCS has successfully demonstrated solutions to these issues, though further development will be required to increase regulator and operator confidence. Further, these solutions will also underpin efforts to gain social licence to sequester CO_2 in sub-seafloor geologic storage.

Prior to any CO_2 storage at a site, an environmental assessment needs to be carried out in order to identify any site-specific risks and characterise natural environmental variation sufficiently to allow the efficient detection of environmental anomalies and impacts throughout the lifetime of the storage site. One of the challenges for regulators is to understand what information is required to sufficiently characterise an environment, while for operators, it is obtaining that baseline environmental data cost effectively. STEMM-CCS has not only shown how to establish and interpret baseline data using traditional surveying and sampling but has shown that modelling and other numerical analysis can be used that negate the need for intensive surveying and/or enable targeted surveying, thus balancing the needs of regulators, the public and industry. These approaches can also be utilised for continued monitoring once storage commences.

To enable the demonstration of techniques for CO_2 detection and quantification in a 'real world' environment, a controlled release of CO_2 beneath the surface sediments was carried out at the seabed at the Goldeneye site in the North Sea. Four papers here describe the establishment of environmental baseline data including comprehensive data collected prior to the experiment (Blackford et al., 2021; Dale et al., 2021; Esposito et al., 2021), the setup of the experiment and the deployment of a wide range of sensors, instruments, and detection techniques (Flohr et al., 2021b). Several papers are devoted to the results of the techniques deployed during the CO_2 release: novel real time water column and mapping measurements using lab-on-chip sensors (Gros et al., 2021; Martínez-Cabanas et al., 2021; Monk et al., 2021; Schaap et al., 2021), passive acoustic measurements (Li et al., 2021a), combined optical/acoustic methods (Li et al., 2021b), eddy covariance techniques (Koopmans et al., 2021), and both natural and artificial geochemical tracers (Flohr et al., 2021a). All the tested approaches are reviewed and assessed including their relative costs (Lichtschlag et al., 2021b). Migration of CO_2 within the sediments and the impact of the CO_2 release on the sediments is investigated using chemical, geophysical and hydromechanical methods (de Beer et al., 2021; Falcon-Suarez et al., 2021; Lichtschlag et al., 2021a; Robinson et al., 2021; Roche et al., 2021), electromagnetic techniques are applied to the investigation of fluid flow pathways in sediments (Gehrmann et al., 2021), while the feasibility of seismic techniques for detection and monitoring of a CO_2 leak is assessed (Waage et al., 2021). Modelling papers cover environmental monitoring and assessment including both detection, quantification, and impacts of a CO_2 leak in the water column (Blackford et al., 2020; Cazenave et al., 2021; Dewar et al., 2021; Omar et al., 2021; Yakushev et al., 2021), and migration in the sediments (Saleem et al., 2021). Finally, there is an assessment of the knowledge gained from

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https://doi.org/10.1016/j.ijggc.2021.103553
Received 5 November 2021; Received in revised form 2 December 2021; Accepted 7 December 2021
Available online 18 December 2021
1750-5836/

STEMM-CCS and two other related projects (Dean et al., 2020) and a study of stakeholder views on North Sea CCS (Gonzalez et al., 2021).

The project has delivered comprehensive knowledge, technologies and techniques to facilitate offshore CO_2 storage site selection and monitor CCS operations. As a result of STEMM-CCS we can demonstrate a robust understanding of potential impact and detectability of a wide range of hypothetical leak events. We have developed new methodologies for detecting leakage and demonstrated these in an appropriate marine environment and have developed efficient strategies for obtaining baseline characterisations that are relevant to the operational life of the storage site. This work also confirms previous studies that small operational leaks of CO_2 have very limited impact, and that the ability to detect leakage at levels well below significant environmental impact is now assured.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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