Act on Offshore Monitoring

Report on regulations and technological capabilities for monitoring CO_2 storage sites

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Executive summary

A central objective of ACTOM is to establish a web-based toolbox that will enable the derivation of optimal environmental monitoring strategies specifically tailored to individual offshore CCS storage sites or regions. The toolkit will enable operators to combine different monitoring technologies to design monitoring programmes based on assessed risks, thereby enabling operators to consistently communicate capabilities, limitations, knowledge and uncertainties associated with monitoring. This report is part of WP 1 BASELINE in the ACTOM project, concerning regulations and technological capabilities. It consists of two parts, Part I: CCS regulatory framework, Part II: Assessment of geophysical and marine monitoring technologies. The main purpose of this report is to survey the regulatory requirements, opportunities and technical limitations that form the basis for a marine monitoring programme.

Responsible Research and Innovation (RRI) actions raise the quality of research and innovations through open science and participatory processes. In RRI activities, academic experts, innovation users and other stakeholders, including local experts, engage in discussions about the creation and deployment of future innovations. Therefore, the approach of the ACTOM consortium is to have an ongoing dialogue on the state-of-the-art of marine monitoring and to bring these discussions ‘into the lab’ of ACTOM. Interactive webinars and workshops have also been used to incorporate RRI principles for the required multi-sector engagement into the work on this report.

Any country around the globe aiming to develop sub-seabed CO_2 storage programmes and projects will be helped by the development of policy and regulatory frameworks. In some regions and countries, CCS regulation is either lacking or it is in an immature state, both in general and for specific offshore CCS projects. Other regions, such as the EU, have more sophisticated regulation. The ACTOM toolbox is designed to have generic relevance regardless of the jurisdiction for which a project is planned. This report documents the generic relevance of the toolbox, or to what extent the toolbox can have generic relevance.

Monitoring elements of regulation could be characterised as the co-production of regulations, flexible principle-based regimes and reflexive and adaptive management instruments. Monitoring requirements within a specific CCS project are decided in a dialogue-based process between the regulators/administration, the operator and third-party stakeholders, i.e. the general public, fishermen’s organisations etc., which is facilitated by participatory assessment and decision processes. However, the process is framed by law and regulations. To document the generic relevance of the toolbox, we elaborate on how legal prerequisites frame how offshore sub-seabed CO_2 storage must or could be monitored with respect to the environment. A key question arises as to whether there are any minimum legal requirements or precise descriptive requirements for monitoring and monitoring technologies for such projects, and whether they are based on international, regional or national regulation. As this report does not consider national, site-specific requirements that an operator designing a CCS monitoring programme needs to take into consideration, the toolbox will have to address this.

Despite their different objectives and varying levels of detail, existing CCS monitoring policy, international agreements, legislation, regulations, guidelines, and protocols at the international and regional level have similar principles and requirements for monitoring. In the report, we find that, globally and regionally, the guidelines and regulations are based on the principles of best available practice, best available technology, and recognition of the fact that monitoring needs to be site-

specific. The new studies of Brazilian and Mexican legislation were added to the report in April 2023, see section 1.5.8. The studies show that in these countries, existing and proposed legislation does not prescribe any specific monitoring technologies. These added studies confirms that storage monitoring regulation and practices ought to be developed and based on the principles of best available practice, best available technology, and recognition of the fact that monitoring needs to be site-specific, which is consistent with the recommendations in this report and comparative global practice (See section 1.4.4 of this report).

If national law prescribes specific monitoring-technologies, this could undermine these principles. General legislation could be outdated as regards what the best available technologies are, and prescriptive requirements might not be flexible enough to allow for a site-specific, designed monitoring programme. As far as we have been able to establish, no specific monitoring technologies are prescribed by law, neither globally nor regionally. In the EU, in accordance with the principle of best available technology, the accuracy of monitoring technologies is not laid down in the minimum requirements of the CCS Directive. An EU-contextual argument against more rigorous implementation in nation states, as opposed to the minimum requirements of the CCS Directive, is that this could interfere with the level playing field/lead to disturbance of competition.

Based on international and regional CCS guidelines and regulations, even if no specific technology is required for monitoring storage, the regulations identify different storage phases: pre injection of CO_2, during injection and after (post) storage is sealed. There are different monitoring aims in these phases, as described by Dixon and Romanak, 2015. Thus, even though there are no regulatory specifics on technology, monitoring phases with pertaining aims are recommended (soft law, guidelines) or mandatory (hard law, prescribed). This has implications for the design of the toolbox. Our presumption is that existing and future national regulation could potentially relate to all these phases and prescribe all these monitoring aims. An online monitoring tool needs to be able to address these phases and aims if it is to be relevant in all jurisdictions globally.

In a separate section, we compare national regulations based on an analysis of legal texts, and take a functional approach, comparing structures and rules that fulfil the same functions in the national systems. The purpose is to document the generic relevance of the ACTOM toolbox, and how designing a monitoring programme based on the toolbox will align with national policies and regulations. The question here is whether there are any deviations compared to the findings concerning global and regional regulation within specific countries that add new mandatory monitoring phases or monitoring aims, or that add requirements for specific monitoring technology that the ACTOM toolbox needs to meet. As we will document, no examples of such deviations have been found in national legislation.

Successful monitoring depends on a number of technological components working in harmony. Gathering and analysing the data required to assess storage performance and manage risks may require deployment platforms, reliable and accurate measurement technologies, and data processing methods. In ACTOM WP1, a framework was developed for assessing how optimal existing measurement technologies and methods perform relative to regulatory requirements and technical capabilities. As described in Part II of this report, the framework was developed by first collecting a comprehensive inventory of existing measurement technologies and methods, based on two earlier compilations: the online IEAGHG Monitoring Selection Tool and the STEMM-CCS Online Monitoring and Decision Tool. Next, uniform criteria were defined and the capabilities of each technology/method were assessed by awarding scores ranging from 1, meaning that a method performs poorly in relation the given criterion or setting; 2, meaning that a method results in reasonable overall performance; to 3, meaning that a method achieves high performance, impact and value of information. The different technologies were assessed with respect to the following 18 criteria for capabilities, cost and regulatory requirements. Note that the criterion Regulation has six sub-criteria, while Coverage and Resolution each have two sub-criteria.

Criterion	Legend
1. Cumulative sum	Sum of all scores
2. Sea water column	Performance in sea water column
3. Sea bottom	Performance around sea bottom
4. Sea bottom subsurface	Performance in sea bottom subsurface
5. Regulation	Monitoring requirement/phase (Dixon and Romanak, 2015), either: baseline (B), performance (P), detection (D), attribution (A), quantification (Q), or impact assessment (IA)
6. Sensitivity	Sensitivity / signal-to-noise of method
7. Effort	Overall required effort as regards power, logistics
8. Accessibility	Method's capability of accessing target measurement area
9. Time required	Time required to perform acquisition / processing of method
10. Practicality	Practicality of executing the method on site
11. Coverage	Spatial coverage of a method
	Temporal coverage of a method
12. Resolution	Spatial resolution of a method
	Temporal resolution of a method
13. Penetration	Penetration depth / distance of method
14. Repeatability	Repeatability of comparable results of method
15. Baseline/versus/repeat	Suitability of method to be used for baseline or repeat surveys
16. Cost/km	Cost of method per kilometre
17. Cost/hour	Cost of method per hour
18. SYNERGY	Synergy of method with other methods

The result was an inventory table that enables searches for the best suitable technology by filtering according to criteria and score. Information from the inventory table will be further improved and used for the Toolbox. Furthermore, both the technologies included in the inventory table and the expert opinion-based scores are currently preliminary. They will be further discussed within ATCOM and refined accordingly. Thus, the inventory table should be regarded as a living document that will be subject to modification throughout the ACTOM project.

A few novel techniques are also described briefly in Part II of this report. They include methods for water column CO_2 anomaly identification, and attribution and surveying techniques (high resolution acoustics, seismics, and fibre-optic and interferometric imaging).

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Preface

Introduction

This report is part of WP1 BASELINE in the Act on Offshore Monitoring (ACTOM) project. The main purpose of WP1 is to survey the regulatory requirements, and the opportunities and technical limitations that form the basis for a marine monitoring programme. As such, WP1 underpins the other WPs in ACTOM by providing the necessary information about what level of assurance is expected from a monitoring programme, and about available marine monitoring technologies and methods, and their capabilities.

One central objective of ACTOM is to establish a web-based toolbox that will enable the derivation of optimal environmental monitoring strategies specifically tailored to individual offshore storage sites or regions. The toolkit will enable operators to combine different monitoring technologies to design and update adequate and efficient monitoring programmes based on assessed risks, thereby enabling operators to consistently communicate capabilities, limitations, knowledge and uncertainties associated with monitoring to regulators, stakeholders and the public at large.

The ACTOM toolbox will be capable of autonomously delivering recommended environmental monitoring strategies, where the recommendations are largely dependent on established operational marine simulation models. Both these factors reduce costs. The formulation of appropriate monitoring programmes, from either a regulatory or operator viewpoint, will be greatly aided by a properly quantified cost-benefit analysis of what that monitoring could achieve. Cost-benefit analyses are addressed in the second part of this report. In addition, communicating risks and uncertainties is important for offshore sub-seabed storage projects, and tools that can facilitate the dialogue with stakeholders, governments and the public at large will add value to the process.

The report consists of two parts: Part I documents the regulatory monitoring requirements for an environmental monitoring framework for CCS. This is achieved by reviewing current global, regional and national regulatory frameworks for monitoring sub-seabed offshore carbon capture storage (CCS). Part II of this report provides an overview of the technical capabilities and limitations that form the basis for a marine monitoring programme. A comprehensive list of monitoring technologies and methods is assessed with respect to how optimally they perform in relation to many different criteria, including regulatory requirements, cost-efficiency, user friendliness, stakeholder engagement etc.

RRI and perspectives on public perception

The overall goal for Responsible Research and Innovation (RRI) actions is to raise the quality of research and innovations through open science and participatory processes by involving all relevant stakeholders. In RRI activities, academic experts, innovation users and other stakeholders, including local experts, engage in discussions about the creation and deployment of future innovations.

The success criteria for marine monitoring in a CCS context is twofold: first, the promised technological products must function, and, second, the users of these products must find them useful. As such, these stakeholder discussions are both anticipatory (discussing future monitoring needs for CCS technologies) and responsive (tailoring approaches to marine monitoring that address the needs of industry and regulators/the administration).

Therefore, the ACTOM consortium's approach is to have an ongoing dialogue on the state-of-the-art of marine monitoring and to bring these discussions 'into the lab' of the ACTOM tasks as the development of marine monitoring for CCS takes shape. The dissemination of ACTOM scientific reports through interactive webinars and workshops is a specific approach that incorporates RRI principles for the necessary multi-sector engagement.

Transparent decision-making, open and credible science technology, social, legal and ethical considerations are prerequisites for high public acceptance of new technologies. The multi-level CCS management systems, and the assessment and monitoring programmes for specific projects will play a role in communicating the risks and benefits of storage, and in counteracting unjustified accusations of adverse environmental effects.

Information concerning public perception of CCS projects has been growing. A review of 42 articles on CCS and public perception found evidence that trust in CCS and stakeholder collaboration on CCS projects go hand in hand.[1] Accordingly, environmental impact assessment (EIA) processes have also been met with demands for increased data production and public participation. To respond to the need for increased public participation, international and national financing institutions have adopted their own version of the EIA process, in which they use stakeholder consultations as a key determinant to identify the risk of an energy project. Nevertheless, research on the performance of CCS projects is limited.

There is no doubt, however, that a CCS project will need to secure what is referred to as a 'social licence-to-operate' (SLO). The need for an SLO is increasing in many sectors, and what used to be a relatively informal agreement between the project developer and the stakeholders will now need some degree of formalisation. It will be of vital importance for new technologies, and consequently for CCS, that they secure this SLO and subsequently maintain a trustworthy relationship with the public over time.

Responsible Research and Innovation is an integral part of the ACTOM project's research, and stakeholder engagement in the research itself has been used in this report. Public perception plays a vital role in ensuring that CO_2 storage meets operational, regulatory and community expectations.[2] The RRI approach has also framed the work on this report, by aiding stakeholder-scientist engagement exercises that are anticipatory and reflexive and part of a co-production process of designing environmental monitoring, measurement and verification of fully functioning CCS infrastructures. It is paramount to understand that public needs for environmental monitoring and verification of CCS infrastructures and facilities may differ from what the industry finds important. Since public perception is key to the overall success of CCS projects, environmental monitoring programmes must include both public and industry needs if CCS projects are to be credible, salient and legitimate.

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[1] Selma L'Orange Seigo, Simone Dohle and Michael Siegrist, 'Public perception of carbon capture and storage (CCS): A review.' Renewable and Sustainable Energy Reviews (2014) 38: 848–863.

[2] Global status of CCS 2019. Targeting climate change. Global CCS Institute, p 29.

Part I: CCS regulatory framework

1.1 Introduction

The ACTOM toolbox is designed to have generic relevance regardless of the jurisdiction in which a project is planned. This report documents the generic relevance of the toolbox, or to what degree the toolbox can have generic relevance.

Any country around the globe aiming to develop sub-seabed CO_2 storage programmes and projects will be helped by the development of policy and regulatory frameworks. In countries like the USA, Canada, the UK, Norway, Japan, Australia and China, the government plays an important role in the development of CCS projects by supporting this activity with investment and by systematically improving policies.[3] The global portfolio of large-scale CCS projects expanded to 43 in 2019. Eighteen are in operation, five are under construction, mostly in North America, while 20 CCS projects are at early to advanced stage of development, mostly in China and Europe.[4] However, in some regions and countries, CCS regulation is either lacking or it is in an immature state, both in general and specifically as regards offshore CCS. Other regions, such as the EU, have more sophisticated regulation,[5] but little experience of implementing licensing procedures under the regulation, and even less of starting and completing projects.

Three different elements can be distinguished in the full CCS storage chain: the capture, transport and storage of CO_2. This project relates to storage, and the focus is on offshore storage. Because the geology of any potential CO_2 storage site varies, as do other site-specific circumstances, existing regulatory frameworks have been carefully designed to avoid being prescriptive, instead outlining what should be accomplished rather than how it should be accomplished.[6] Regulations set requirements for the types of activities and outcomes that are necessary to satisfy the goals as prescribed by law and, for a specific project, in the licence. It is evident that there are as many possible project outcomes as there are projects. Licensing is not a single point of contact, as the administration works with project developers over time to design and agree on a plan for moving it forward. However, there are regulations or guidelines that have become virtually standard procedure. Simply put, they include: 1) site selection/characterisation and risk assessment, 2) monitoring, and 3) reporting.[7]

Thus, one core element in any offshore sub-seabed CO_2 storage project development, regardless of jurisdiction, is *site selection and risk assessment.* In addition to geological conditions being appropriate for storage (e.g. reservoirs and seals) a large part of site selection consists of an assessment of the potential risks and related impacts of the specific site. A scientifically sound and commercially viable monitoring plan can only be achieved when risk assessment is intrinsically linked to the development of the site-specific monitoring plan.[8] A second core element of offshore sub-seabed CO_2 storage projects that is being addressed by ACTOM, is *the development of an environmental monitoring*

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[3] Natalia Romasheva and Alina Ilinova. 'CCS Projects: How Regulatory Framework Influences Their Deployment'. Resources 2019, 8, 181 on p 2.

[4] Ibid., with further references to Hiroshi, N. Presentation of Global CCS Institute. In Proceedings of the CCS Knowledge Sharing Meeting between Global CCS Institute and St, Petersburg Mining University, Saint Petersburg, Russia, 23 May 2019.

[5] See section 1.4.3.

[6] See section 1.3.

[7] Dixon and Romanak (2015).

[8] M Jagger, E. Drosin, Risk assessment of CO2 storage complexes and public engagement in projects, Ch. 8 in Geological Storage of Carbon Dioxide (CO2), Woodhead Publishing Limited, 2013, p 195.

programme, designed around the potential risks and impacts, (identified in the risk assessment). Finally, *reporting*, supported by monitoring data, communicates that the project is performing as planned, with no unintended consequences or leakages to the seawater column.

This report aims to elaborate on how legal prerequisites frame how offshore sub-seabed CO_2 storage must or can be *monitored* with respect to the environment. A key question that arises is whether there are any minimum legal requirements or precise descriptive requirements for monitoring and monitoring technologies for such projects, and whether they are based on international, regional or national regulations. International and regional regulations are more fixed frames, because altering international, multinational or regional conventions is a time-consuming and slow process.

Regulatory frameworks of relevance to monitoring sub-seabed CO_2 storage encompass specific licensing and related monitoring requirements. Monitoring requirements cannot be understood and interpreted in isolation, as they are closely related to aspects such as CCS site characterisation and selection, risk and project impact assessments, stakeholder and public participation, as well as public access to information. The management of CCS through strategic marine plans, marine spatial planning (MSP) and, finally, licensing, sheds light on an even broader management perspective and potential. When looking at core elements of a management system, such as licensing, the multiple levels of the systems cannot be ignored.[9] How the separate parts, such as the licence-system, perform relates to the context within which the parts operate in the overall management system. The CCS regulatory context is elaborated on in section 1.2 below.

The toolbox developed herein is designed to have generic relevance regardless of the jurisdiction, and thereby regulatory framework, within which the project is planned. National traditions relating to policy and regulation impact a country's regulatory approach. The regulatory challenges countries are facing in connection with CCS are still the same, such as the fact that the geology of any potential CO_2 storage site is different and site-specific. Thus, general theories on regulation and regulatory approaches can shed light on what kind of regulation we are looking at for CCS in general, and for monitoring CCS in particular; see section 1.3 below.

Existing international and regional (e.g. EU) law can set premises and requirements for national regulation. We will therefore examine relevant global and regional instruments before national law, see section 1.4 below. Thus, despite the fact that different countries operate with separate legal systems, national law is not developed in a vacuum. In section 1.5 we compare national regulations, including examples from case studies. Here, we only consider and compare political-legal factors, since the purpose is to document the generic relevance of the ACTOM toolbox and how designing a monitoring programme based on the toolbox will align with national policy and regulation. We focus on regulation, because law mirrors policy. The comparison is based on an analysis of legal texts, and takes a functional approach, comparing structures and rules that fulfil the same functions in national systems.[10] In addition, some particular marine CCS projects will be presented.

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[9] Schütz, S. E. and Slater, A. M. (2019). 'From strategic marine planning to project licenses: Striking a balance between predictability and adaptability in the management of aquaculture and offshore wind farms'. *Marine Policy*, *110.* https://doi.org/10.1016/j.marpol.2019.103556.

[10] The functional comparative method does not focus on rules but on their effects, see R. Michaels, 'The Functional Method of Comparative Law', in: M. Reimann and R. Zimmermann (eds.), *The Oxford Handbook of Comparative Law,* Oxford University Press, Duke Law School Legal Studies Paper No 87, p. 4.

1.2 Monitoring in the marine management context. The CCS-licensing process

Requirements for monitoring geological storage sites are elements of the CCS regulatory framework, alongside elements such as risk and project impact assessments. Further, the CCS regulatory framework is normally a component of a national regulatory regime, which can sometimes allow for variations between different countries and different regions of the world. A general distinction between common law and civil law countries is often highlighted as important, but in relation to the management of new and emerging industries, this distinction does not seem particularly relevant.[11] Rather than differences, some common trends or features of the development of marine management are worth noting. While it is beyond the scope of this report to consider national, site-specific requirements that an operator designing a CCS monitoring programme needs to take into consideration, some common trends or features of the development of marine management will be described. The aim is to illustrate their potential relevance to designing a specific monitoring programme.

In the last 20 years, more strategic and holistic instruments have been developed for the management of (sea) areas and resources, compared to the traditional sector- and case-by-case-oriented system of granting licences to operate. For example, the designation of Marine Protected Areas (MPA) is high on the international agenda, alongside area-based management tools like Marine (or Maritime) Spatial Planning (MSP).[12] MSP comprises plans for opening marine areas for industry, typically based on Strategic Environmental Assessments (SEA). SEAs are impact assessments at a higher decision-level, such as plans or programmes for industrial development, than impact assessments related to projects and the licensing process related to a specific project.

Thus, the management system can have multiple levels, ranging from strategic marine plans or policy documents to marine spatial plans (policy, soft law or hard law) and licences. In a multi-layered system, the performance of the management system does not just depend on its separate parts, such as the licensing system, but also on the context within which the parts operate in the overall system. There can be clear legal links between the multiple tiers of the management process, from strategy to project.

In the ocean governance context, marine spatial planning has attracted considerable interest in recent years and it is a rapidly developing management concept.[13] Marine spatial planning (MSP) was originally only a tool for the environmental protection of marine areas.[14] It has been transformed into a process for minimising and avoiding conflicts of interest in ocean use, while also taking ecological

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[11] Schütz and Slater (2019).

[12] In its resolution 72/249 of 24 December 2017, the UN General Assembly decided to convene an Intergovernmental Conference, under the auspices of the United Nations, to draft the text of an international, legally binding instrument under the United Nations Convention on the Law of Sea, addressing the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction, in particular, together and as a whole, marine genetic resources, measures such as area-based management tools, including marine protected areas, environmental impact assessments and capacity-building and the transfer of marine technology, see s. 2 of res. 72/249.

[13] See, e.g., the work done by UNESCO / the Intergovernmental Oceanographic Commission promoting management procedures and policies for ecosystem-based management through MSP, and the development in the EU of the directive on Maritime Spatial Planning (MSP) (2014/89/EU).

[14] Fanny Douvere, 'The importance of marine spatial planning in advancing ecosystem-based sea use management', Marine Policy 32 (2008): 766.

values and benefits of human usage into consideration.[15] The United Nations Educational, Scientific, and Cultural Organization (UNESCO) defines MSP as 'a public process of analysing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic, and social objectives that usually have been specified through a political process'.[16] MSP is thus an integrated and comprehensive ecosystem-based management approach to ocean governance that is used to reconcile conflicting interests in an ocean area. If a marine spatial plan encompasses one specific sector, such as offshore wind, the holistic approach is then first and foremost secured to the extent that the plan relates to existing, developing and subsequent marine plans of geographical relevance. A dialogue between plans can be facilitated by best practice or prescribed by law.

An MPA or MSP does not just relate to waters, but can itself be multi-layered, this time in a geographical context. The scope of the plan could be prescribed by law, as in the EU MSP directive.[17] According to the Directive Art. 6 no 1, an MSP should take into account 'relevant activities and uses in marine waters', where marine waters means 'the waters, the seabed and subsoil', Art. 3 (4). An MSP could thus encompass sub-seabed CO_2 storage activities and facilities. In addition to monitoring activities, infrastructure, installations or monitoring equipment could be permanently placed on the seabed, in the sea column or above sea level, thus constituting 'activities and uses in marine waters'. For the storage itself, however, a Marine Spatial Plan under the Directive will not be a relevant instrument, as the subsoil is linguistically speaking the layer (stratum) of earth immediately below the surface. The CO_2 storage will not be immediately below the surface, but in deeper layers, and thus not part of the marine plan.

As a process for minimising and avoiding conflicts of interest in ocean use, MSP is of interest for CCS activity and equipment in the subsoil, on the seabed, the sea column and above sea level. Infrastructure from sea to the shore is typically subject to conflicting interests relating to sea use. Potential conflicts of interest in the use of marine areas could exist between geological CO_2 storage and fisheries. In Norway, economic compensation for fishermen who lose fishing grounds due to a CO_2 storage project is prescribed by law.[18] Conflicts can also arise about the use of areas in connection with sub-seabed storage, and it is vital that the integrity of the storage is preserved and protected by law. Here, the EU CCS directive[19] Art. 5 no 4 explicitly requires that the holder of an exploration permit 'shall have the sole right to explore the potential CO_2 storage complex' and that Member States 'shall ensure that no conflicting uses of the complex are permitted during the period of validity of the permit'.

How can we understand or describe a multi-layered national management system? Regulatory, administrative, and societal challenges can be structured based on the process timeline for CCS project licensing (fig. 1). Offshore CO_2 storage requires a licence with an Environmental Impact Assessment (EIA) (Fig. 1 Licence, EIA). Private bodies may only apply for licences after the state has conducted a

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[15] Jens-Uwe Schröder-Hinrichs, Henrik Nilsson and Jonas Pålsson, 'Sustainable Ocean Development in the Arctic: Making a Case for Marine Spatial Planning in Offshore Oil and Gas Exploration', Ocean Yearbook Online 27(1) (2013): 522. See further Schütz, S.E. 2018 'Marine Spatial Planning – Prospects for the Arctic'. Arctic Review on Law and Politics Volume 9, 2018 pp. 44–66.

[16] http://msp.ioc-unesco.org/about/marine-spatial-planning/.

[17] EU Framework Directive on Maritime Spatial Planning (MSP) (2014/89/EU).

[18] Forskrift om utnyttelse av undersjøiske reservoarer på kontinentalsokkelen til lagring av CO_2og om transport av CO_2 på kontinentalsokkelen, FOR-2014-12-05-1517, chapter 9, section 9-2,'If the transport and storage of CO_2in an area completely or partially seizes a fishing field, the state is obliged to the extent that fishing becomes impossible or significantly difficult to compensate for the financial loss this entails' (author's translation).

[19] See section 1.4.3 on the directive.

Strategic Impact Assessment (SEA) in conjunction with Marine Spatial Planning and 'opened' or otherwise cleared certain areas for licensing applications (Fig. 1 MSP/MPS, SEA). That said, the process is not necessarily linear, as licences can be granted in areas subject to an MSP, and an MSP is typically a cyclical process that is repeated e.g. every six years.

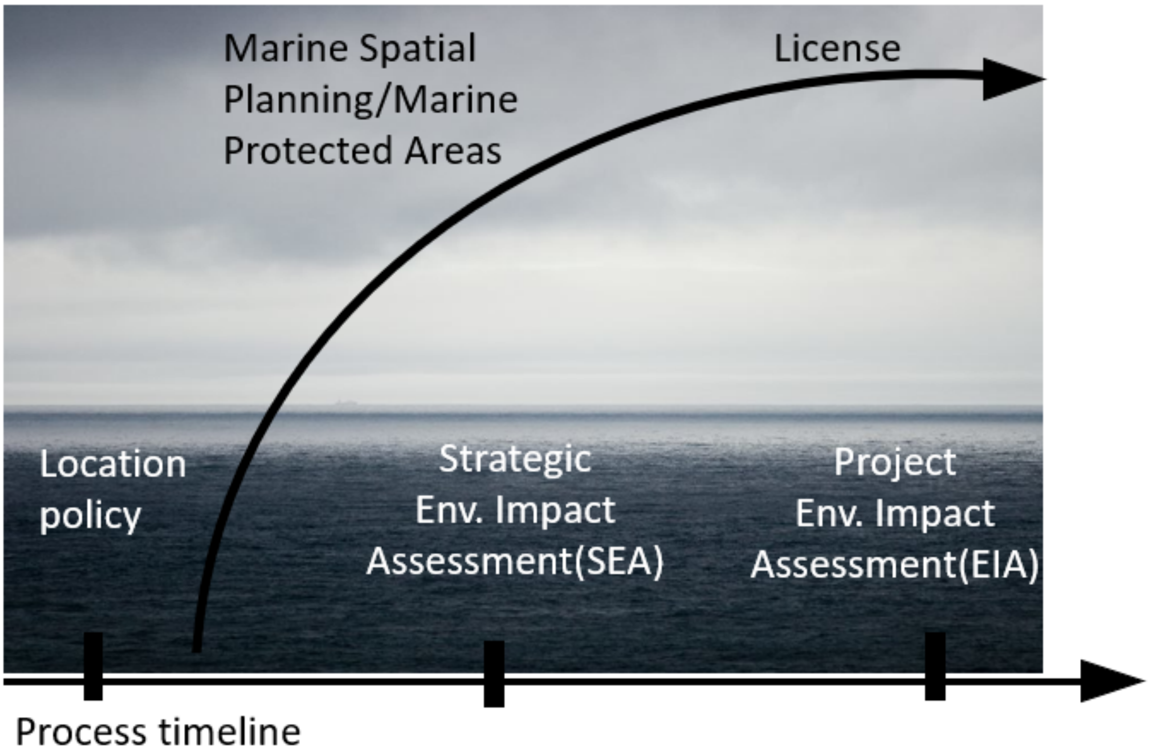

Fig. 1. Illustrating how regulatory, administrative and societal challenges can be structured based on the process timeline for CCS project licensing.

To the extent that a specific jurisdiction has a comprehensive marine management system, the situation surrounding the license application may be different from a situation where no such prior processes or planning takes place. Knowledge sampled and assessed in the marine spatial plan and the strategic impact assessment, and any relevant restrictions or requirements for sea use in law and the established marine plan, will frame the licensing process, the impact assessment and related licence conditions/terms. If the marine spatial plan prescribes multi-use in a potential offshore sub-seabed CO_2 storage site, for example allowing for fishing by trawling, this could have implications for which seabed CO_2-monitoring activity and equipment can be used at the site. Since this report does not consider such national, site-specific requirements that an operator designing a CCS monitoring programme needs to take into consideration, the toolbox needs to address this.

1.3 Regulatory approach. Command and control, co-production and reflexive regulation

In light of the aim of this report, to document the generic relevance of the toolbox, and the focal question of whether there are any minimum legal requirements or precise descriptive requirements for monitoring and monitoring technologies for sub-seabed CCS projects, it is of interest to elaborate on the nature or characteristics of CCS regulation in general, and of monitoring in particular. The CCS regulatory challenges are the same across jurisdictions, and general theories on regulation and regulatory approaches can shed light on the challenges facing us.

It could be argued that the specific regulatory challenge that *monitoring* an offshore storage site faces calls for bottom-up, co-production of regulation and reflexive management-instruments, as opposed to prescriptive command-and-control regulation. Still, strict, prescriptive ruled-based command-and-control regulation – also called top-down regulation – can offer clear rules and certainty for industrial actors. In regulatory theory, this regulation model is commonly understood to involve a centralised authority, usually wielding legal powers of inspection and sanction, overseeing the sector. The system whereby there is a *legal requirement for a licence to start operating* a geological CO_2 storage facility, issued by central authorities, followed by inspections and sanctions, bears these characteristics. The picture is somewhat different as regards the regulation of CCS monitoring.

Industrial complexity and specialisation can result in a burgeoning of siloed sets of 'regulatory spaces'.[20] As each industry is complex, there is a tendency to regulate in silos, ignoring interdisciplinary and crosscutting perspectives. However, it is evident that CCS regulation is not created in a vacuum. Firstly, CCS regulation rests heavily on management and regulatory experience of resource management in general and, for the storage part, of the extraction of hydrocarbons, in particular.[21] Secondly, CCS is restricted by the same global and regional regulatory frameworks and principles as other industries. One example is the no-harm rule, a widely recognised principle of customary international law whereby a state is duty bound to prevent, reduce and control the risk of environmental harm to other states. Other examples are the principles of environmental impact assessment and risk assessment. These are regulatory principles that frame national industries across sectors. It can be noted that it is generally difficult to draw a strict line defining which norms are considered to be international 'law', and, within environmental law, it has been particularly difficult to develop new international rules by custom or by treaties. This has led to widespread use of instruments that are not seen as legally binding, but which still establish standards or norms in the form of guidelines, codes of conduct, declarations of principles etc.[22]

CCS operates in a rapidly changing socioeconomic, technological and physical environment – complex adaptive systems characterised by unpredictable behaviour. One common strand in many areas of international and EU marine regulation is a call for adaptive management that would facilitate a close link between the latest scientific knowledge on the condition and functioning of the marine environment, on the one hand, and the management of human activities at sea, on the other.[23] An

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[20] Frank Vibert, *The new regulatory space: Reframing democratic governance* (Edward Elgar Pub, Cheltenham, 2014).

[21] Global status of CCS 2019. Targeting climate change. Global CCS Institute. For Norwegian regulation, the reliance on the regulatory experience from hydrocarbon production is highlighted in the preparatory works, see PRE-2014-12-05-1517, PRE-2014-12-05-1518 Gjennomføring av EUs lagringsdirektiv: Forskrift om utnyttelse av undersjøiske reservoarer på kontinentalsokkelen til lagring av CO2 og om transport av CO2 på kontinentalsokkelen, and Forskrift om endring av forskrift 27. juni 1997 nr 653 om petroleumsvirksomhet Kongelig resolusjon. Statsråd Tord Lien, section 2.2. The arrangement of extraction of hydrocarbons and storage of CO2 in Norway, bears traits of a symbiotic relationship between the state and operators, see generally on the 'symbiotic relationship', Erich Schanze, 'Symbiotic Arrangements', Journal of Institutional and Theoretical Economics (JITE) / Zeitschrift für die gesamte Staatswissenschaft, Vol. 149, No 4 (1993), pp. 691–97.

[22] Ernst Nordtveit, 'Legal Character of Petroleum Licenses under Norwegian Law' in Tina Hunter, Ignacio Herrera, Penelope Crossley and Gloria Alvarez (eds.), *Routledge Handbook of Energy Law,* (Chapter 8, Routledge, 2020).

[23] Maria Froukje Platjouw and Niko Soininen, 'Reconciling the rule of law with adaptive regulation of marine ecosystems – Challenges and opportunities for the Arctic and beyond', Marine Policy, Volume 110 (2019).

adaptive approach acknowledges that management must adapt and should incorporate new information as it becomes available. It is argued that public institutions must shift from using top-down regulation focused on risk management and instead build resilient, adaptive systems.[24] At the same time, efficiency and the question of having sufficient resources and competence in the administration, could indicate that it is necessary for public institutions to expand the managerial capacities of CCS operators to solve monitoring problems, foster cooperative behaviour and strengthen innovation among operators. Thus, industry actors do not just play the role of regulatory recipients, since they also take part in modelling regulation and conditions for operation. However, adaptive regulation may be problematic if political discretion in environmental management is not sufficiently controlled by law,[25] and if the administration does not have sufficient capacity and competence.

Cyclical monitoring planning is a reflexive and flexible element we typically find in CCS monitoring.[26] The monitoring programme is not fixed for the whole lifespan of storage site, but should be revised to take account of changes in the assessed risk of leakage, changes in the assessed risks to the environment and human health, new scientific knowledge, and improvements in best available technology.[27] Principles for monitoring to assure environmentally safe storage within a proportionality framework[28] can be identified. What constitutes proportional monitoring requirements within a specific CCS project is decided in a dialogue-based process between the regulators/administration, the operator and third-party stakeholders, i.e. the general public, fishermen's organisations etc., facilitated by participatory assessment and decision-making processes.

Even though core elements of the CCS regulation have traits of command-and-control, the particular monitoring elements of the regulation may be better characterized as bottom-up, co-production of regulation and flexible principle-based regimes using reflexive and adaptive management instruments.

1.4. Global and Regional Regulations

1.4.1 Introduction

The regulation of capture, transport and storage of CO_2 has implications for a wide range of national laws and regulations, from land-use planning and energy regulation to tort law. In this section, the focus is on national law and the requirement for a licence to start operating geological CO_2 storage, and a related monitoring programme. We will look at international and regional regulation, examining whether there are any minimum legal requirements or precise descriptive requirements for monitoring and monitoring technologies. As we will document, there are no legal requirements prescribing the use of specific monitoring *technologies* in relation to storage of CCS, since, as far as we

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[24] Nikolaos Giannopoulos, 'Global environmental regulation of offshore energy production: Searching for legal standards in ocean governance' RECIEL 28:289 (2019).

[25] Platjouw and Soininen (2019).

[26] On the general notion of adaptive management in the CCS regulatory context, see S. Bell, 'The Legal Framework for carbon capture and storage' (CCS), in Geological Storage of Carbon Dioxide (CO2), Woodhead Publishing Limited, 2013, Chap. 9 p 221. It is stated that this 'notion of adaptive management involves the design of a project, complete with monitoring and active management as a method of testing assumptions and predicted behaviours. This puts law and regulation at the heart of a learning system which can adapt and change to different circumstances, evolving and responding to the information received. In particular, it is a participatory system involving key stakeholders in making decisions about the most effective and efficient responses to the changing circumstances'.

[27] See, e.g., the CCS directive art. 13 (2) and, on similar regulation, sections 1.4 and 1.5 below.

[28] Proportionality is well-recognised as a crucial element of flexible regulatory systems; for health regulation, see Fletcher, Birko, Dove et al. (2020).

have been able to establish, the regulation is *technology-neutral*, reflecting *the principle of best available technologies*. Even if no specific technology is required for monitoring storage, the regulation identifies different storage *phases* and different *monitoring aims* in these respective phases. Thus, even though there are no specific regulations as regards technology, monitoring phases with pertaining aims are recommended (soft law, guidelines) or mandatory (hard law, prescribed). This has implications for the design of the toolbox.

To elaborate, in this section we will examine the international and regional regulatory level. Existing CCS monitoring policy, international agreements, legislation, regulation, guidelines and protocols include a wide range of instruments, such as the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, the United Nations Framework Convention on Climate Change (UNFCCC) Clean Development Mechanism (CDM) Modalities and Procedures (for developing countries), the London Convention and Protocol, regional instruments, such as the European Union (EU) CCS Directive and Emission Trading Scheme (ETS) Directive, and the OSPAR convention.

The instruments have different aims and objectives, making them more or less relevant to monitoring. For the purpose of this study, it is of relevance to identify the *legal character* of the instruments. Some are *soft law* instruments such as guidelines and recommendations, while others are *hard law* and set minimum requirements. It is important to note that, even though a regulation is a hard law instrument, it can use different regulatory techniques, ranging from prescriptive requirements – which state what should be done, and how – to regulations that set requirements for the types of activities to be performed, or the outcomes or goals to be reached. Thus, with a project licensed under hard law, mere regulatory recommendations setting out what 'may' be done, could still be a relevant approach. This makes the label 'hard law' less informative. Instead, we here use the term/question of whether hard law prescribes something/is prescriptive. The international and regional level was studied by Dixon and Romanak in 2015,[29] and Dixon et al. in 2015,[30] so here we simply aim to provide an overview. The text will, however, go further in elaborating on the EU CCS directive, which is the most refined legal instrument for offshore CCS.

1.4.2 Global

The IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) are, as their title indicates, *soft law* instruments, with no legally binding force. The inventory methods are consistent with the IPCC Special Report on Carbon Dioxide Capture and Storage (2005).[31] The guidelines were refined in 2019 to help all UNFCCC Parties to use good practice inventory methodologies based on up-to-date scientific knowledge, but none of the changes are relevant to CO_2 transport, injection and geological storage.

In the guidelines, CCS is recognised as an emissions reduction technology, see Volume 2, Energy, Chapter 5 on 'Carbon Dioxide Transport, Injection and Geological Storage'. The guidelines primarily concern GHG accounting, and provide methodologies for estimating and reporting national anthropogenic greenhouse gas sources and sinks.[32] Dixon and Romanak state that this methodology

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[29] Dixon and Romanak (2015).

[30] Dixon et al. (2015) pp. 431–448.

[31] Overview 10 2006 IPCC Guidelines for National Greenhouse Gas Inventories, p. 10.

[32] The *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* was adopted and accepted during the 49th Session of the IPCC in May 2019. (Decision – IPCC-XLIX-9 – Adoption and Acceptance of 2019 refinement).

‘has become the basis for all subsequent international regulation and legal guidance for CO_2 geological storage’.[33] This makes the guidelines particularly interesting.

> The guidelines only apply to geological storage. Any other type of storage, such as ocean storage (in the sea column), or conversion of CO_2 into inert inorganic carbonates, is not encompassed. The guidelines address the following phases: capture, transport, injection and storage. The focus here is on storage, but we note that there are no technology-specific recommendations for capture, transport or injection. However, the guidelines are quite elaborate, for example concerning injection and monitoring at the wellhead, section 5.5: ‘The amount of CO_2 injected into a geological formation through a well can be monitored by equipment at the wellhead, just before it enters the injection well. A typical technique is described by Wright and Majek (1998). Meters at the wellhead continuously measure the pressure, temperature and flow rate of the injected gas. The composition of the imported CO_2 commonly shows little variation and is analysed periodically using a gas chromatograph. The mass of CO_2 passing through the wellhead can then be calculated from the measured quantities. No default method is suggested and the reporting of the mass of CO_2 injected as calculated from direct measurements is *good practice*.’

Even though the technique and specific instruments are mentioned, the wording ‘typical technique’ and ‘good practice’ indicate the guidance character of this document.

According to Dixon and Romanak the guidelines do not use an approach that calculates emissions from emitting activities and technologies, but instead a ‘measurement-based methodology (a Tier 3 approach)’, monitoring potential leakage. For the purpose of monitoring leakage, understanding the interaction between sea and atmosphere is not crucial, due to the very definition of ‘leakage’: ‘the term leakage is defined as a transfer of CO_2 from beneath the ground surface or sea bed to the atmosphere or ocean’, see section 5.6.1 of the guidelines. Thus, when CO_2 reaches the ocean, a leakage exists. It is further stated that ‘the only emissions pathways that need to be considered in the accounting are CO_2 leakage to the ground surface or seabed from the geological storage reservoir’.

Dixon and Romanak propose that the Tier 3 approach should consist of:[34]

> ‘a) site characterization and identification of potential leakage pathways:
> b) assessment of risk of leakage by combining site characterization and modelling of CO_2 behavior:
> c) monitoring of leakage and of CO_2 behaviour during injection and subsequent updating of models: and
> d) reporting of CO_2 injected and emissions from storage. The measurement-based Tier 3 methodology is further defined to require a monitoring plan to include the following activities:
> - Measurement of background CO_2 fluxes through the ground surface and/or seabed
> - Measurement of CO_2 injected
> - Monitoring of emissions from the injection system
> - Monitoring to determine fluxes through the ground surface and seabed
> - Post-injection monitoring
> - Incorporation of improvements in monitoring techniques/technologies
> - Periodic verification of emissions estimates.’

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[33] Dixon and Romanak (2015).

[34] Ibid.

An activity under the monitoring plan shall thus incorporate improvements in monitoring techniques and/or technologies. This illustrates that a monitoring plan is a reflexive and adaptive regulatory instrument, also as regards technology.

It is interesting to note that the guidelines comment on technology, revealing that it is a *conscious choice* not to point to specific technologies in the guidelines, see section 5.7:

> 'However, a site-specific Tier 3 approach can be developed. Monitoring technologies have been developed and refined over the past 30 years in the oil and gas, groundwater and environmental monitoring industries (also see Annex 1). The suitability and efficacy of these technologies can be strongly influenced by the geology and potential emissions pathways at individual storage sites, so the choice of monitoring technologies will need to be made on a site-by-site basis. Monitoring technologies are advancing rapidly, and it would be good practice to keep up to date on new technologies.'

The view that it would be *good practice* to keep up to date with new technologies is more commonly known as the principle of 'best available technologies'. This site-by-site basis and the best available technology principle are elaborated on in the Guidelines Annex 5.1, summary of potential monitoring technologies:

> 'The techniques that will produce the most accurate results given the circumstances should be used. The appropriate techniques will usually be apparent to specialists, but different techniques can also be assessed for relative suitability. There are no sharply defined detection limits for most techniques. In the field, their ability to measure the distribution, phase and mass of CO_2 in a subsurface reservoir will be site-specific. It will be determined as much by the geology of the site and surrounding area, and ambient conditions of temperature, pressure and water saturation underground as by the theoretical sensitivity of the techniques or measurement instruments themselves.'

In the guidelines, the most commonly used technologies are described in Chapter 5, Annex I, Tables 5.1–5.6. The guidelines are neither exhaustive nor prescriptive, and it is explicitly stated that the monitoring programme 'should … (vi) Incorporate[e] improvements in monitoring techniques/technologies over time', which is also highlighted by Dixon and Romanak. The guidelines further underline that international cooperation will be advantageous for developing monitoring methodologies and technologies.

The guidelines distinguish between 'common monitoring techniques and measurement tools that can be used for monitoring CO_2 in the deep subsurface (here considered to be the zone approximately 200 metres to 5 000 metres below the ground surface or sea bed), the shallow subsurface (approximately the top 200 metres below the ground surface or sea bed) and the near surface (regions less than 10 metres above and below the ground surface or sea bed)'. Deep monitoring and simulation of how CO_2 behaves and migrates, i.e., 'the movement of CO_2 within and out of a geological storage reservoir whilst remaining below the ground surface or the sea bed in the reservoir' as described in section 5.6.1 of the guidelines, are needed to validate the required simulations of CO_2 behaviour in the storage formation. Here, like Dixon and Romanak, we focus on near-surface techniques.

Potential emission pathways are illustrated in Table 5.3 in the guidelines, and 'it is anticipated that every effort will be made to identify abandoned wells in and around the storage site. Inadequately constructed, sealed, and/or plugged wells may present the biggest potential risk for leakage. Techniques for remediating leaking wells have been developed and should be applied if necessary'. Again, we see that the guidelines do not choose specific techniques but point to the fact that such techniques 'have been developed', making the guidelines flexible.

Dixon and Romanak state that the 'attribution of gases is most important for determining leakage accounting and inventories. In effect, the IPCC Guidelines create a monitoring protocol for leakage monitoring in the near-surface (i.e., emissions from storage) that consists of: 1 Measurement of background CO_2 concentrations 2 Leakage detection 3 Leakage quantification'. The authors further state that the concept of 'attribution monitoring' is mentioned in the IPCC guidance, adding: 'however attribution is not included as a decision step in the overall process'. The monitoring protocol, and attribution, are used as models in our analyses; see the conclusions in section 1.4.4 below.

On one point, Dixon and Romanak find the guidelines too specific as regards technology: 'Also contained in the document is a recommendation to use isotopic analysis, specifically in the context of use with baseline measurements, to attribute the source of CO_2; however, as we will show, isotopic and baseline measurements may not be appropriate for attribution at every site. In light of recent technical advances in attribution, the mention of these techniques could be misleading if followed literally.'[35] Still, from a regulatory point of view, it is not a problem if guidelines are specific as regards technology, since they are merely guidelines, not prescriptive rules. The criticism illustrates that the more specific guidelines are, the higher the risk of quickly becoming outdated.

The IPPC guidelines thus build on the principles of best available practice, best available technology and recognition of the fact that monitoring needs to be site-specific. If national law prescribes specific monitoring technologies in general legislation,[36] this could undermine these principles. The legislation could be outdated as to what the best available technologies are, and prescriptive requirements are not flexible enough to allow for a monitoring programme designed on a site-specific basis.

One global regulation is the UNFCCC Clean Development Mechanism (CDM), a mechanism of The United Nations Framework Convention On Climate Change (1997), the 1997 Kyoto Protocol, Article 12, in force from 2005. The Kyoto Protocol is *hard law*, but only binds developed countries, and still only has non-prescriptive commitments, ref. Art. 3 no 1: 'do not exceed their assigned amounts'.[37] The *aim* relates to GHG accounting and protection of the environment, particularly for developing countries.

In addition to national measures, the Kyoto Protocol offers International Emissions Trading, CDM and Joint implementation (JI). A CDM rewards low-carbon projects in developing countries through the creation of carbon credits. In 2011, 'Modalities and Procedures' for CCS were agreed, stating that the monitoring plan shall 'reflect the principles and criteria of international good practice for the monitoring of geological storage sites and consider the range of technologies described in the relevant

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[35] Ibid.

[36] General legislation is legislation that is relevant to more than one project. Some states have a tradition of granting specific projects, often major projects of high economic or environmental impact, licences through a legislative act related to the specific project.

[37] For context, Art. 3 no 1 states: 'The Parties included in Annex I shall, individually or jointly, ensure that their aggregate anthropogenic carbon dioxide equivalent emissions of the greenhouse gases listed in Annex A do not exceed their assigned amounts, calculated pursuant to their quantified emission limitation and reduction commitments inscribed in Annex B and in accordance with the provisions of this Article, with a view to reducing their overall emissions of such gases by at least 5 per cent below 1990 levels in the commitment period 2008 to 2012.'

sections of the Intergovernmental Panel on Climate Change (IPCC) 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006) and other good practice guidance'.[38] Thus, since, as stated above, the IPCC guidelines do not prescribe specific technologies but focus on site-specific monitoring technologies and best available technology, they will be guiding for the Kyoto Protocol.

It is a requirement to provide for 'specific techniques and methods that can: . . . (ii) Detect potential seepage; (iii) Estimate the flux rate and total mass of carbon dioxide from any seepage'.[39] The CDM provides for the use of a variety of monitoring techniques. However, the CDM monitoring protocol only includes performance assessment, leakage detection and leakage quantification. Dixon and Romanak point to the fact that there is no interim step between detecting potential seepage and the requirement to quantify seepage, and that 'this omission could cause difficulties if the CO_2 considered as potential seepage is not from the storage project. It does not preclude the use of attribution monitoring, but neither does mention it as a step. For many of the countries using these rules, there may not be the confidence to encourage additional steps in the monitoring protocol which are not unambiguously already referred to'.[40] As pointed out above, attribution is used as a model in our analyses; see also the conclusions in section 1.4.4 below.

Before we leave the global regulatory arena, we will comment on the global London Convention,[41] and the regional OSPAR Convention.[42] The 1972 London Convention, in force since 1975, *aims for* global protection of the marine environment. The Convention is not concerned with emissions accounting. It is hard law, and promotes the effective control of all sources of marine pollution and to take all practicable steps to prevent pollution of the sea by dumping of wastes and other matter.[43] In 1996, the London Protocol was agreed under the Convention. Under the Protocol, all dumping is prohibited, except for possibly acceptable waste on what is referred to as the 'reverse list'. The Protocol entered into force on 24 March 2006.[44]

OSPAR is a regional hard law instrument on which 15 governments and the EU cooperate to pursue the *aim of* protecting the marine environment of the North-East Atlantic.[45] Emission accounting is not an objective. As regards the scope and purpose of the convention, Article 2, paragraph 1 (a) states that the Contracting Parties are obliged to 'prevent and eliminate pollution' and 'protect the maritime area against the adverse effects of human activities so as to safeguard human health and to conserve marine ecosystems', in accordance with the relevant provisions.

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[38] Decision 10/CMP.7 Modalities and procedures for carbon dioxide capture and storage in geological formations as clean development mechanism project activities.

[39] Ibid.

[40] Dixon and Romanak (2015).

[41] The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972.

[42] Convention for the Protection of the Marine Environment of the North-East Atlantic, 1992.

[43] http://www.imo.org/en/OurWork/Environment/LCLP/Pages/default.aspx

[44] Ibid. There are currently 53 Parties to the Protocol.

[45] OSPAR started in 1972 with the Oslo Convention against Dumping, and was broadened to cover land-based sources of marine pollution and the offshore industry by the Paris Convention of 1974. These two conventions were unified, updated and extended by the 1992 OSPAR Convention. See https://www.ospar.org/about.

The London Protocol was amended in 2006 to allow for CCS, and guidelines were developed in 2006 and 2007.[46] OSPAR was amended to allow for CCS in 2007.[47] OSPAR regulates the storage of CO_2, not capture and the transport, and storage of CO_2 in the water column is prohibited. The framework developed for OSPAR is designed to make 'use of relevant developments within the framework of the London Convention/Protocol (LC/LP), including developments relating to the draft Risk Assessment and Management Framework for CO_2 Sequestration in Sub-Seabed Geological Formations and developments relating to a specific LP waste assessment guideline'.[48] The London Convention and Protocol and OSPAR each have a two-stage monitoring protocol in place for CO_2 geological storage in a similar way to the EU monitoring protocols, although these were developed prior to the EU Directives.[49]

In addition to the protocol, general obligations under the OSPAR convention set the framework for management, some of relevance to monitoring technology. Article 6, in the main text, regulates the '[a]ssessment of the quality of the marine environment'. These assessments are intended to result in the Parties undertaking and publishing 'regular joint assessments of the quality status of the marine environment and of its development' (letter a). Art. 2, paragraph 3 (a) under General obligations, states that, in implementing the Convention, the Parties shall adopt 'programmes and measures' which take 'full account of the use of the latest technological developments and practices designed to prevent and eliminate pollution fully'. While this statement does not directly address the topic of monitoring, it still puts forward the *principle of best available technologies*. Article 2, paragraph 3 (b) accentuates this point by stating that the technology shall take 'into account the criteria set forth in Appendix 1', and represent 'best available techniques', as well as 'best environmental practice'. Appendix 1, paragraph 6, defines '[b]est environmental practice' as the 'application of the most appropriate combination of environmental control measures and strategies'.[50] While this definition seems relevant to the topic of monitoring, it could be argued that the following letters and paragraphs tend to deal more with concrete products and practices that in themselves have the potential to pollute and damage maritime areas.

From a legal perspective, the monitoring protocol of the London Protocol is formulated as mere recommendations, e.g. 'may be included/may include':

> '. . .Monitoring programs should also be designed to minimize the impact of monitoring on the marine environment. The monitoring of sequestration of carbon dioxide streams may include:
> 1 performance monitoring that correlates to how well the injected carbon dioxide stream is retained within the intended sub-seabed geological formation;

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[46] Dixon and Romanak (2015). Transboundary export of carbon dioxide (CO_2) for the purpose of carbon capture and storage can now be provisionally allowed under certain circumstances under the Convention, see http://www.imo.org/en/MediaCentre/PressBriefings/Pages/22-CCS-LP-resolution-.aspx

[47] OSPAR Decision 2007/2 on the Storage of Carbon Dioxide Streams in Geological Formations, OSPAR Guidelines for Risk Assessment and Management of Storage of CO2 Streams in Geological Formations1(Reference Number: 2007-12)

[48] Ibid section I.4.

[49] Dixon and Romanak (2015).

[50] The criteria highlighted in Appendix 1 and the first heading, '[b]est available techniques', paragraph 2 letters a-e, state that certain factors shall be given 'special consideration' when evaluating the techniques. These include 'comparable processes […] which have recently been successfully tried out' (a), 'technological advances and changes in scientific knowledge and understanding' (b), 'economic feasibility' (c), 'time limits' (d), and 'the nature and volume of the discharges and emissions concerned' (e). Paragraph 5 clarifies that the term 'techniques' includes 'both the technology used and the way in which the installation is designed, built, maintained, operated and dismantled'. It seems reasonable to assume that the wording 'technology used' includes monitoring systems.

> 2 monitoring the surrounding geological layers to detect migration of the carbon dioxide stream and the substances mobilized as a result of the disposal of the CO_2 stream, as appropriate, within and beyond the intended sub-seabed geological formation;
> 3 monitoring the seafloor and overlaying water to detect leakage of the carbon dioxide stream, or substances mobilized as a result of the disposal of the CO_2 stream, into the marine environment.
> 4 monitoring marine communities (benthic and water column) to detect effects of leaking carbon dioxide streams and mobilized substances on marine organisms.
> Monitoring the seafloor and marine communities may be included, especially if it is suspected that migration of CO_2 above the formation could extend to the seafloor.'

Similarly, the monitoring protocol of OSPAR is formulated as:

> 'Monitoring of CO_2 containment and migration may include the following elements:
> a) performance monitoring (sometimes referred to as testing the Impact Hypothesis) which measures how well the injected CO_2 stream is retained within the intended geologic formation; and
> b) monitoring the geological layers above the formation to detect and measure possible migration of the CO_2 stream out of the intended formation;
> The following items may be included, especially if it is suspected that migration of CO_2 above the formation could extend to the seafloor:
> a) monitoring the seafloor and overlaying water to detect and measure possible leakage of CO_2 (and incidental associated substances) into the marine environment.
> b) monitoring biological communities to detect and measure the effects of leakages on marine organisms.'

Dixon and Romanak (2015) summarise these protocols and argue that attribution is imperative; 'It can be seen that within these monitoring protocols, the first stage is for performance monitoring of the CO_2 in the storage formation and leakage detection at depth. The second stage is for environmental impact assessment in the event that leakage is suspected, which then requires monitoring of the seafloor and marine communities. Such monitoring of the seafloor, overlaying water, and biological communities for environmental and ecological change could be challenging and costly. Furthermore, with climate change altering ecosystems it is important to understand if environmental damage is from the project or from naturally occurring CO_2 increases in the ocean. Thus, attribution would be imperative not only for justifying heightened monitoring (which in itself could impact the marine ecosystem) but also for separating the impacts of leakage from those arising from atmospheric-driven ocean acidification.'[51] The issue of attribution is also relevant to distinguishing between a natural biogenic/volcanic seep and a CCS project or a seep from a nearby reservoir, in the case of multiple storage projects. As pointed out above, attribution is used as a model in our analyses; see further the conclusions, section 1.4.4 below.

1.4.3 EU

For EU members, the EU CCS Directive[52] is *hard law*, and Member States were obliged to transpose the directive into their national legislation by 25 June 2011. The *aim* of the directive is to establish a legal

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[51] Dixon and Romanak (2015).

[52] Consolidated text: Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006 (Text with EEA relevance).

framework for the 'environmentally safe geological storage of carbon dioxide (CO_2)' in order to contribute to the fight against climate change, as stated in Article 1. The purpose of environmentally safe geological storage of CO_2 is permanent containment of CO_2 in such a way as 'to prevent and, where this is not possible, eliminate as far as possible negative effects and any risk to the environment and human health'. The directive provides a minimum set of rules (minimum harmonisation), which means that Member States may adopt more stringent rules on the national level. Thus, Member States 'have considerable discretionary powers while implementing the Directive. In addition, Member States may still issue additional rules governing CCS'.[53] In general, more stringent rules cannot undermine the purpose of the regulation.

Art. 3 defines concepts in the directive. The definitions are interesting in relation to, e.g., the detection of leakages. The concepts all reflect the fact that detection and attribution of leaks and anomalies relate to the *CO_2 injected by the developer;* 'leakage' means 'any release of CO_2 from the storage complex' (5); 'significant irregularity' means 'any irregularity in the injection or storage operations or in the condition of the storage complex itself, which implies the risk of a leakage or risk to the environment or human health' (17).

Monitoring of storage is closely related to site selection and assessment of risk of leakage. The selection of a storage site is regulated in Art. 4, which states that '[t]he suitability of a geological formation for use as a storage site shall be determined through a characterisation and assessment of the potential storage complex and surrounding area pursuant to the criteria specified in Annex I' (3-4). It is a criterion that a geological formation shall only be selected if there is no 'significant risk of leakage' and if no significant environmental or health risks exist under the proposed conditions. Annex I contains three steps for the characterisation and assessment of the potential storage complex and surrounding area referred to in Article 4(3). The characterisation and assessment shall be carried out in three steps 'according to best practices at the time of the assessment and to the following criteria' (Annex 1, introduction). However, the steps and relevant criteria are not strict provisions, as the national state can grant derogations: 'Derogations from one or more of these criteria may be permitted by the competent authority provided the operator has demonstrated that the capacity of the characterisation and assessment to enable the determinations pursuant to Article 4 is not affected.' This reflects the fact that in this context the regulation is oriented towards the overall objective or goal that is to be reached, rather than being descriptive. This leads to the conclusion that the directive, by regulating site selection, does not set absolute requirements for the monitoring of storage.

Here, some details of the above-mentioned three steps of regulation of characterisation and assessment in Annex I will be provided. Step 1 consists of data collection:

> 'Sufficient data shall be accumulated to construct a volumetric and three-dimensional static (3-D)-earth model for the storage site and storage complex, including the caprock, and the surrounding area, including the hydraulically connected areas. This data shall cover at least the following intrinsic characteristics of the storage complex: (a) geology and geophysics; … (c); (d) geochemistry (dissolution rates, mineralisation rates); (e) geomechanics (permeability, fracture pressure); (f) seismicity; (g) presence and condition of natural and man-made pathways, including wells and boreholes which could provide leakage pathways.'

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[53] Lako P, van der Welle AJ, Harmelink M, van der Kuip MDC, Haan-Kamminga A, Blank F, and de Wolff J, Nepveu M. 'Issues concerning the implementation of the CCS Directive in the Netherlands'. Energy Procedia; 201; 4 (2011): 5479–5486.

Further, (h) to (l) relate to characteristics of the vicinity of the complex.

Using the data collected in Step 1, Step 2 will build a ‘three-dimensional static geological earth model, or a set of such models, of the candidate storage complex, including the caprock and the hydraulically connected areas and fluids shall be built using computer reservoir simulators’.

Step 3 relates to characterisation of the storage dynamic behaviour, sensitivity characterisation and risk assessment. Three sub-steps are identified: 3.1. Characterisation of the storage dynamic behaviour; 3.2. Sensitivity characterisation, ‘where multiple simulations shall be undertaken to identify the sensitivity of the assessment to assumptions made about particular parameters’, where any ‘significant sensitivity shall be taken into account in the risk assessment’; 3.3. Risk assessment, which shall comprise hazard characterisation ‘undertaken by characterising the potential for leakage from the storage complex, as established through dynamic modelling and security characterisation described above’, and shall include consideration of, ‘inter alia: (a) potential leakage pathways; (b) potential magnitude of leakage events for identified leakage pathways (flux rates); (c) critical parameters affecting potential leakage … (e) any other factors which could pose a hazard to human health or the environment (for example physical structures associated with the project). The hazard characterisation shall cover the full range of potential operating conditions to test the security of the storage complex’. Further, the risk assessment shall comprise an exposure assessment, ‘based on the characteristics of the environment and the distribution and activities of the human population above the storage complex, and the potential behaviour and fate of leaking CO_2 from potential pathways identified under Step 3.3.1’ and effects assessment, ‘based on the sensitivity of particular species, communities or habitats linked to potential leakage events identified under Step 3.3.1. Where relevant, it shall include effects of exposure to elevated CO_2 concentrations in the biosphere (including soils, marine sediments and benthic waters (asphyxiation; hypercapnia) and reduced pH in those environments as a consequence of leaking CO_2). It shall also include an assessment of the effects of other substances that may be present in leaking CO2 streams (either impurities present in the injection stream or new substances formed through storage of CO_2). These effects shall be considered at a range of temporal and spatial scales and linked to a range of different magnitudes of leakage events’. Finally, a risk characterisation, which ‘shall comprise an assessment of the safety and integrity of the site in the short and long term, including an assessment of the risk of leakage under the proposed conditions of use, and of the worst-case environment and health impacts. The risk characterisation shall be conducted based on the hazard, exposure, and effects assessment. It shall include an assessment of the sources of uncertainty identified during the steps of characterisation and assessment of storage site and when feasible, a description of the possibilities to reduce uncertainty’.

Leaving Annex I and returning to the Directive’s main text, Member States shall, when granting exploration permits, ensure that they are open to ‘all entities possessing the necessary capacities and that the permits are granted or refused on the basis of objective, published and non-discriminatory criteria’, Article 5.2. Article 13, in Chapter 4 on ‘[o]peration, closure and post-closure obligations’, directly tackles the topic of monitoring. The article’s first paragraph, letters a through g, states the purpose of the monitoring. The second paragraph says that the monitoring plan needs to be in accordance with the requirements in Annex II, Articles 7(6) and 9(5) of the CCS directive, as well as Articles 14 and 23(2) of Directive 2003/87/EC.

Annex II (as referenced in Article 13) and its point 1.1, ‘Establishing the plan’, states that the monitoring plan ‘shall provide’ details of the monitoring to be deployed in the main stages of the project, including baseline, operational and post-closure monitoring. Due to this provision, and the heading of Chapter 4 (which contains Article 13), which states its relevance to 'operation, closure and post-closure', the above-mentioned aspects of the directive are relevant to all the phases of the CCS procedure.

Annex II point 1.1 is relevant for understanding what the ACTOM toolbox must deliver. Here, it is stated that the following 'shall' be specified *for each phase:* 'a) parameters monitored; (b) monitoring technology employed and justification for technology choice; (c) monitoring locations and spatial sampling rationale; (d) frequency of application and temporal sampling rationale'. The monitoring technology employed and justification for technology choice will be helped by the ACTOM web-based monitoring design tool.

Annex II, specifically its third paragraph, sections j, k and l, gives some clear-cut directions as regards the monitoring technology. They relate to '[t]he choice of monitoring technology', underlining the situational, site-by-site approach. This choice 'shall be based on best practice available at the time of design'. It then follows that certain features 'shall be considered and used as appropriate', for example that they 'can detect the presence, location and migration paths of CO2 in the subsurface and at surface' (j), as well as further requirements in k and l. This part of the directive seems to be highly relevant to deciding what type of technology to use, albeit not in such a way that it promotes one type of technology or product over another. Rather, it refers to best practice/best available technology.

Returning to the Directive and its main text, both Articles 7(6) and 9(5) deal with the topic of storage permits, but are not relevant to the topic of monitoring specifically. Article 14 of Directive 2003/87/EC (with reference to Annexes I and IV) tackles the question of how to monitor emissions accurately (in more technical terms). Article 23(2) does not seem to be relevant.

The Directive thus has parts which states what standards should be met by the monitoring technology. Besides that, it does not prescribe the direct choice of that technology.

Operators of CCS in the EU need to carry out an Environmental Impact Assessment of the project under the EIA Directive,[54] and, according to the Preamble to Directive no 18, Article 6 of the Aarhus Convention provides for public participation in decisions. The EIA process under the Directive is thus open for public and stakeholder participation. Operators of CCS are further included in the EU Emissions Trading System (ETS).[55] The ETS Directive establishing a system for trading[56] includes CCS in Annex I. Emissions stored according to the CCS Directive will be considered as not emitted, and emissions allowances need not be surrendered. In the event of leakage from the storage, the operator

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[54] Directive 2011/92/EU of the European Parliament and of the Council of 13 December 2011 on the assessment of the effects of certain public and private projects on the environment Text with EEA relevance, and Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment Text with EEA relevance. See Section 4 no 1, which states that Annex I projects shall be made subject to an assessment; Annex I; no 16 for pipelines with a diameter of more than 800 mm and a length of more than 40 km (b) for the transport of carbon dioxide streams for the purposes of geological storage, including associated booster stations; no 22 for storage sites pursuant to the CCS Directive; no 23 for installations for the capture of CO2 streams for the purposes of geological storage pursuant to the CCS Directive from installations covered by Annex I, or where the total yearly capture of CO2 is 1.5 megatonnes or more. For projects below the thresholds listed in Annex II, Member States shall, pursuant to Art. 4 no 2, determine whether the project is likely to have significant effects on the environment, Art. 2, and be made subject to an assessment.

[55] For the main legislation see https://ec.europa.eu/clima/policies/ets_en#Main_legislation

[56] Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a system for greenhouse gas emission allowance trading within the Union and amending Council Directive 96/61/EC.

will have to surrender emission allowances. To quantify allowances, any emissions from leakage must be measured. It is a regulatory barrier that projects planning to transport CO_2/deliver to the transporter by other means than pipelines, such as the Norwegian Longship, which is designed for transport by ships, would need to pay for emissions. For the time being, therefore, the legislation represents a regulatory barrier to projects that wish to transport CO_2 by different means (e.g. trains and barges).[57]

If we read the monitoring requirements of the directives, and the aims they are intended to fulfil, in context, it is only quantifying leakages attributed to a storage leakage, as opposed to emissions of natural CO_2, that is a legal requirement. Dixon and Romanak (2015) argue that, while the CCS and ETC directives 'do not preclude the use of attribution techniques, neither do they specify them', and point to 'one incidence of over-rigorous application of these monitoring requirements in a way that was not intended in their design'. Therefore they argue that 'adding a step for unambiguous clarification of attribution in these protocols would be helpful'.[58]

Lako et al. underline problems relating to the regulatory approach (minimum harmonisation) taken in the CCS Directive.[59] First, they argue that the way in which Member States apply their discretionary powers may negatively impact the development of CCS in individual Member States. Second, they argue that

> 'It is possible that requirements in the Directive are implemented in a more rigorous manner in one Member State than in another Member State. This can lead to the situation that investors' propensity to invest in CCS is likely to differ substantially between Member States (there will be no level playing field).'[60]

The EU's single market is a developed *level playing field*, which is a trade policy term that refers to a set of common rules and standards regarding workers' rights and environmental protection (that prevent businesses in one country from undercutting their rivals in other countries). CCS as a climate technology could thus be hindered by rigorous national regulation. Another argument for national states showing caution as regards adding specific national requirements when implementing the CCS Directive, is the general limitation related to minimum harmonisation, i.e. that more stringent rules cannot undermine the purpose of the regulation.

Lako et al. further relate this second problem to monitoring:[61]

> 'Accuracy of monitoring technologies is not laid down in the CCS Directive. The Directive describes the assessment which should take place to guarantee complete and permanent containment of CO_2 in storage facilities, but does not prescribe any particular monitoring technology. Because the monitoring method applied influences the storage costs of the operator, this might cause unfair competition for location of CO_2 storage across EU Member States if monitoring is given different interpretations by several Member States. However, the recent CCS monitoring and reporting guidelines for the Emission Trading System provide more direction on the way monitoring and reporting of emissions of greenhouse gas in the CCS chain should be carried out. As leakage is included as one of the potential sources of

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[57] Global status of CCS 2019. Targeting climate change. Global CCS Institute, p 33.

[58] Dixon and Romanak (2015).

[59] Lako et al. 2011.

[60] Ibid.

[61] Ibid.

> CO_2emissions, this guideline does also include emission quantification rules for leakage from storage sites. Leakage of a storage complex has to be quantified with a maximum total uncertainty of ±7.5%. If the uncertainty is above ±7.5%, the “excess” uncertainty with respect to ±7.5% requirement has to be added to the reported greenhouse gases. Note that it is up to the operator to prove the overall uncertainty he claims for the results, which in itself will require non-trivial numerical “experimenting”. This method seems fair, as it helps to keep monitoring costs to an acceptable level for emissions that will probably not occur. And from the other side it keeps the uncertainty of the emission in line with uncertainty generally required in the MRG for emission accounting under ETS.’

The authors thus conclude that stricter requirements ‘seem not necessary as a higher accuracy in emission estimates will imply higher costs. Furthermore, the EC guidelines narrow the scope for unfair competition for location of CO_2 storage across the EU’. Therefore, they conclude that the problem – if monitoring is given different interpretations by several Member States due to the regulatory technique of minimum harmonisation– ‘has been resolved’ by the guidelines quantifying a maximum total uncertainty of ±7.5%.

1.4.4 Conclusions on global/regional regulations; premises for further analyses

Existing CCS monitoring policy, international agreements, legislation, regulations, guidelines and protocols at the international and regional level have, despite their different objectives and varying levels of detail, similar principles and requirements for monitoring.[62]

We find that, globally and regionally, the guidelines and regulations are based on the principles of best available practice, best available technology, and recognition of the fact that monitoring needs to be site-specific. If national law prescribes specific monitoring technologies, this could undermine these principles. General legislation could be outdated as regards what the best available technologies are, and prescriptive requirements might not be flexible enough to allow for a site-specific designed monitoring programme. As far as we have been able to establish, no specific monitoring technologies are prescribed by law, globally or regionally. In the EU, in accordance with the principle of best available technology, the accuracy of monitoring technologies is not laid down in the minimum requirements of the CCS Directive. An EU-contextual argument against more rigorous implementation in national states, compared to the minimum requirements of the CCS Directive, is that this could interfere with the level playing field/lead to disturbance of competition.

Based on international and regional CCS guidelines and regulations, even though no specific technology is required for monitoring the storage, the regulation identifies different storage *phases: pre* injection of CO_2, *during* injection, and after (*post*) storage is sealed. Monitoring has different *monitoring aims* in these respective phases, as described by Dixon and Romanak. Thus, even if there are no regulatory specifics on technology, monitoring phases with respective aims are recommended (soft law, guidelines) or mandatory (hard law, prescribed). The EU CCS Directive could be viewed as the most elaborate here, as some in-depth examples form the Directive illustrate, see section 1.4.3. Dixon and Romanek identify these phases and monitoring aims and suggest yet other aims that should be included in the guidance, namely leakage attribution. The consolidated list of monitoring aims in different phases, taken from Dixon and Romanek, is illustrated in Fig 2.

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[62] Dixon and Romanak (2015).

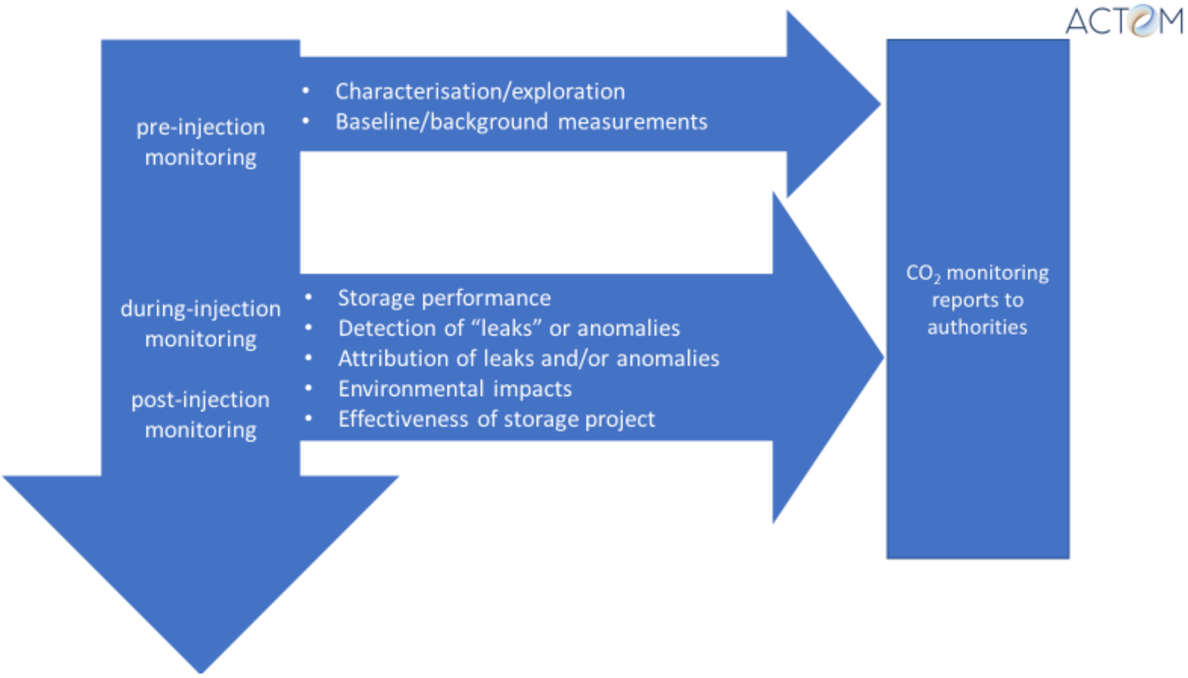

Fig 2. Storage *phases*; *pre*-injection, *during* injection and after (*post*) storage, and *monitoring aims* in these respective phases, as described by Dixon and Romanak.

Monitoring to detect leakages is important, as leakages call for countermeasures, for example ceasing to inject CO_2. Monitoring to quantify (quantification monitoring) any leakage from the storage is likewise important due to the economic implications for carbon quotas and trade. However, as CO_2 can be emitted as a result of natural processes on the seabed and underground, and since the CO_2 level in the sea column is naturally variable, it is vital to identify the source of 'excess' CO_2. Existing monitoring instruments have been criticised, as they do not all include the clarification that quantification monitoring should only be undertaken in cases where CO_2 has been attributed to a leakage and not when leakage is only suspected.[63] Quantifying suspected emissions is a significant monitoring challenge and may rely on acquiring large data sets over long time periods, and this level of effort in monitoring would be unnecessary if the source of CO_2 detected at the surface is attributed to natural sources rather than to leakage.[64] Technical advances in leakage monitoring and new technical advances in attribution suggest that CO_2 'attribution monitoring' could now be included in monitoring protocols to avoid unnecessary and costly quantification monitoring unless it is fully warranted.[65]

From a legal perspective, it could be argued that, when regulations prescribe quantification, this is, seen in context, in order to evaluate potential environmental impacts or to account for loss of storage under carbon quotas. Thus, even if not explicitly stated, a particular quantification monitoring requirement, interpreted in the regulatory context, could lead to the conclusion that it is only a legal requirement to quantify leakages attributed to storage leakage, as opposed to emissions of natural CO_2. Further, even if not explicitly stated, imposing new technical advances in monitoring and

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[63] Ibid.
[64] Ibid.
[65] Ibid.

attribution could be supported by general principles of law relating to 'best available technology' and practice as expressed in many international and national regulations, also in relation to CCS.

Further, our presumption is that existing and future national regulation could potentially relate to all these phases (Fig. 2) and prescribe all these monitoring aims (Fig. 2). An online monitoring tool needs to be able to address these phases and aims to be relevant in all jurisdictions globally.

1.5 National regulation and CCS projects

1.5.1 Introduction

In this section, as stated in section 1.1, national regulations, based on an analysis of legal texts and taking a functional approach, we compare structures and rules that fulfil the same functions in the national systems. The purpose is to document the generic relevance of the ACTOM toolbox, and how designing a monitoring programme based on the toolbox will align with national policy and regulation. The discussion here concerns whether there are any deviations compared to the findings in 1.4.4 within specific countries – are new monitoring *phases* or monitoring *aims* added as mandatory, or are *requirements for specific monitoring technology* added that the ACTOM toolbox needs to meet. As we will document, no examples of such deviations have been found in national legislation.

As pointed out in section 1.1., regulations set requirements for the types of activities and outcomes that are necessary to satisfy the goals prescribed by law, and there are as many possible project outcomes as there are projects. We stated that the CCS licensing process is not a single point of contact, as the administration works with project developers over time, but with virtually standard procedures for site selection/characterisation and risk assessment, monitoring and reporting. An Environmental Impact Assessment for the project will be open to public and stakeholder participation. These participatory assessment and decision-making processes define the framework for the content of the site-specific monitoring plan. The specifics of the monitoring plan are developed in a dialogue-based process between the operator and regulators/administration, making the monitoring plan a co-product, as discussed in section 1.3. In this process of designing a site-specific monitoring plan, framed by participatory environmental impact and risk assessment and decision-making processes, it could be argued that it would be a disadvantage if the specific choice of monitoring technology were pre-defined in regulations. The monitoring plan and choice of monitoring technology need to address the specific risks, public concerns and stakeholder interests raised in the process.

In addition to comparing national regulation in this section, we include examples from some particular marine CCS licensing processes carried out under national law, and their monitoring programmes. A particular monitoring programme for a CCS project, as part of the licence, is usually not categorised as 'law' or 'regulation' but as terms of a specific licence. These terms are specific management decisions and, as such, are not law, and the specific content of such management decisions is thus not relevant to the design of the ACTOM toolbox. It is worth noting that the distinction between law/regulation and management decisions is still vague, as, over time, management decisions can evolve into good practices. Good practice developed over time with generic relevance will typically be transformed into law or regulations. What is suitable for regulation, as opposed to what is left to the executive agencies to decide on a case-by case basis, typically evolves over time. Case studies of particular marine CCS licensing processes and their monitoring programmes merely illustrate how monitoring requirements are operationalised in specific cases, but they could also reflect what may become tomorrow's regulation. However, the study of technologies chosen in monitoring plans under specific licences has less relevance as illustrations of what could become regulation, because, as stated above, it would be a disadvantage if the specific choice of monitoring technology were pre-defined in regulations. Rather than focusing on the technologies in the specific monitoring plans, the cases will be used to illustrate the dialogue-based process between the operator and regulators/administration when developing the monitoring plan and choosing the technology.

Our case studies exemplify the use of national regulation in specific cases, and are not intended to be exhaustive. Cases are chosen based on which projects have been developed or are under development, and how far they have come in the licensing process. An important source of information on the projects is the CCUS Projects Network, which comprises and supports major industrial projects under way in the field of carbon capture and storage CCS and CCU across Europe.[66] The Network aims to speed up delivery of these technologies, which the European Commission recognises as crucial to achieve 2050 climate targets.

1.5.2 China

Despite efforts by China to limit coal in its energy mix, it is argued that coal is expected to remain a dominant fuel in the country in the foreseeable future, and that CCS is the only viable option for reducing CO_2 emissions in carbon-intensive, coal-chemical, steel, cement, and refinery plants.[67] There are a large number of coal-chemical plants in the vicinity of oilfields in which CO_2 capture is a low-cost possibility that enables CO_2-Enhanced Oil Recovery (EOR).[68] The shortage of water for onshore EOR is another argument that makes CCS very interesting. However, in 2018, annual operational CCS capacity in China was no more than 2 million tonnes.[69] The onshore Yanchang Integrated Carbon Capture and Storage facility in the Ordos Basin, Shaanxi province, the country's coal heartland, is the first large-scale CCS facility to move into construction in China, as well as in Asia.[70] Over the past decade, the government has developed its capacity across the CCS chain.[71] Research, the initiation of pilot projects and extensive international cooperation have led to an adequate level of readiness to build large-scale CCS demonstration projects, allowing the deployment of CCS in the next 10–15 years in China's 23 main onshore basins and nine main offshore basins.[72]

It is argued that countries such as Australia, Canada, Norway, the United Kingdom (UK), and the United States (USA) and their demonstration projects present significant opportunities for China, which can learn from sharing these countries' knowledge and practical experience when planning and executing large-scale demonstration projects. The absence of an adequate price for carbon and targeted incentives to offset higher capital investments and the lack of proven suitable storage sites are mentioned as reasons for the lack of an economic driver for CCS.[73] It is stated that early stage demonstration projects will need financial support, enabling policies, and an appropriate regulatory

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[66] See https://www.ccusnetwork.eu/

[67] Roadmap for Carbon Capture and Storage demonstration and deployment in the People's Republic of China, Nov. 2015, Asian Development Bank, ISBN 978-92-9257-042-2 (Print), 978-92-9257-043-9 (e-ISBN)

[68] Ibid.

[69] Global CCS institute, Insights, 18 June 2018, Carbon capture and storage in de-carbonising the Chinese economy.

[70] Ibid.

[71] Roadmap for Carbon Capture and Storage demonstration and deployment in the People's Republic of China, Nov. 2015, Asian Development Bank, ISBN 978-92-9257-042-2 (Print), 978-92-9257-043-9 (e-ISBN)

[72] See ibid. section 26 p 7, which states that, for the Roadmap, the storage capacity potential of saline aquifers, oil fields, and gas fields in the 23 main onshore basins and nine main offshore basins was reviewed and assessed.

[73] Roadmap for Carbon Capture and Storage demonstration and deployment in the People's Republic of China, Nov. 2015, Asian Development Bank, ISBN 978-92-9257-042-2 (Print), 978-92-9257-043-9 (e-ISBN).

framework to cover associated risks.[74] It is recommended that a Comprehensive CCS regulatory framework be put in place, and that China in this process can benefit from international experience.[75] It is argued that progressing the establishment of CCS-specific legal and regulatory regimes will support CCS in China.[76]

The first CCS demonstration projects are expected to be with CO_2-EOR in the coal-chemical sector, and they will need to meet several key criteria.[77] The projects should (i) comprise a large-scale coal-chemical process that will provide a high-purity CO_2 source, not less than 100,000 t per year and preferably close to or in excess of 1 $MtCO_2$ per year; (ii) be able to demonstrate that CO_2-EOR is technically feasible; (iii) provide a CO_2 source and CO_2-EOR location close enough to guarantee economic feasibility; and (iv) include the design and implementation of a comprehensive monitoring and verification programme to confirm that injected CO_2 will remain stored in the oil field.[78] It is recommended to adopt crucial standards and norms for monitoring, reporting, quantification and verification. Appropriate greenhouse gas accounting rules should be established to accurately award net emission reductions that are achieved through CCS with CO_2-EOR. In principle, these accounting rules should apply the same criteria as would be applied to a 'pure' storage project to ensure equal treatment.

1.5.3 Japan

Promoting CCS and CCU is part of the Japan's Long-term Strategy under the Paris Agreement.[79] Japan has no CCS-specific legislation and thus no CCS-specific regulatory requirements regarding monitoring phases, aims or specific monitoring technology. There is an ongoing discussion about selecting the most relevant policy instruments for CCS.[80] Progress has been made in relation to selecting potential storage sites. A joint project by the ministries and Japan CCS Co., Ltd. (JCCS) was commissioned to conduct the project 'Investigation of Potential CO_2 Storage Sites'.[81] The project selects prospective sites by acquiring geophysical data and analysing geological structure, taking into consideration the nationwide candidates survey sites for CO_2 storage and an assessment of suitability for CO_2 storage. Tomakomai, in Hokkaido, has been identified as a promising site. It covers an area under the seabed in the offshore area 1 to 3.5 km offshore of Tomakomai Port. Tomakomai was selected from among 115 candidate sites and was authorised by the Evaluation Committee organised by the Ministry of Economy, Trade and Industry of Japan (METI). The data collected in detailed site surveys were used to establish a geological model and to perform simulations of long-term CO_2 behaviour. The results revealed that the geological structures and formations in the Tomakomai area were highly suitable for geological CO_2 storage. Tomakomai is a large-scale, first of its kind, integrated industrial demonstration

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[74] Ibid.

[75] Ibid.

[76] Global CCS institute, Insights, 18 June 2018, Carbon capture and storage in de-carbonising the Chinese economy.

[77] Roadmap for Carbon Capture and Storage demonstration and deployment in the People's Republic of China, Nov. 2015, Asian Development Bank, ISBN 978-92-9257-042-2 (Print), 978-92-9257-043-9 (e-ISBN).

[78] Ibid.

[79] See https://www.env.go.jp/press/802.pdf, and The Long-term Strategy under the Paris Agreement, June 2019 (Cabinet decision, 11 June 2019) The Government of Japan, for further details, see Chapter 3, section 1 (3) b.

[80] Kenichiro Yanagi, Akihiro Nakamura, Eiji Komatsu, 'Policy Instrument Options for Commercialising Carbon Capture and Storage (CCS) in Japan', https://mrepo.lib.meiji.ac.jp/dspace/bitstream/10291/20175/1/lawjournal_26_17.pdf

[81] https://www.japanccs.com/en/business/research/

project of CCS offshore in Japan. It consists of two formations; a formation of sandstone at a depth of 1,000–1,200 m, and volcanic rocks at a depth of 2,400–3,000 m.[82]

Since Japan has no CCS-specific regulation, already existing laws and regulations were applied to Tomakomai.[83] The Act on Prevention of Marine Pollution and Maritime Disaster (Law No 136, 1970) prohibits waste disposal into the sub-seabed. Responding to the amendment of Annex I of the London Protocol 1996, the Act was amended in 2007, allowing operators to dispose of gases overwhelmingly consisting of CO_2 into the sub-seabed,[84] with permission from the Minister of the Environment. When applying for permission, the operator must submit an implementation plan, monitoring plan and environmental impact assessment report. A monitoring plan is a prerequisite for being granted a licence, and the operator has to comply with the plan.[85] The operator has responsibility for monitoring while disposal is ongoing.[86] As there were no management standards for CO_2 -injection, the Tomakomai project took measures to comply with the 2009 guidelines for safe operation of a CCS demonstration project, taking into account international CCS regulations, technical standards and guidelines. This resulted in a 'Reservoir Management Standards Manual During CO_2 -injection'. [87]

A 'Monitoring Plan' pursuant to the Act on Prevention of Marine Pollution and Maritime Disaster was followed at Tomakomai.[88] The monitoring requirements will relate to the disposed CO_2 (volume, location, injection temperature/pressure of geological formations etc.), CO_2 location and extent, and seawater above the disposal site (changes in geological property, seawater chemistry, marine organisation etc.).[89] Before permission is granted, the authorities will evaluate the monitoring plan for adequate leakage detection and a recovery plan for minimising the influence on marine environments if CO_2 leaks.[90] Permission is renewed every five years, the aim being to ensure long-term monitoring in the sea area above the disposal site.[91] Provisions concerning long-term liability and the transfer of such liability have not been established.[92]

The London Protocol seems to be the framework for managing sub-seabed CO_2 geological storage at Tomakomai, which indicates that the policy approach in Japan is technology-neutral. This means that, when the operator proposes a monitoring plan, the proposed monitoring technologies are the starting point for the authorities' evaluation of the plan.

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[82] Tomakomai CCA Demonstration Project, Japan CCS Co., Ltd, https://www.japanccs.com/wp/wp-content/uploads/2018/02/191118_JCCS-Brochure-3.pdf

[83] Report of Tomakomai CCS Demonstration Project at 300 thousand tonnes cumulative injection ('Summary Report') May 2020, Ministry of Economy, Trade and Industry (METI) New Energy and Industrial Technology Development Organization (NEDO) Japan CCS Co., Ltd. (JCCS).

[84] Kenichiro Yanagi, 'Relevant regulation for CO2 sub-seabed storage in Japan, International CCS Symposium for Low-Carbon Society', 12 Feb. 2015, https://www.env.go.jp/earth/CCS/mat06_1.pdf

[85] Kenichiro Yanagi (2015).

[86] Kenichiro Yanagi (2015).

[87] Report of Tomakomai CCS Demonstration Project at 300 thousand tonnes cumulative injection ('Summary Report') May 2020, Ministry of Economy, Trade and Industry (METI) New Energy and Industrial Technology Development Organization (NEDO) Japan CCS Co., Ltd. (JCCS).

[88] Ibid.

[89] Ibid.

[90] Ibid.

[91] Ibid.

[92] Ibid.

At Tomakomai, marine environmental surveys were conducted in 2013 and 2014, and, from 2016, seasonal surveys will be conducted quarterly.[93] Marine environmental surveys were conducted in accordance with the 'Monitoring Plan'. Some issues have become apparent, such as the possibility that the index currently used to detect possible CO_2 leakage into the sea could generate false positives caused by natural variations rather than actual leakage, and that the effectiveness of surveying the sea-bottom soil and condition of marine organisms as a method of detecting CO_2 leakage is believed to be low. These issues should be taken into account in the application procedure for the next period, with a view to reducing the current number of survey points, survey frequency and survey items.[94] This indicates high awareness of the attribution problem.

JCCS commenced CO_2 injection at Tomakomai from April 2016, and CO_2 was injected until 2019 when the target for cumulative CO_2 injection of 300,000 tonnes was reached. Accordingly, injection has been suspended.[95] On 6 September 2018, the Hokkaido Eastern Iburi-earthquake occurred, with a magnitude of 6.7, and Tomakomai CCS demonstration site recorded a seismic intensity of lower than 5. No indication of CO_2 leakage was confirmed in the reservoir pressure and temperature data.[96] Micro-seismic monitoring did not detect any events. A Review Meeting in 2018, including experts in seismology, reached the common understanding that no CO_2 leakage was caused by the earthquake, and no data have been confirmed suggesting a connection between the CO_2 storage and the earthquake.[97] The monitoring is reported to verify that natural earthquakes do not affect the stored CO_2, and that CO_2 injection does not cause any increase in noticeable tremors.[98]

Several obstacles to CCS in Japan have been identified.[99] Past surveys of suitable sites for CO_2 storage show that the location of sources and suitable CO_2 storage sites are not necessarily close to each other. Therefore, an adequate business model for safely and economically transporting CO_2 will need to be developed to enable private operators to consider investment. For CO_2 storage below the seabed, the monitoring period and methods are stipulated in the Act on Prevention of Marine Pollution and Maritime Disaster, as well as other issues. Safer and more suitable monitoring periods and methods will be examined. A comprehensive system will therefore need to be developed that covers separation, capture, transport, and storage in a both economical and safe manner, with a suitable division of roles between the public and private sectors. This will be accompanied by active awareness campaigns to achieve further understanding between relevant parties, such as local

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[93] Tomakomai CCA Demonstration Project, Japan CCS Co., Ltd, https://www.japanccs.com/wp/wp-content/uploads/2018/02/191118_JCCS-Brochure-3.pdf

[94] Report of Tomakomai CCS Demonstration Project at 300 thousand tonnes cumulative injection ('Summary Report') May 2020, Ministry of Economy, Trade and Industry (METI) New Energy and Industrial Technology Development Organization (NEDO) Japan CCS Co., Ltd. (JCCS).

[95] https://www.japanccs.com/en/business/research/

[96] Tomakomai CCA Demonstration Project, Japan CCS Co., Ltd, https://www.japanccs.com/wp/wp-content/uploads/2018/02/191118_JCCS-Brochure-3.pdf

[97] A report summarising the conclusions was posted on the JCCS homepage, see Report of Tomakomai CCS Demonstration Project at 300 thousand tonnes cumulative injection ('Summary Report') May 2020, Ministry of Economy, Trade and Industry (METI) New Energy and Industrial Technology Development Organization (NEDO) Japan CCS Co., Ltd. (JCCS).

[98] Tomakomai CCA Demonstration Project, Japan CCS Co., Ltd, https://www.japanccs.com/wp/wp-content/uploads/2018/02/191118_JCCS-Brochure-3.pdf

[99] The Long-term Strategy under the Paris Agreement, June 2019 (Cabinet decision, June 11, 2019) The Government of Japan, for further details, see Chapter 3, section 1 (3) b.

[99] See https://www.japanccs.com/en/business/research/

authorities, and social acceptance of CCS in general. The Government will continue to seek international collaboration on research, demonstration, standardisation and further rulemaking.[100]

1.5.4 Australia

In Australia, the 2005 Regulatory Guiding Principles for Carbon Dioxide Capture and Geological Storage, endorsed by the Ministerial Council on Mineral and Petroleum Resources, set out a nationally consistent regulatory carbon capture and storage framework.[101] It is stated that storage, particularly in offshore areas, raises several novel issues under international law.[102] With respect to monitoring, it is underlined that 'though projects will necessarily be assessed on a case-by-case basis', any monitoring and verification system needs to ensure that relevant information is readily available to the community and independently verifiable.[103] No specifics concerning technology are mentioned, and monitoring phases are described in accordance with global regulations, see Fig. 3 in section 1.4.4 above.

CCS regulation is set out in federal law, but is also issued by state and territory governments. The Offshore Petroleum Amendment (Greenhouse Gas Storage) Act of 2006 regulates CCS storage in Federal Waters, i.e. waters offshore beyond three nautical miles, and preserves many of the features found in the existing petroleum model. Amendments were made by the Offshore Petroleum and Greenhouse Gas Storage Amendment (Cross-boundary Greenhouse Gas Titles and Other Measures) Bill 2019, which was approved by the Australian Senate in May 2020, but these amendments seem to be irrelevant to monitoring and monitoring technologies.

The Act, as amended, has, as far as we have been able to establish, no deviations that add new monitoring phases or monitoring aims as mandatory, or add requirements for specific monitoring technology, that the ACTOM toolbox needs to meet. Among other things. the 2006 Act regulates monitoring and contains references to best available technology in several of its provisions. With respect to the regulation of potential greenhouse gas storage formation, it is stated in section 20 (3), that, in determining whether part of a geological formation is suitable for permanent storage, with or without engineering enhancements, 'regard may be had to reasonably foreseeable technological developments'.Under section 313, the responsible Commonwealth Minister must have regard to 'any relevant scientific or technological developments', 5 (c). The Act does not prescribe specific monitoring technology, and the examples illustrate that the regulation is based on the principle of best available technology.

Onshore areas and coastal waters (areas less than 3 nautical miles offshore) are administered by state and territory governments. Onshore CCS frameworks established by the territory governments of South Australia and Queensland build on their existing experience from the oil and gas industries, using dedicated regulatory frameworks.[104] They are not part of our study. Victoria has established regulation for onshore/coastal waters, and Western Australia has adopted regulations for the Gorgon project.

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[100] The Long-term Strategy under the Paris Agreement, June 2019 (Cabinet decision, 11 June 2019) The Government of Japan, for further details, see Chapter 3, section 1 (3) b.

[101] https://www.industry.gov.au/data-and-publications/regulatory-guiding-principles-for-carbon-dioxide-capture-and-geological-storage. See Dixon et al (2015) section 5 for some of the key elements of these frameworks, including a more detailed examination of their management of long-term liabilities.

[102] 2005 Regulatory Guiding Principles for Carbon Dioxide Capture and Geological Storage, p. 17.

[103] Ibid p. 37.

[104] https://www.ucl.ac.uk/cclp/ccsonozvictorian.php

The Victorian Greenhouse Gas Geological Sequestration Act 2008 (No 61 2008) provides a legal framework enabling onshore injection and permanent storage of greenhouse gas substances. Even if it is an onshore regulation, it is worth noting that specific monitoring technologies are not described in the act. In section 93 2), it is stated that an 'injection and monitoring plan must be taken to form part of the operation plan and may be submitted by the holder of an injection and monitoring licence', while in section 94 f), it is stated that the plan should encompass 'a description of the proposed injection and monitoring techniques'. Thus, the proposed choice of monitoring technique is made by the developer and evaluated by the administration.

The state government of Victoria has also developed a regulatory framework for offshore storage sites. The Offshore Petroleum and Greenhouse Gas Storage Act 2010 regulates Victorian state waters, i.e. sites falling within the three-nautical-mile extent of state jurisdiction. This Act largely mirrors the federal Offshore Petroleum Amendment (Greenhouse Gas Storage) Act 2006 for offshore waters, with the exception of the treatment of long-term liability.[105] Like the Federal Act, the Victorian State Waters Act does not prescribe specific monitoring technology and is based on the principle of best available technology.

Western Australia does not have in place a state wide legal framework, however the state government have adopted project specific legislation to support the Gorgon Joint Venture project.[106] The Gorgon CO_2 injection project, approved in 2009, is an important part of the development of the Greater Gorgon Area gas fields off the northwest coast of Western Australia. It started injecting in August 2019, with a predicted project lifespan of more than 40 years. The plan is to inject 3.3 to 4 million tonnes of carbon dioxide per year into the Dupuy Formation, a geological layer more than two kilometres beneath Barrow Island.

The project is regulated under a separate Act, the Barrow Island Act 2003, which is the first legislation regulating carbon dioxide storage in the world. A range of monitoring, reservoir management and uncertainty management activities are used to monitor the movement of carbon dioxide in the subsurface.[107] Approval to sequester the reservoir CO_2 is regulated under section 13 of the Barrow Island Act 2003 and administered by the Department of Jobs, Tourism, Science and Innovation (JTSI). However, the requirement to sequester the Gorgon reservoir CO_2 is regulated under the Environmental Protection Act 1986 and administered by the Department of Water and Environmental Regulation.[108]

1.5.5 Canada

According to the Government of Canada, Canada is already a 'world leader in CCS', while it is still committed to exploring new technology and strengthening its current technology.[109] CCS plays an important role in pursuing the country's emission reduction targets. Much of Canada's prominent role in the field of CCS is due to its world-class geological storage potential for CO_2, making it an ideal place for large-scale projects. When it comes to regulations relating to CCS, a great deal falls within provincial

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[105] Ibid.

[106] Dixon et al (2015) at p. 440.

[107] Ibid.

[108] Ibid.

[109] 'Carbon capture and storage: Canada's technology demonstration leadership' (Government of Canada, 12.18.2015) https://www.nrcan.gc.ca/energy/publications/16226

jurisdiction in Canada.[110] However, federal regulation does apply to Federal Lands and to certain legal topics. In Canada, CCS projects are therefore mainly approved under oil and gas-related legislation, regulations and directives, often amended to fit the unique requirements of carbon capture and storage.[111] Large-scale CCS project development has largely been limited to the western provinces of Alberta and Saskatchewan. British Columbia is seen as having a great potential when it comes to carbon storage, although it does not currently host any projects.[112]

As regards operations in *Alberta*, regulation is partly included in the Carbon Capture and Storage Statutes Amendment Act of 2010. In this regulation, which amends the Mines and Minerals act, it is stated that anyone seeking rights to inject captured carbon dioxide for sequestration shall 'submit a monitoring, measurement and verification plan for approval' and comply with this plan if it is accepted, see Article 116 (3) letters a) and b).[113] It is also required to 'provide reports with respect to the lessee's compliance with the monitoring, measurement and verification plan', letter c). There is no mention of any specific requirements for the monitoring technology. In the part concerning Carbon Sequestration Tenure Regulation of 68/2011, the amendment also states that a monitoring plan is required for any potential lessee, although it does not set out any specific requirements for the technology, see Articles 7, 8, 9, 11, 14, 15, 16 and 17.[114] Moreover, the Alberta Environmental Protection and Enhancement Act (EPEA) is relevant with respect to CCS. In Article 36.1, it is stated that '[t]he Minister may make regulations respecting the establishment and operation of one or more environmental monitoring programs'.[115] The article does not mention, however, what monitoring technology shall be used. The relevant regulations in Alberta are all centred on land areas, or water below land areas, as Alberta does not have a coastline. The projects in Alberta are focused on reducing CO_2 emissions from oil sand and the fertiliser sector.[116]

Some guidance regarding specific requirements for the monitoring technology can be found in the Regulatory Framework assessment, which was carried out from 2011 to 2013, with more than 100 global experts on CCS participating. The final report includes conclusions and recommendations 'that continue to inform the ongoing development of the carbon capture and storage regulatory framework in Alberta to ensure the safest and most environmentally responsible regulatory environment for carbon capture and storage'.[117] The report tackles monitoring in the pre-injection, injection, closure

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[110] Patricia Larkin et al., 'An integrated risk assessment and management framework for carbon capture and storage: a Canadian perspective', International Journal of Risk Assessment and Management, Vol. 22 (2019).

[111] Patricia Larkin, William Leiss and Daniel Krewski, 'The evolution of regulatory practice for CCS projects in Canada', International Journal of Risk Assessment and Management, Vol. 22, (2019).

[112] 'Carbon Capture & Storage' (Government of British Columbia) https://www2.gov.bc.ca/gov/content/industry/natural-gas-oil/responsible-oil-gas-development/carbon-capture-storage?keyword=carbon&keyword=storage

[113] The Carbon Capture and Storage Statutes Amendment Act can be found at https://www.canlii.org/en/ab/laws/astat/sa-2010-c-14/147754/sa-2010-c-14.html

[114] The Mines and Minerals Act can be found at https://www.qp.alberta.ca/1266.cfm?page=2011_068.cfm&leg_type=Regs&isbncln=9780779790500&display=html

[115] The Environmental Protection and Enhancement Act can be found at https://www.qp.alberta.ca/documents/Acts/E12.pdf

[116] 'Carbon capture and storage' (Government of Alberta) https://www.alberta.ca/carbon-capture-and-storage.aspx

[117] Ibid.

and post-closure stages.[118] In the pre-injection period, the monitoring tasks 'are identified based on a site-specific risk assessment', and the 'specific technologies to monitor areas of potential leakage are screened, evaluated and selected' to assess the appropriate baseline data.[119]

When it comes to the injection phase, the monitoring is used to gather data to 'demonstrate containment, conformance and use of the pore space'. This is done in order to 'inform and optimize project operations as well as trigger the investigation of non-conformance and mitigation and/or remediation activities as required'. The data that are gathered are intended to ensure 'public safety and to confirm that the environment and availability of underground sources of drinking water are not adversely affected'.[120] The monitoring technology is evaluated based on its effectiveness with respect to these overarching goals. During the closure period, the operators must continue monitoring activities in order to 'demonstrate containment and conformance of the sequestered CO_2'.[121] As regards the post-closure phase, the monitoring is an important part of detecting any unforeseen release of CO_2, which is an integral part of developing and maintaining public support for CCS development.[122] Once the project is closed, and the ownership and liability are transferred to the government, the province will be responsible for any monitoring activities.

In *Saskatchewan,* Saskatchewan's Boundary Dam, the Weyburn-Midale enhanced oil recovery project, as well as the Shand test facility, are prominent examples of CCS projects.[123] They are all regulated under the existing regulatory tools governing subsurface injection of fluids.[124] The Weyburn-Midale project is also regulated by the federal Canadian Environmental Assessment Act (CEAA).[125] This act was repealed with effect from 28 August 2019.[126] On the provincial level, the Saskatchewan Environmental Assessment Act (SEEA) has made an impact as regards regulating carbon storage, although it does not seem to mention the topic of monitoring technology.[127] The act defines 'environment' as 'air, land and water', yet the scope of the act must be seen in conjunction with the fact that Saskatchewan, like Alberta, has no coastline. Nor does the Saskatchewan Oil and Gas Conservation Act (OGCA) currently contain any mention of what technology should be applied in the monitoring process.[128] As the Boundary Dam project was not deemed to be a 'development' under the aforementioned SEEA, the carbon capture component was given clearance on the basis of the description and the environmental

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[118] 'Carbon capture and storage – Summary report of the regulatory framework assessment' (2013). Available at https://open.alberta.ca/dataset/5483a064-1ec8-466e-a330-19d2253e5807/resource/ecab392b-4757-4351-a157-9d5aebedecd0/download/6259895-2013-carbon-capture-storage-summary-report.pdf

[119] Ibid., p. 86.

[120] Ibid., p. 91.

[121] Ibid., p. 101.

[122] Ibid., p. 111.

[123] 'Market snapshot: CCS in Alberta and Saskatchewan – long-term storage capacity and the potential to lower industrial sector emissions intensity' (Government of Canada, 10 Sept. 2020) https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/market-snapshots/2020/market-snapshot-ccs-alberta-saskatchewan-long-term-storage-capacity.html

[124] Jose Condor and Malcolm Wilson 'Options to implement a regulatory framework to accommodate geological storage of CO_2 in Saskatchewan' SciVerse ScienceDirect (2013).

[125] Larkin, Leiss and Krewski (2019).

[126] The Canadian Environmental Assessment Act can be found at https://www.canlii.org/en/ca/laws/stat/sc-2012-c-19-s-52/latest/sc-2012-c-19-s-52.html

[127] The Saskatchewan Environmental Assessment Act can be found at https://publications.saskatchewan.ca/#/products/488

[128] Larkin, Leiss and Krewski (2019), p. 289.

protection commitments of the project itself.[129] The operators of the project, SaskPower, did, however, commit to using best management practices in the technology it used.[130]

As mentioned, there are, currently no CCS-projects in *British Columbia*. While the province has a comprehensive regulatory system for all oil and gas industry activities, they were not developed with large-scale CCS in mind.[131] Therefore, the Ministry of Natural Gas Development proposed a project for developing a regulatory framework with carbon capture and storage specifically in mind. This project culminated in the Natural Gas Development Statutes Amendment Act of 2015, which amended the Petroleum and Natural Gas Act[132] and the Oil and Gas Activities Act.[133] None of them appear to have anything specific to say about the monitoring technology used in CCS projects.

As British Columbia is a coastal province, future CCS projects could be located outside the its land areas. The question of jurisdictional authority over Canadian waters exists on a federal, provincial, municipal, international and indigenous level.[134] The Constitution Act of 1867 is the legal point of departure and provides the framework for the division of powers.[135] In Canada, the federal government controls coastal waters from what is deemed as 'the ordinary low watermark', seaward to 200 nautical miles (which converts to roughly 370 kilometres).[136] Marine areas that fall under federal control are therefore regulated through federal legislation. The Oceans Act is important in this regard.[137] It does not, however, directly regulate the question of CCS and related monitoring technology.

To *sum up*, we can conclude that the regulatory framework regarding CCS in Canada, is highly dependent on the area in which the project is located. This means that the choice of methodologies and transparency, for example with respect to the monitoring process, is inconsistent across jurisdictions.[138] Furthermore, while CCS projects exist within a regulatory framework, the way in which each project is adapted is dependent on wide-ranging risk management options, such as the existing regulations, economic, advisory, community-based and technological approaches.[139] However, what can be said across the board is that CCS project development within Canada has thus far been regulated within the bounds of gas and environment-related legislation and regulations. Some of these projects were also assessed under the federal Canadian Environmental Assessment Act.

1.5.6 USA

The United States has a wealth of experience of implementing and thus regulating onshore CCS projects. However, its offshore storage programme is immature at the time of writing of this manuscript. To date, there are no current or planned offshore CO_2 injection projects in the United

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[129] Ibid., p. 290.
[130] Ibid., p. 291.
[131] 'Carbon capture and storage regulatory policy framework' (Government of British Columbia) https://www2.gov.bc.ca/gov/content/industry/natural-gas-oil/responsible-oil-gas-development/carbon-capture-storage/ccs-reg-framework?keyword=carbon&keyword=storage
[132] The Petroleum and Natural Gas Act can be found at https://www.bclaws.ca/civix/document/id/complete/statreg/96361_01#section51
[133] The Oil and Gas Activities Act can be found at https://www.bclaws.ca/civix/document/id/complete/statreg/08036_01
[134] East Coast Environmental Law, 'Who owns the coast?' (2018), pp. 1–2.
[135] Ibid.
[136] Ibid.
[137] The Oceans act can be found at https://laws-lois.justice.gc.ca/eng/acts/o-2.4/
[138] Larkin, Leiss and Krewski (2019), p. 302.
[139] Ibid.

States, and no established regulatory framework. However, the USA is looking to develop both. In 2010, the Presidential Interagency Task Force on CCS recommended that regulations be developed for offshore CO_2 storage beneath the federal waters of the outer continental shelf.[140] In 2015, the U.S. Department of Energy National Energy Technology Laboratory (DOE NETL) funded research projects to assess the prospective geological storage potential of offshore subsurface formations of the Mid Atlantic, South Atlantic, and Gulf of Mexico. A set of best management practices for CO_2 transport and storage in the outer continental shelf was finalised in April 2018.[141] Finally, the DOE established two offshore partnerships (managed by the University of Texas in Austin and the Southern States Energy Board) that would remain active from 2018 to 2023 to prepare the way for offshore projects in the Gulf of Mexico.

For onshore projects in the United States, the US Environmental Protection Agency (EPA) regulates CO_2 geological storage via its underground injection control well permitting programme, with Class II wells designated for CO_2 storage through CO_2-EOR[142] and Class VI wells designated for CO_2 storage in saline formations.[143] Both well classes focus on protecting underground sources of drinking water (USDW)[144] and require monitoring, but the monitoring requirements for each well class are starkly different. Whereas Class II monitoring requirements are generally well-based, relying on standard oil and gas practices, such as mechanical well integrity and pressure testing, Class VI monitoring requirements add extensive site characterisation, monitoring of CO_2 injection and storage, and monitoring ground water quality during the injection and post-injection periods. Whereas the requirements for monitoring well integrity are prescriptive because well construction is generally standardised, the requirements for monitoring the geologic storage site are not prescriptive due to the site-specific nature of the geology. For geologic storage, a guidance document is available as an aid to choosing monitoring methods, but the choice of these methods is optional.[145] Thus, extensive record keeping and continual reporting on operations to confirm USDW protection are required for Class VI. The only exception to EPA jurisdiction in this area exists for states that have acquired Class VI primacy from the EPA, which gives them power to regulate and approve CCS projects by their designated state agencies. Primacy may lead to streamlining of the application process, and enable tailoring to state resources and objectives, but regulations are not allowed to be less stringent than required by the underground injection control programme.

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[140] Tew, B. et al. 'Preliminary Eva Evaluation of Offshore Transport and Geologic Storage of Carbon Dioxide' Atlanta: Southern States Energy Board, Interstate Oil and Gas Compact Commission, and US Department of Energy National Energy Laboratory, (2013).

[141] Smyth RC, Hovorka SD. 2018. Best management practices for offshore transportation and sub-seabed geologic storage of carbon dioxide. Sterling (VA): US Department of the Interior, Bureau of Ocean Energy Management. OCS Study BOEM 2018-004. 259 p.

[142] EPA 2002 Technical Program Overview: Underground Injection Control Regulations. U.S. Environmental Protection Agency, Washington, DC and EPA 2015 Memorandum on Key Principles in EPA's UIC Program Class VI Rule Related to Transition of Class II EOR Wells to Class VI.

[143] EPA 2010a Federal Requirements Under the Underground Injection Control (UIC) Program for Carbon Dioxide (CO2) Geologic Sequestration (GS) Wells, 75 Fed. Reg. 77230, 77303 (10 Dec. 2010) (amending 40 C.F.R. Sections 124, 144, 145, 146, and 147).

[144] A USDW is defined in the Code of Federal Regulations (40 CFR 144.3) as: 'an aquifer or its portion: (a)(1) Which supplies any public water system; or (2) Which contains a sufficient quantity of ground water to supply a public water system; and (i) Currently supplies drinking water for human consumption; or (ii) Contains fewer than 10,000 mg/l total dissolved solids; and (b) Which is not an exempted aquifer.'

[145] US EPA, 2010c, General technical support document for injection and geologic sequestration of carbon dioxide: Subparts RR and UU, report, Washington, D. C.

Building on, and complementary to the EPA's underground injection control permit requirements, the Geologic Sequestration and Injection of Carbon Dioxide Subparts RR and UU[146] require annual reporting of greenhouse gases for accounting purposes. Subpart RR applies to facilities that inject carbon dioxide underground for long-term geological sequestration, while Subpart UU applies to subsurface CO_2 injection for any other reason including CO_2-enhanced EOR. Subpart RR requires basic information on the CO_2 received for injection, mass balance accounting of the amount of CO_2 sequestered, and a monitoring, reporting and verification (MRV) plan to be developed and approved by the EPA. In contrast, Subpart UU only requires reporting of basic information on the CO_2 received for injection. Projects utilising CO_2-EOR may, however, choose to hold Class VI well permits and/or opt into subpart RR.

EPA approved the first MRV plan under Subpart RR in December 2015 and, to date, four MRV plans have been approved for industrial CO_2-EOR projects (wells permitted under Class II) and one approved for a saline storage project (wells permitted under Class VI). These monitoring plans are currently being used to demonstrate secure storage, which is required in order to gain tax credits under the Internal Revenue Service 45Q tax credit for carbon capture projects.

The approved MRV plans under Subpart RR illustrate a smaller regulatory burden for Class II wells compared to Class VI wells, as they rely on the operators' own oil and gas protocols. This type of approval reflects the regulators' respect for the subsurface experience and knowledge of oil and gas operators. In addition, post-injection site care has in many instances been reduced from 50 years as stipulated in the original rule to around 3–5 years. Thus, in the USA, we see a history of communication and willingness to work out agreements between the regulator and the operators of CO_2 storage projects. This bears traits of co-production of regulation as discussed in section 1.3 above.

The USA's offshore area is divided into the jurisdictions of state and federal waters. State waters generally extend three nautical miles from the coast for all states except Texas and the Gulf coast of Florida, which extends nine nautical miles out from the coast. The extent of federal waters is 200 nautical miles, after which comes the international jurisdiction of the open ocean. Although it is true that significant volumes of USDW do not generally exist beneath submerged lands, parts of coastal aquifers that could be affected do exist offshore. Thus, the Safe Drinking Water Act (SDWA) requires the EPA to establish minimum requirements for State underground injection control programmes that regulate the subsurface injection of fluids both 'onshore and offshore under submerged lands within the territorial jurisdiction of States'. The SDWA therefore prescribes that the EPA issue regulations for State underground injection control programmes that contain 'minimum requirements for protections for underground injection which endangers drinking water sources''. Thus, the EPA is currently the jurisdiction that oversees the injection of CO_2 in offshore state waters through the underground injection control programme. However, the main aims of onshore project regulation, which is to protect the USDW, is not directly applicable to offshore storage due to a lack of defined USDW offshore.

In federal waters, the Outer Continental Shelf Lands Act (OCSLA) of 1953 was enacted with the aim of studying and preventing environmental harm from energy development and mineral extraction on the Outer Continental Shelf. The OCSLA assigns responsibility to the Department of the Interior (DOI),

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[146] EPA 2015 Memorandum on Key Principles in EPA's UIC Program Class VI Rule Related to Transition of Class II EOR Wells to Class VI, (EPA, 2010b), EPA 2010c).

Bureau of Ocean Energy Management (BOEM) and the Bureau of Safety and Environmental Enforcement (BSEE) for regulating the development of mineral resources and specific energy and marine activities. The EPA also has jurisdiction to regulate such projects under general programmes, such as the ocean Marine Protection, Research, and Sanctuaries Act (MPRSA) of 1972, which fulfils the USA's obligations under the London Convention to prevent the dumping of waste at sea.

Currently, the DOI has the authority to permit CO_2 storage during EOR on existing oil and gas leases on the outer continental shelf. BOEM has the power to issue leases, easements, and rights-of-way for activities that 'produce or support production, transportation, or transmission of energy from sources other than oil and gas'[147] BOEM may issue leases for sub-seabed CO_2 storage when CO_2 is generated as a by-product of electricity production from an onshore, coal-fired power plant. However, BOEM may not issue outer continental shelf leases to store CO_2 emitted from refineries, natural gas power plants, and non-energy industries (e.g. steel or cement).[148] Similarly, the MPRSA is intended to prevent pollution of the seas by 'waste generated by a manufacturing or processing plant'. Under the existing statute, CO_2 would be considered a waste and offshore storage of it would therefore be prohibited. A review by the US National Petroleum Council in 2018 recommended that Congress amend the OCSLA and MPRSA to explicitly allow CO_2 storage in federal waters from all anthropogenic sources, and that BOEM and BSEE should establish processes to enable access to pore space in federal waters and regulate CO_2 storage in those waters.[149]

The best practice guidance for CO_2 storage was developed by the BOEM in 2017. Like many other regulations, this guidance covers the entire project lifecycle from site characterisation through site closure, including:

- Site Selection and Characterisation (data collection, capacity/injectivity assessments, and modelling)
- Risk Assessment
- Project Planning and Execution (design, construction, operation, and maintenance)
- Monitoring
- Mitigation
- Inspection and Performance Auditing Reporting Requirements
- Emergency Response and Contingency
- Decommissioning and Site Closure

A database was compiled and technical gaps were also defined. They included geological and geophysical data gaps in certain geographic areas and an overall lack of data in the shallow overburden, normally not characterised in oil and gas operations. Refining capacity estimates and understanding potential leakage pathways and mechanisms are important. CO_2 transport, potential use of existing

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[147] Smyth RC, Hovorka SD., 2018. Best management practices for offshore transportation and sub-seabed geologic storage of carbon dioxide. Sterling (VA): US Department of the Interior, Bureau of Ocean Energy Management. OCS Study BOEM 2018-004. 259 p.

[148] Batum, Melissa, 2017, Best Management Practices: Sub-Seabed Geologic Carbon Dioxide Transport and Storage on the United States Outer Continental Shelf, presentation to the 2nd International Workshop on Offshore CO2 Geologic Storage, Beaumont, Texas.

[149] NPC 2019 Meeting the Dual Challenge. A Roadmap at At-scale Deployment of CCUS.

infrastructure and challenges associated with offshore gas processing are all areas for future expansion of the US programme.

Figure 3. Map indicating the planning areas for the outer continental shelf offshore areas (Batum, 2017).

In summary, offshore CO_2 storage is emerging in the USA. A fully developed regulatory regime will require the integration of existing regulatory protocols, supported by experience gained from offshore pilot-scale projects and integration with offshore industry experience.

1.5.7 EU/EEA member countries and their CCS-related regulation; the UK, the Netherlands and Norway

Globally, the EU and the CCS Directive represent one of the most refined regulations of offshore CCS storage, see section 1.4.3 above. Three countries with different relationships with the EU, and which are at the same time at the forefront of the development of offshore CCS projects, are used as examples here of national regulation under the EU CCS regime, namely the Netherlands, as an EU-member, Norway as an EEA member, and the UK, as a former EU member.

For EU members like the Netherlands, the EU CCS Directive[150] is *hard law*, and Member States were obliged to transpose the directive into their national legislation by 25 June 2011. As stated in section 1.4.3, the Directive represents minimum harmonisation. Norway is not a member of the EU, but an

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[150] On the Directive, see section 1.4.3 above.

EEA member,[151] and the CCS Directive has been adopted under the EEA Agreement,[152] making the Directive hard law involving minimum harmonisation also in Norway. As a former EU member, the UK transposed the CCS Directive into national legislation. After BREXIT, as of 31 January 2020 (exit day), the UK is no longer an EU Member State. From 1 February 2020 until 31 December 2020, the relationship between the EU and the UK is governed by the Withdrawal Agreement.[153] During this transition period under the Agreement, the continued application of EU law is ensured, but, as a third country, the UK can no longer participate in the EU's institutions and governance structures. The transposed CCS Directive is national UK law, and future revisions of the Directive are not binding on the UK after BREXIT. However, an 'evolution' or 'ratchet clause' to ensure that regulatory standards do not diverge significantly, leaving British or European businesses at a significant competitive disadvantage, will probably be part of a future UK-EU Agreement.[154] Despite Brexit, we can therefore expect that CCS regulation under UK law will not be altered and standards lowered. As a result of the above, the EU CCS regulation has framed CCS regulation in UK, Dutch and Norwegian law.

The regulation of capture, transport and storage of CO_2 has implications for a wide range of national laws and regulations, although the focus here is on national law implementing the CCS directive and the requirement for a licence to start operating a geological CO_2 storage facility, and related monitoring programme.

The Directive is based on a 'monitoring plan designed by the operator pursuant to the requirements … submitted to and approved by the competent authority…. The plan shall be updated pursuant to the requirements … in any case every five years... Updated plans shall be re-submitted for approval to the competent authority', pursuant to Art. 13 (2). This illustrates the adaptive management approach. As regards technology, the Directive contains parts that set out what standards the monitoring technology should meet, see section 1.4.3, but, apart from that, it does not prescribe the direct choice of technology. In sections 1.4.3 and 1.4.4, we stated that, when the accuracy of monitoring technologies is not laid down in the minimum requirements of the CCS Directive, this is in accordance with the principle of best available technology. This spills over into national regulation as an argument against using national discretionary powers when implementing the Directive into national law to lay down accurate monitoring technology requirements. Another EU-law contextual argument against more rigorous implementation, compared to the minimum requirements of the CCS Directive, is that this could interfere with the level playing field/lead to disturbance of competition. In line with the above, in Norway, the UK and the Netherlands, the legislation is based on the requirements of the CCS Directive relating to the process of creating the monitoring plan, and national legislation implementing the directive does not prescribe the direct choice of monitoring technology.

In the UK, the Energy Act of 2008 provides for a licensing regime governing offshore storage comprising both UK territorial waters and beyond, which is designated as a gas importation and storage zone

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[151] The European Economic Area links the EU Member States and Iceland, Liechtenstein and Norway into an internal market governed by the same basic rules.

[152] Decision of the EEA Joint Committee 115/2012 of 15 June 2012 amending Annex XX (Environment) to the EEA Agreement. The Decision shall enter into force on 16 June 2012, see Art. 3. Some amendment of EEA-technical relevance is part of the decision. The EFTA states were obliged to transpose the Directive into national legislation by 1 June 2013.

[153] https://ec.europa.eu/info/european-union-and-united-kingdom-forging-new-partnership_en

[154] https://www.theguardian.com/politics/2020/dec/13/brexit-what-are-the-major-unresolved-topics-uk-and-eu-must-agree-on. At the time of writing, negotiations on an agreement are still ongoing.

(GISZ) under section 1(5), in most cases equivalent to the exclusive economic zone.[155] In addition to applying for a licence, developers must be granted the appropriate rights from the Crown Estate or the Scottish Crown Estate. The Storage of Carbon Dioxide (Licensing etc.) Regulations 2010 (SI 2010/2221) transpose many other requirements of the directive. Under the regulations, a proposed monitoring plan should be 'drawn up in accordance with Annex II to the Directive and that takes into account the obligations imposed on the operator under legislation implementing Article 14 of the ETS Directive'. Thus, the regulations directly transpose the obligations under the directive into UK law.

In Dutch law, the CCS Directive is implemented in law by the Act of 6 June 2011 on the amendment of the Mining Act, and the Decree of 29 August 2011 on the amendment of the Mining Decree. The legislation implementing the Directive in Dutch law merely aims to ensure strict and correct implementation of the CCS Directive.[156]

In Norway, two separate legislative acts regulate CCS. Storage related to enhanced oil recovery is regulated by the Petroleum Act of 29 Nov. 1966 no 72. Genuine CCS storage falls under the Act on Scientific Exploration and Investigation for and Exploitation of Subsea Natural Deposits other than Petroleum Deposits of 21 June 1963 no 12, and delegated regulation FOR-2014-12-05-1517 (FOR-2014). The monitoring requirements of the Directive are repeated in FOR-2014 Section 5-4 (1). The wording of Article 13 and the Norwegian Section 5-4 is similar.[157] Under FOR-2014 Section 5-4, the monitoring plan should be in accordance with the criteria established in Annex II. The wording of this part of Annex II is a direct translation of the CCS Directive and its Annex II.

If we follow the second referral from Annex II, to part three of Annex I in FOR-2014, titled '[c]haracterisation of the storage dynamic behaviour, sensitivity characterisation and risk assessment',[158] it is a direct translation of the same part in the CCS Directive Annex 1. Like the CCS Directive, FOR-2014 first makes a general statement highlighting what the '[c]haracterisation and assessments' of the storage dynamic behaviour, sensitivity characterisation and risk, shall be based on. The following sections 3.1, 3.2 and 3.3 provide more detailed instructions on these processes, all copied from the CCS Directive's Annex I Step 3.

Annex II, the part of FOR-2014 that contains the criteria relevant to the updating of the monitoring plan, is likewise a direct translation of the CCS Directive. The first part, point 1.1, is titled '[e]stablishing the plan',[159] and, like the CCS version, it can be divided into three parts. The first formulates what details the monitoring plan shall contain in the main stage of the project (letters a–d). The second part presents items that should always be subject to monitoring (letters e–i), while the third part, FOR-

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[155] In 2016, licensing powers were transferred from the Secretary of State for Business, Energy and Industrial Strategy to the Oil and Gas Authority (OGA), the licensing authority for offshore storage, except within the territorial sea adjacent to Scotland, over which Scottish ministers have authority, see https://www.gov.uk/guidance/uk-carbon-capture-and-storage-government-funding-and-support#regulatory-regime-for-ccus-in-the-uk

[156] Ceilia van der Weijden, Implementation of the CCS Directive into the Dutch mining legislation (CO2-storage), https://cms.law/en/nld/publication/implementation-of-the-ccs-directive-into-the-dutch-mining-legislation-co2-storage.

[157] With the exception that Article 13 (1) contains two additional points, letters e and f, concerning the purpose of the monitoring. Letter e deals with the issue of 'detecting significant adverse effects on the surrounding environment', and letter f deals with 'assessing the effectiveness of any corrective measures taken pursuant to Article 16'.

[158] Translated from Norwegian by the authors.

[159] Translated from Norwegian by the authors.

2014, provides some directions regarding the choice of monitoring technology (letters j–l), introduced by stating that the choice of technology should be based on 'best practice available at the time of the design of the plan'.[160]

Annex II then continues with section 1.2, which deals with the issue of updating the monitoring plan. It first states that the data collected from the monitoring shall be gathered and interpreted, and then compared with the 3-D-pressure-volume and saturation simulation. This shall be done in connection with Section 1-10 and Annex I Step 3. This part is similar to the CCS Directive Annex II part 1.2. Annex II ends with section 2, which shares its heading with the CCS Directive, namely '[p]ost-closure monitoring'. This part states that the monitoring shall be based on the information gathered during the implementation of the monitoring plan pursuant to Section 5-4 (2) and Annex II section 1.2 (in the CCS Directive, Article 13(2) and Annex II section 1.2). The similarities between these two parts of FOR-2014 and the CCS Directive have already been highlighted. The legislation implements the Directive in Norwegian law to ensure implementation of the CCS Directive.[161]

The UK, the Netherlands and Norway have ambitions for capture, transport and offshore CCS storage. In the Netherlands, a project originally called ROAD was cancelled in 2017.[162] The project continued as the Port of Rotterdam CO_2 Transport Hub and Offshore Storage (Porthos) project.[163] In the UK, there is a huge potential for offshore geological storage with numerous potential storage reservoirs within the UK offshore basins,[164] and their potential for storage is being explored, for example the Peterhead-Goldeneye Gas Post-combustion CCS Project.[165] In Norway, through the Longship project, the Government proposes to first implement carbon capture at a cement factory, then if sufficiently funded, at a waste incineration facility. This also includes funding for the transport and storage project Northern Lights. Northern Lights will transport liquid CO_2 from capture facilities to a terminal in Vestland County. From there, CO_2 will be pumped through pipelines to a reservoir beneath the sea bottom. All the projects have developed storage permit applications under national law after the implementation in national law of the CCS Directive. They have been developed in a dialogue-based process between regulators/administration, the operator and third-party stakeholders.

1.5.8 Brazil and Mexico

Brazil has no specific laws on CCS, but a draft legislation establishing the CCS regulatory framework that covers also offshore activities is before the Brazilian Congress. Brazil has a detailed environmental licensing framework that is broad enough to cover CCS-related activities. Currently, the oil industry deploys activities related to CCS through enhanced oil recovery technologies, with the respective permits and licenses setting forth specific rules. Under current environmental laws, the operator is required to obtain, maintain, and renew its license concerning the (i) environmental

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[160] Translated from Norwegian by the authors.

[161] See PRE-2014-12-05-1517, PRE-2014-12-05-1518 Gjennomføring av EUs lagringsdirektiv: Forskrift om utnyttelse av undersjøiske reservoarer på kontinentalsokkelen til lagring av CO2 og om transport av CO2 2 på kontinentalsokkelen, og Forskrift om endring av forskrift 27 June 1997 no 653 om petroleumsvirksomhet Kongelig resolusjon. Statsråd Tord Lien, section 1.

[162] https://www.portofrotterdam.com/en/news-and-press-releases/road-project-to-be-cancelled-ccs-to-continue

[163] https://www.rotterdamccus.nl/en/

[164] UK, 2015 S. UK Storage Development Plan (2015) https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/531016/DECC_Ready_-_KKD_11.128_Storage_Development_Plan.pdf

[165] A risk-based framework for Measurement, Monitoring and Verification (MMV) of the Goldeneye storage complex for the Peterhead CCS project, UK, M Dean, O Tucker - International Journal of Greenhouse Gas Control, 2017 - Elsevier

impact assessment, which may include the deployment of CCS monitoring technologies; and (ii) environmental impact report, which should include a report of any CCS monitoring activity that is carried out.

In June 2022, Senator Jean-Paul Prates introduced a draft bill before the Federal Senate of Brazil.[166] The draft bill, which is currently before the Commission of Services and Infrastructure of the Senate, sets forth a regulatory framework for the permanent storage of carbon dioxide and its future utilisation to enable and support the deployment of large-scale CCUS projects. The draft bill was backed by studies by the Research Centre for Greenhouse Gas Innovation, University of São Paulo.[167] Shell Brazil has been one of the stakeholders involved with the research through a special grant by the FAPESP, the research council for the State of São Paulo.[168] The draft bill provides that "the injection and permanent storage of CO2 must occur in geological formations located in the sedimentary basins of the national territory, in the exclusive economic zone or on the continental platform under the jurisdiction of Brazil" (section 1:2). Among its objectives, the bill aims to contribute to the national emission reduction targets; to promote the adoption of appropriate technologies, and to motivate the use of CO2 as raw material for commercial and industrial purposes (section 3).

The legal framework that the draft bill creates has several similarities with those in force in other jurisdiction. The draft bill is a direct outcome of research carried out by academics in dialogue with the industry,[169] and it is based on the principles of best available international practices and technologies. In respect to monitoring, the bill is careful not to prescribe any specific technology. The concern about not cementing any technology at the legal level was present in the drafting of the bill.[170] The three phases of the storage identified in the main report (pre-, during and after-injection) are present in the draft bill, which, in this respect, does not deviate from what the ACTOM toolbox contemplates.

Stage	Examples of responsibilities imposed on government and operator	Section
Pre-injection	The executive branch of the Federal Government discloses a list of geological reservoirs	Section 8
	Operator submits to the authority a study on the CO2 storage capacity of the block subject of the request for grant of license	
	Operator submits a Monitoring and Contingency Plan	
	Operator obtains a Qualified Grant Term	
During injection	Operator identifies, alerts, and acts in case of undesirable events, including any signs of potential leakage, to initiate preventive and corrective measures	Section 11
	Operator keeps calibrated, measured and operational any tools and equipment capable of identifying and preventing undesirable events	
	Operator carries out an inventory of CO2 storage and leakage, and compares the amount of storage with the predicted and realized leakage	

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[166] Senator Jean-Paul Prates (PT/RN), Projeto de Lei n. 1425 2022.

[167] Research Centre for Greenhouse Gas Innovation, 'Carbon Capture and Utilization – CCU' (*Research Centre for Greenhouse Gas Innovation*, 28 October 2021) <https://www.rcgi.poli.usp.br/carbon-capture-and-utilization-ccu/> accessed 27 February 2023.

[168] FAPESP, 'RCGI – Research Centre for Greenhouse Gas Innovation' (*FAPESP - Engineering Research Centers*) <https://fapesp.br/cpe/rcgi_%E2%80%93_research_centre_for_greenhouse_gas_innovation/22> accessed 27 February 2023.

[169] An outcome of the studies is the edited volume, Hirdan Katarina de Medeiros Costa and Carolina Arlota, *Carbon Capture and Storage in International Energy Policy and Law* (Elsevier Science 2021).

[170] Meeting with Hirdan Katarina de Medeiros Costa, 16 November 2022, Author's own notes.

	Operator regularly updates the Monitoring and Contingency Plan	Section 13
After injection	Operator maintains the activities of monitoring and managing up to 20 years after the permanent cessation of the activity	Section 12

Although the draft does not go into the precise descriptive requirements on monitoring, it sets forth clear principles that also direct monitoring activities – for instance, environmental protection, efficiency and economic sustainability, participation of civil society with ample access to information, and incentive to research, innovation, and implementation of appropriate technologies (section 4).

Before activities begin, the Operator must obtain,[171] in addition to the proper complete environmental license procedure, a qualified permit issued by the federal executive branch (Qualified Grant Term or QTG) which is valid for a period of 30 years, renewable for more 30 years (section 5). When applying for the QTG, the Operator must submit an operation plan and a Monitoring and Contingency Plan (MCP, Section 8). No specific or minimum requirements for such plans are established in the bill. Once granted the necessary permits and licenses for operation, the Operator must comply with the approved plans. Section 12 sets forth that monitoring activities, including an updated CO2 injection inventory, must be carried out throughout the term of the QTG and for up to 20 years after the cessation of the activities. The Operator must maintain any equipment and tools needed for the storage operation duly calibrated (Section 11). Updates of the MCP are due whenever there are changes in the assessed risk of leakage, geological migration, or other changes in the geological site; changes in the assessed risk to the environment and human health; new scientific knowledge and improvements in technologies and techniques (Section 13). Changes in assessed risks, leakages and anomalous geological migration must be communicated immediately to the regulatory authority (Section 14).

Chapter VI of the bill sets forth that the Operator is responsible for the environmental damage that its activities cause, without prejudice to the joint and several liability of consortium members (Section 15). The Operator is strictly liable for any damage caused by the project (Section 18). There is shared responsibility for the purpose of, among others, ensuring the maintenance of adequate monitoring after the permanent cessation of the injection by the operation (Section 16).

The draft bill is currently before the Senate and may change during the legislative process which involves both chambers of the Congress (Senate and Chamber of Deputies) and sanctioning by the President of the Republic.

Mexico, the second largest economy in Latin America behind Brazil, is a pioneer in adopting Carbon Capture, Utilization, and Storage (CCUS) technologies and solutions, and is among the first developing countries in the world to do so.[172] Since the mid-2010s, the Mexican government has explored the development of CCUS projects related to heavy carbon industries, such as oil and gas extraction and electricity production, and attempted to develop a governance framework for them, including storage and monitoring.[173] However, a regulatory framework for CCUS is still lacking,

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[171] The Operator is defined as "the legal entity that performs injection activities of CO2 in geological formations, or its withdrawal for reuse" (Section 2).

[172] Asia-Pacific Economic Cooperation, Energy Working Group, *CCS Capacity Building in Mexico*, May 2015, p. 5.

[173] See also: de Carvalho Nunes, R; de Medeiros Costa, H. K., Carbon capture and storage technologies and efforts on climate change in Latin American and Caribbean Countries, in de Medeiros Costa, H. K., & Arlota, C. (Eds.). (2021). *Carbon Capture and Storage in International Energy Policy and Law*. Elsevier, p. 91-93.

including storage rules. Several pilot projects are in the pipeline. This contribution discusses the current CCUS context in Mexico, pilot projects, and the applicable legal regime.

Mexico's size translates into significant CO2 emissions. Its 126 million inhabitants,[174] industrial and agricultural activity, and the production of 1.9 million barrels of oil, generated 407 million tons of CO_2 in 2021. This amounts to about 1.3% of the earth's total emissions,[175] and per capita Mexicans emit 3.6 metric tons of CO2 annually, which is down from its peak of 4.2 in 2012.[176] 80% of these emissions are linked to the combustion of fossil fuels.[177]

CO2 and greenhouse gas (GHG) emissions in Mexico have serious climate change implications. Additionally, air pollution affects all Mexican regions, with levels that exceed the World Health Organization's recommended maximum.[178] Since the early 2010s, the Mexican government has taken measures to deal with its GHG emissions. During COP 27 in 2022, Mexico increased its ambitions to cut GHG emissions by up to 35% by 2030,[179] up from a more modest target of 22% announced in 2015.[180] This is accompanied by local policies, such as a tax on CO_2 emissions linked to the consumption of hydrocarbons.

In the Mexican framework, CCUS is considered a tool to reduce GHG emissions and achieve climate targets, support the decarbonization of the electricity sector, and promote the efficient extraction of oil and gas through enhanced oil and gas recovery and shale gas production.[181] CCUS was mentioned in the 2010 Mexican National Energy Strategy as a decarbonization solution for the energy sector.[182] Shortly after, the 2012 General Law on Climate Change was enacted, enabling policies and granting regulatory powers to issue other laws and administrative rules related to the regulation of gas emissions.

International support was pivotal for this rapid takeoff. In 2010, the World Bank CCUS Mexican initiative supported five studies covering: the feasibility of pilot projects, legal framework, and public engagement strategies.[183] Assessments were conducted to determine storage potential onshore and

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[174] INEGI, *Censo de Población y Vivienda* (March 2021), https://www.inegi.org.mx/programas/ccpv/2020/.

[175] European Commission – EU Science Hub, Global CO2 emissions rebound in 2021 after temporary reduction during COVID lockdown (2022), https://joint-research-centre.ec.europa.eu/jrc-news/global-co2-emissions-rebound-2021-after-temporary-reduction-during-covid19-lockdown-2022-10-14_en.

[176] World Bank, CO2 emissions (metric tons per capita) – Mexico (2020), https://data.worldbank.org/indicator/EN.ATM.CO2E.PC?locations=MX.

[177] World Bank, *Development of a regulatory framework for carbon capture, utilization and storage in Mexico* (June 2016), p. 5.

[178] OECD, *Regional Outlook 2021 - Country notes, Mexico* (2021) https://www.oecd.org/regional/RO2021%20Mexico.pdf, p. 7.

[179] Bloomberg, Mexico Pledges Tougher 35% Emissions Cutting Target for 2030 (12 November 2022) https://www.bloomberg.com/news/articles/2022-11-12/mexico-pledges-tougher-35-emissions-cutting-target-for-2030.

[180] Reuters, Mexico agrees to expand climate goals by 2022, foreign minister says (20 October 2021), https://www.reuters.com/business/environment/mexico-agrees-expand-climate-goals-by-2022-foreign-minister-says-2021-10-19/.

[181] Castrejón D, Zavala AM, Flores JA, Flores MP, Barrón D. Analysis of the contribution of CCS to achieve the objectives of Mexico to reduce GHG emissions. International Journal of Greenhouse Gas Control. 2018;71:184-93., p. 185; World Bank, *Development of a regulatory framework for carbon capture, utilization and storage in Mexico* (June 2016), p. 5.

[182] Secretaría de Energía, Estrategia Nacional de Energía (February 2011), available at: https://energia.org.mx/wp-content/uploads/2011/09/EstrategiaNacionalEnergia2011-2025-25-Febrero2011HCU-Ratificacion.pdf.

[183] Banacloche S, Lechon Y and Rodríguez-Martínez A, 'Carbon capture penetration in Mexico's 2050 horizon: A sustainability assessment of Mexican CCS policy' (2022) 115 International Journal of Greenhouse Gas Control 103603

offshore. Additionally, in 2014, a collaborative pilot project with PEMEX – the Mexican state-owned petroleum company - was conducted. These projects and assessments were based on the 2012 Mexican Atlas of CO2 Geological Storage, which evaluated carbon capture potential.[184] From these efforts two potential projects and sites in the Veracruz state were highlighted, including a project related to the Poza Rica thermal electricity generation plant to capture CO2 and an oil-enhanced recovery program for the onshore Cinco Presidentes oilfield.[185] Currently, there are political ambitions to develop ten demonstrative and large-scale potential projects, also onshore, but to date, none of these projects are in operation.[186]

Policy instruments were also supported by the World Bank. In 2014, a CCUS Roadmap was launched to "coordinate the efforts to conduct a strategic planification (sic) to implement [CCUS] nationally".[187] In 2018, a follow-up Road Map was drafted by 11 institutions, including PEMEX and the Secretary of Energy ("SENER").[188] The 2018 Road Map highlighted the need to develop a regulatory framework for CCUS across the value chain.

Mexico currently lacks a specific regulatory framework for CCUS.[189] However, there are some existing regulations that indirectly deal with CCUS, such as those related to project planning or environmental protection in general. Exceptionally, the Mexican energy regime has direct provisions regarding CCUS in the oil and gas extractive industry, as well as in the classification of "clean energy sources".[190] This divide has led to a distinction between CCUS regulation within and outside the hydrocarbon sector in Mexico, which is discussed below.

The 2014 Mexican Hydrocarbons Law contains several provisions regarding the use of carbon for enhanced oil recovery. The National Hydrocarbons Commission is authorized to establish technical and operative standards to maximize hydrocarbon recovery, as stated in the 2014 Hydrocarbons Law, and the 2008 Law of the National Hydrocarbons Commission (Articles 3 and 4). Furthermore, the Hydrocarbons Act grants powers to the Mexican Agency for Industry Security, Energy, and Environment, a newly created entity, to regulate the generation, capture, transportation, and storage of CO2 in the sector.[191] The Ministry of Environment ("Secretaría de Medio Ambiente y Recursos Naturales") has the authority to regulate other sectors of the hydrocarbon value chain regarding CCUS.[192]

CCUS is used to define "clean energy" in the Mexican regulatory framework. For instance, Article 3, XXII. m) of the 2014 Industrial Electricity Act considers energy generated by thermal plants with CO2 capture and storage processes as "clean" if they have an efficiency that is the same or higher than

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[184] Gobierno de México, Atlas de Almacenamiento Geológico de CO_2 (2015), available at: https://www.gob.mx/sener/articulos/atlas-de-almacenamiento-geologico-de-co2-mexico.

[185] Mourits F and others, 'Overview of World Bank CCUS program activities in Mexico' (2017) 114 Energy Procedia 5916.

[186] Leonardo Beltrán, CCUS in Mexico for a low-carbon economy: Mexico's experience in CCUS implementation (2018).

[187] Secretaría de Energía (SENER), Mapa de Ruta Tecnológica de CUS en México (November 2018), p. 5.

[188] Ibid.

[189] World Bank, *Development of a regulatory framework for carbon capture, utilization and storage in Mexico* (June 2016), p. 5; Enrique Garza (Clyde&Co), Production of Hydrogen and Carbon Capture and Storage (CCS) in Mexico: A Regulatory Analysis (2 March 2022), https://www.clydeco.com/en/insights/2022/03/production-of-hydrogen-and-carbon-capture.

[190] Quetzalli Ramos Campos, Aspectos regulatorios y legales de la tecnología CCUS (March 2021), available at: https://es.ai.org.mx/wp-content/uploads/2020/11/Aspectos-Regulatorios.pdf.

[191] Heras B and Mota J, Development of Mexico's CCUS Regulatory Framework (14th International Conference on Greenhouse Gas Control Technologies, 2018), p. 1.

[192] Ibid, p. 3.

the standard of kWh by CO2 equivalent ton set by the competent authority. Similarly, the Energy Transition Act defines "clean energy" using CCUS, setting a threshold of no more than 100 kg/MWh for energy production using CO2 capture.[193]

Various legal instruments contain scattered and indirect regulation of CCUS. These rules apply generally and cover various issues related to the conceptualization of carbon, property rights, its capture, transport, storage permits, environmental protection rules around it, and utilization.[194] Some particular applications or areas are more regulated than others. For instance, regarding capture, the General Law on Ecological Equilibrium and Environmental Protection sets basic rules for project design and licensing, even if there is no current authorization procedure for CO2 capture activities in Mexico.[195] A license would cover CO2 capture aspects as part of the general permitting requirements for installations such as electricity plants.[196] Additionally, Environmental Impact Authorization and the Sole Environmental License rules are required to authorize CCUS activities.[197]

Transportation of CO2 is insufficiently regulated.[198] However, legislative changes in the current regimes could expand the scope of application of existing rules. For example, by modifying those related to the transportation of natural gas via pipelines, and the transport of materials, hazardous materials, and hazardous waste.[199]

The monitoring and reporting requirements depend on the classification of the installation and whether it falls under federal or state jurisdiction. Further, the 2012 General Law on Climate Change applies to installations capturing CO2 emissions but only those generating more than 25,000 metric tons of CO2.[200]

Key CCUS areas for our report, such as long-term storage regimes,[201] site transfer from the operator to the state, and rules regarding leaks and liability, are either very lightly regulated or not regulated at all. Mexican legislation does not prescribe any specific monitoring technologies or rules for storage. Storage monitoring regulation and practices ought to be developed and based on the principles of best available practice, best available technology, and recognition of the fact that monitoring needs to be site-specific, as recommended in this report and comparative global practice (See section 1.4.4 of this report).

In conclusion, while Mexico has legislation covering most aspects of CCUS projects and applications, many of these rules are generic and not specifically designed for CCUS. This creates regulatory gaps and suboptimal solutions, especially when compared to best regulatory practices. In particular, the regulation of storage both onshore and offshore is underdeveloped, leading to legal uncertainty and

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[193] Transitorio, Décimo Sexto, Ley de Transición Energética (2015).

[194] Quetzalli Ramos Campos, Aspectos regulatorios y legales de la tecnología CCUS (March 2021), available at: https://es.ai.org.mx/wp-content/uploads/2020/11/Aspectos-Regulatorios.pdf.

[195] Mourits F and others, 'Overview of World Bank CCUS program activities in Mexico' (2017) 114 Energy Procedia, p. 5930.

[196] World Bank, *Development of a regulatory framework for carbon capture, utilization and storage in Mexico* (June 2016), p. 10.

[197] Mourits F and others, 'Overview of World Bank CCUS program activities in Mexico' (2017) 114 Energy Procedia, p. 5930.

[198] World Bank, *Development of a regulatory framework for carbon capture, utilization and storage in Mexico* (June 2016), p. 10.

[199] Ibid, p. 10.

[200] Ibid, p. 10.

[201] Enrique Garza (Clyde&Co), Production of Hydrogen and Carbon Capture and Storage (CCS) in Mexico: A Regulatory Analysis (2 March 2022), https://www.clydeco.com/en/insights/2022/03/production-of-hydrogen-and-carbon-capture.

increased risks for project developers, future storage operators, and the Mexican state. As a result, stakeholders have suggested developing an "Official Mexican Framework for CCS/CCUS"[202] to create a more comprehensive and concentrated regulatory regime. While efforts are reportedly underway, no concrete results have yet materialized.

1.5.9 Conclusions on national regulation and CCS projects

In this section, we have compared national regulations, based on analysis of legal texts and taking a functional approach. The purpose is to document the generic relevance of the ACTOM toolbox and how designing a monitoring programme based on the toolbox will align with national policy and regulation. The aim has been to discuss whether there are any deviations compared to the findings concerning global and regional regulation in section 1.4.4, in specific countries, which add new monitoring phases or monitoring aims as mandatory, or add requirements for specific monitoring technology that the ACTOM toolbox needs to meet. No examples of such deviations have been found in national legislation.

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[202] Secretaría de Energía (SENER), Mapa de Ruta Tecnológica de CUS en México (November 2018), p. 8.

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Part II: Assessment of selected geophysical and marine monitoring technologies

2.1 Introduction

One take-away message from Part I of this report is that monitoring and verification are a regulatory requirement for offshore CCS projects. Successful monitoring depends on a number of technological components working in harmony. Gathering and analysing the data necessary to assess storage performance and manage risks may require reliable and accurate measurements, sensors, deployment platforms, such as sea floor landers and AUVs or boats, and data-processing methods to transfer data in near-real-time and/or translate data into meaningful information. Thus, consideration of the above components will be a central task when designing a monitoring programme.

Here, our aim is to assess existing monitoring technologies and methods with respect to how optimally they perform relative to regulatory requirements and technical capabilities. In order to achieve this, we first created an inventory of geophysical and marine monitoring technologies compiled during earlier projects, notably the online IEAGHG Monitoring Selection Tool and the STEMM-CCS Online Monitoring and Decision Tool (section 2). These online tools catalogue monitoring technologies that cover all the three reservoirs: subsurface, seawater and atmosphere. The focus in ACTOM (and this WP1 report) is on the marine environment, and while subsurface and seafloor connections are relatively close, the connectivity between the water column and the overlying atmosphere is more distributed due to lateral mixing and complex processes that affect the natural dynamics of CO_2 exchange across the sea-surface (Phelps et al., 2015). For our inventory, we therefore selected technologies for seawater and subsurface.

Next, we defined uniform criteria and assessed the capabilities of each technology/method by awarding scores. The results are presented in table form in the next subsection (Table 2.2.2), which enables users to select the technologies/methods that best address legal requirements identified in a given project/scenario. Within the context of this report, there is no conflict between available technology and regulation requirements as long as at least one technology exists that addresses the legal requirements in the project/scenario.

In section 2.3, we describe some novel techniques. They include surveying techniques, such as acoustic and seismic monitoring techniques involving 4D high-resolution imaging and/or fibre-optic sensing and interferometric imaging, and methods for water column CO_2 anomaly identification and attribution. We conclude with a comment on monitoring strategy.

2.2 Technical capabilities and regulation protocols

Selected techniques and methods were assessed for their technical capabilities and their suitability for addressing different steps in regulation protocols. The assessed technologies were selected from pre-existing databases of technologies, such as the IEAGHG inventory of monitoring tools (https://ieaghg.org/ccs-resources/monitoring-selection-tool) (Figure 2.2.1) and the STEMM-CCS Online Monitoring and Decision Tool (stemm-ccs.eu/monitoring-tool/) (Figure 2.2.2). These technologies will be partly included as input for the CO_2 impact simulation toolkit in WP2. The different technologies were assessed with respect to 18 criteria (Table 2.2.1) for capabilities, cost and regulation requirements. As regards the latter, the technologies were assessed for six sub-criteria required by the CCS regulation protocols (Dixon and Romanak, 2015):

1. Background or baseline measurements (B)
2. Performance of the CO_2 storage in the reservoir (P)
3. Detection of leakage/anomalies (D)

And, If leakage is detected, suspected or alleged

4. Attribution of source (A)
5. Quantify leakage (Q)
6. Assess Impacts (AI)

The technologies were also assessed for synergy, and the overall score (the cumulative sum of all scores) was also reported for each technology.

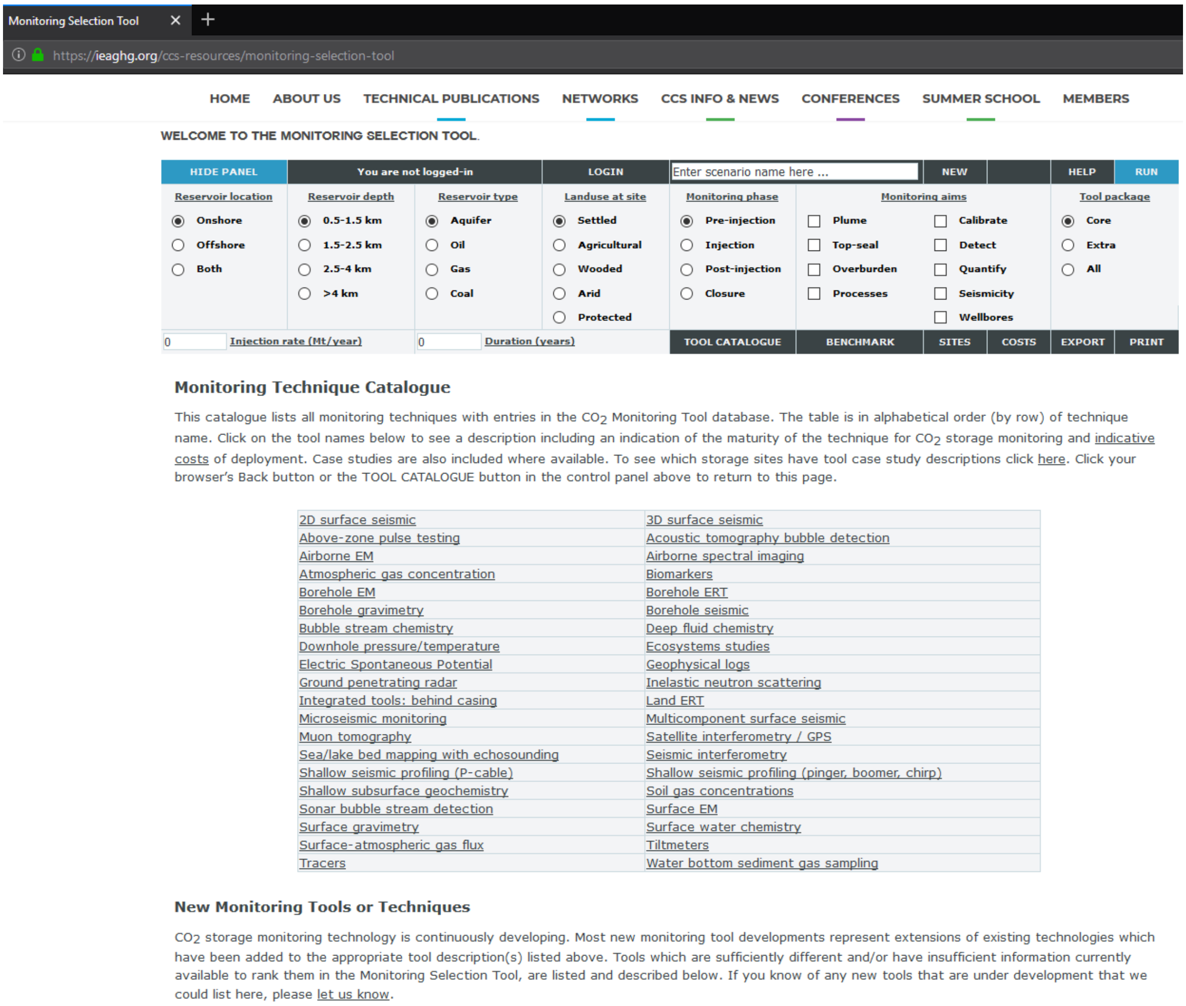
The results of the assessment are summarised in Table 2.2.2., which shows a comprehensive inventory and ranking of geophysical and marine monitoring technologies. The results also show that technology exists for all project phases, surfaces and monitoring purposes. Hence, no conflict between regulation and technology has been identified so far. However, there is a possibility that certain types of monitoring technology will be incompatible with the local conditions at CCS sites. Barriers, such as national legislation and local restrictions, mammal life, environmental hazards, logistical challenges and others, can hinder or prohibit the use of certain monitoring technology. One recommendation following from ACTOM WP1 is to implement a simple front-end in the CO2 impact simulation toolkit that filters out disqualified monitoring technology for each reviewed CCS site.

Criterion	Legend
1. Overall score	Cumulative sum of all scores
2. Sea water column	Performance in sea water column
3. Sea bottom	Performance around sea bottom
4. Sea bottom subsurface	Performance in sea bottom subsurface
5. Regulation	Monitoring requirement/phase (Dixion and Romanak, 2015), either: baseline (B), performance (P), detection (D), attribution (A), quantification (Q), or impact assessment (IA)
6. Sensitivity	Sensitivity / signal-to-noise of method
7. Effort	Overall required effort regarding power, logistics
8. Accessibility	Method’s capability to access target measurement area
9. Time required	Time required to perform acquisition / processing of method
10. Practical	Practicality of executing the method at site
11. Coverage	Spatial coverage of a method
	Temporal coverage of a method
12. Resolution	Spatial resolution of a method
	Temporal resolution of a method
13. Penetration	Penetration depth / distance of method
14. Repeatability	Repeatability of comparable results of method
15. Baseline/versus/repeat	Suitability of method to be used for baseline or repeat surveys
16. Cost/km	Cost of method per kilometre
17. Cost/hour	Cost of method per hour
18. Synergy	Synergy of method with other methods

Table 2.2.1: Assessment criteria and their explanations.

The ranking in Table 2.2.2 was arrived at by assigning scores 1, 2 or 3 (higher is better) to the methods for the 18 categories which are shown above along with their legends. The rationale behind the score system is as follows: 1 is the lowest score, meaning that a method performs poorly in relation to the given criterion or setting; 2 is a medium score, meaning that a method yields overall reasonable performance; while 3 is the highest score, meaning that a method yields high performance, impact and value of information.

The main result here is that we have created a framework (inventory Table 2.2.2) that enables searches of best suitable technology. The best overall methods can be found by filtering Table 2.2.2 for the highest overall score. However, this does not mean that these methods would automatically be the method of choice for a given CCS site. As mentioned above, filtering/weighting based on additional conditions is necessary after the ranking. It must also be mentioned that both the technologies included and the expert opinion-based scores are preliminary and will be further discussed within ATCOM and refined accordingly.



WELCOME TO THE MONITORING SELECTION TOOL.

Reservoir location: ● Onshore ○ Offshore ○ Both
Reservoir depth: ● 0.5-1.5 km ○ 1.5-2.5 km ○ 2.5-4 km ○ >4 km
Reservoir type: ● Aquifer ○ Oil ○ Gas ○ Coal
Landuse at site: ● Settled ○ Agricultural ○ Wooded ○ Arid ○ Protected
Monitoring phase: ● Pre-injection ○ Injection ○ Post-injection ○ Closure
Monitoring aims: ☐ Plume ☐ Top-seal ☐ Overburden ☐ Processes ☐ Calibrate ☐ Detect ☐ Quantify ☐ Seismicity ☐ Wellbores
Tool package: ● Core ○ Extra ○ All
0 Injection rate (Mt/year)
0 Duration (years)

Monitoring Technique Catalogue

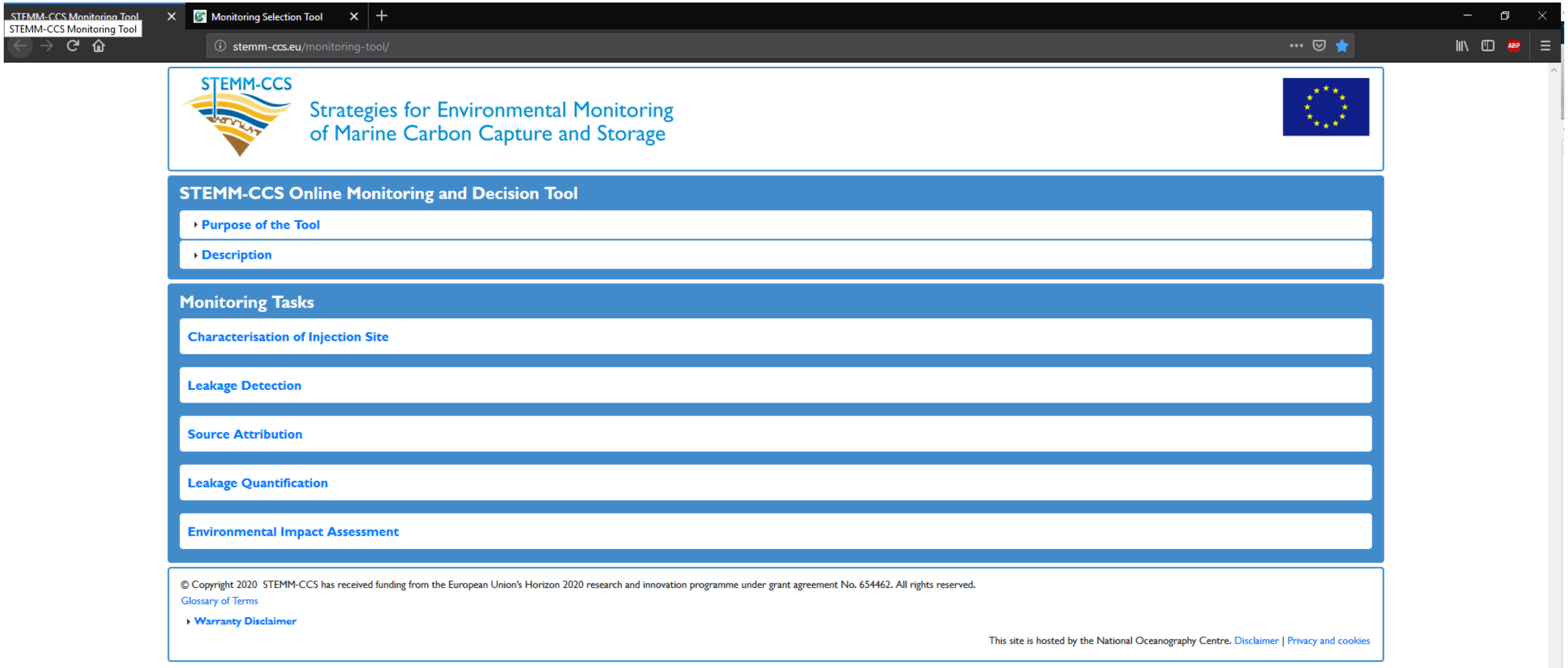
This catalogue lists all monitoring techniques with entries in the CO_2 Monitoring Tool database. The table is in alphabetical order (by row) of technique name. Click on the tool names below to see a description including an indication of the maturity of the technique for CO_2 storage monitoring and indicative costs of deployment. Case studies are also included where available. To see which storage sites have tool case study descriptions click here. Click your browser's Back button or the TOOL CATALOGUE button in the control panel above to return to this page.

2D surface seismic	3D surface seismic
Above-zone pulse testing	Acoustic tomography bubble detection
Airborne EM	Airborne spectral imaging
Atmospheric gas concentration	Biomarkers
Borehole EM	Borehole ERT
Borehole gravimetry	Borehole seismic
Bubble stream chemistry	Deep fluid chemistry
Downhole pressure/temperature	Ecosystems studies
Electric Spontaneous Potential	Geophysical logs
Ground penetrating radar	Inelastic neutron scattering
Integrated tools: behind casing	Land ERT
Microseismic monitoring	Multicomponent surface seismic
Muon tomography	Satellite interferometry / GPS
Sea/lake bed mapping with echosounding	Seismic interferometry
Shallow seismic profiling (P-cable)	Shallow seismic profiling (pinger, boomer, chirp)
Shallow subsurface geochemistry	Soil gas concentrations
Sonar bubble stream detection	Surface EM
Surface gravimetry	Surface water chemistry
Surface-atmospheric gas flux	Tiltmeters
Tracers	Water bottom sediment gas sampling

New Monitoring Tools or Techniques

CO_2 storage monitoring technology is continuously developing. Most new monitoring tool developments represent extensions of existing technologies which have been added to the appropriate tool description(s) listed above. Tools which are sufficiently different and/or have insufficient information currently available to rank them in the Monitoring Selection Tool, are listed and described below. If you know of any new tools that are under development that we could list here, please let us know.

Figure 2.2.1: Screenshot of IEAGHG inventory of monitoring tools (https://ieaghg.org/ccs-resources/monitoring-selection-tool)



STEMM-CCS

Strategies for Environmental Monitoring of Marine Carbon Capture and Storage

STEMM-CCS Online Monitoring and Decision Tool

- **Purpose of the Tool**
- **Description**

Monitoring Tasks

Characterisation of Injection Site

Leakage Detection

Source Attribution

Leakage Quantification

Environmental Impact Assessment

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Glossary of Terms

- **Warranty Disclaimer**

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Figure 2.2.2: Screenshot of STEMM-CCS Online Monitoring and Decision Tool (stemm-ccs.eu/monitoring-tool/)

Domain	Category	Method	Result	Overall score
Near-surface	Meta-analysis	Biomarkers	A useful, low-cost seabed monitoring method of physiological responses to CO_2 exposure by increases in dissolved CO_2 in the sediment	41
Near-surface	Meta-analysis	Cseep	Quantifies natural variability in the concentration of Dissolved Inorganic Carbon (DIC) and filters it out for easy identification of the impact of CO2 seepage	54
Near-surface	Meta-analysis	Ecosystems studies	Identified particular species or patterns that can act as bioindicators, enabling early detection of potential CO_2 leaks using a variety of microbiological, macrofaunal, botanical and biogeochemical techniques	43
Near-surface	Meta-analysis	GEOMAR Leak Model	Simulated behaviour of gaseous or liquid carbon dioxide released into the sea to assess the footprint of impact for different leak scenarios, such as are typically executed in an environmental impact assessment	45
Near-surface	Meta-analysis	MEIA	A model system, which allows us to predict gaseous and dissolved CO_2 flow through the water column as a result of buoyant bubble plumes and hydrodynamic flow in the water column and 'what if' scenarios	44
Near-surface	Meta-analysis	pH Eddy Covariance	Quantified natural variations in seafloor biological O_2 uptake and dissolved inorganic carbon (DIC) production; exceedingly sensitive to a seafloor source of DIC	35
Near-surface	Meta-analysis	ROC model	Recognised unnatural rates of change (ROCs) in CO_2 concentrations utilising the tidally induced mobility of CO_2 plumes, creating fluctuations over space and timescales that are different from those in natural processes	44
Near-surface	Meta-analysis	Seafloor Habitat Mapping	Habitat maps based on a combination of full-coverage environmental information and point-based direct observations, typically recorded using a survey vessel or on an Autonomous Underwater Vehicle	46

Near-surface	Sensoric data	Acoustic tomography bubble detection	Acoustic tomography detecting the dispersion of the acoustic signal by CO_2 bubbles leaking from the sea floor and causing upward currents, thus pinpointing the source of the CO_2 leakage	49
Near-surface	Sensoric data	Active Acoustics (EK60)	Detected gas within the water column by hull-mounted EK60 data, detectable most prominently at 18 kHz. Combined backscatter measurements at different frequencies can determine gas flux	50
Near-surface	Sensoric data	Active Acoustics (SBP)	Gaseous material within the seabed and in the water column easily seen on high-resolution seismic reflection data. The presence of gas is detected, and repeat surveys allow the migration of the gas to be seen in the subsurface	51
Near-surface	Sensoric data	Benthic Chamber	Monitored evolution of solute CO_2 concentrations within incubated volume over 1–2 days; their fluxes across the sediment-water interface can be quantified	41
Near-surface	Sensoric data	Bubble stream chemistry	Bubbles of gas collected by divers using inverted funnels in the offshore environment. The bubbles are collected in sealed containers, allowing detailed analyses of the gas composition to be made, to help identify the source of the gas	40
Near-surface	Sensoric data	Fibre-optic	Distributed Strain Sensoring (DSS), Distributed Acoustic Sensoring (DAS), Distributed Chemical Sensoring (DCS), Distributed Temperature Sensoring (DTS, highly repeatable and with large coverage of tens of kilometres	61
Near-surface	Sensoric data	Inelastic neutron scattering	Mapping of elemental concentrations (including carbon, silicon, oxygen) in the soil. A reduction in carbon relative to the other elements in the soil could indicate CO_2 leakage (successfully tested at a site described below	41
Near-surface	Sensoric data	Lab-on-Chip Gradient	A lab-on-chip sensor for dissolved inorganic carbon (DIC), or a combination of pH and total alkalinity sensor, quantifies the excess DIC in the water which is a result of dissolved CO_2 bubbles	38

Near-surface	Sensoric data	Microprofiler	Strongly miniaturised electrochemical sensors with a tip diameter of less than 50 µm and a sensing surface of less than 0.5 µm recording CO_2, O_2, pH, H_2S, redox and temperature	47
Near-surface	Sensoric data	Multipurpose VCTD	Multipurpose Video Conductivity Temperature Depth (VCTD) system for detecting and monitoring gas-rich fluid seepage from the seafloor and investigating natural CO_2 and CH_4 seepages	37
Near-surface	Sensoric data	Muon tomography	Monitoring density changes based on the changing muon flux could allow accurate long-term passive monitoring of a CO_2 storage site	49
Near-surface	Sensoric data	Passive Acoustics	The acoustic signal recorded by multiple hydrophones can be used to determine the gaseous flux. Quiet sounds of the bubbles can be measured above the background noise	43
Near-surface	Sensoric data	pH Optodes	Indicator dyes that change their fluorescent properties depending on the pH in the analysed media, enabling several months long, continuous pH monitoring	58
Near-surface	Sensoric data	Seabed mapping with echosounding	One of the most accurate tools for imaging large areas of the seabed. Allows detailed mapping of seafloor bathymetry and provides information about the nature of the sediment / seawater interface.	48
Near-surface	Sensoric data	Seafloor Mapping	Seafloor mapping carried out using acoustic techniques, using either multibeam echosounders or sidescan sonars. Acoustic reflectivity of the seabed ('backscatter'): a proxy for seafloor hardness, and hence sediment type	47
Near-surface	Sensoric data	Shallow seismic profiling (P-cable)	Very high resolution 3D seismic in the top ˜1000m of the subsurface. Timelapse surveying would be required to identify changes that could indicate migration and leakage of CO_2	56
Near-surface	Sensoric data	Shallow seismic profiling (pinger, boomer, chirp)	Resolved bed thickness of a metre or less that likely has considerable potential to resolve small amounts of gas (typically represented by acoustic blanking, bright spots etc.)	56
Near-surface	Sensoric data	Shallow subsurface geochemistry	Geochemical computer codes using measurements of the relative proportions of these individual components to estimate the total CO_2 flux into the groundwater	48

Near-surface	Sensoric data	Sonar bubble stream detection	Detected bubbles allow for bubble stream chemistry techniques to be used to confirm the gas and source of the bubbles, and quantification of gas flux	47
Near-surface	Sensoric data	Surface water chemistry	Four typically measured parameters that, together with ancillary information such as conductivity, temperature, pressure, pH and salinity, can be used to describe the CO_2 system for a given water sample	47
Near-surface	Sensoric data	Traditional CTD	A variety of parameters are recorded (hydrography and carbonate chemistry) and several water samples are collected including dissolved gasses (such as O_2, DIC, CH_4...) inorganic nutrients (such as nitrates, phosphate and silicate)	45
Near-surface	Sensoric data	Water bottom sediment gas sampling	Seabottom gas sampling and analysis allows monitoring of the composition and origins of very shallow gas in the near-surface seabed, indicating CO_2 leakage or precursor fluid detection	49
Reservoir	Sensoric data	2D surface seismic	2D surface seismic used to image plume migration, and can help to constrain and verify predictive models. 2D seismic can also be useful for parameter testing, to assess resolution and detection capability.	54
Reservoir	Sensoric data	3D surface seismic	Full volumetric images of subsurface structure in both reservoir and overburden. Under favourable circumstances, they can offer spatial resolution down to a few metres or less, enabling changes in fluid distribution to be mapped	50
Reservoir	Sensoric data	3D/4D Seismic Acquisition	Images of geological formations and structures using reflections from interfaces where the petrophysical parameters change, used to image the migration of CO_2 away from the injection point	49
Reservoir	Sensoric data	Above-zone pulse testing	Monitored changes in bulk formation compressibility resulting from CO_2 incursion due to CO_2 migration from a storage reservoir into an overlying water-filled reservoir	43

Reservoir	Sensoric data	Borehole EM	Images of resistivity in the subsurface between wells. Timelapse imaging can reveal changes in CO_2 saturation or dissolution if other reservoir properties remain constant	54
Reservoir	Sensoric data	Borehole ERT	Monitored storage where there is a strong conductivity contrast between the low conductivity CO_2 and the reservoir fluids, such as in saline formations where CO_2 displaces more conductive formation waters	54
Reservoir	Sensoric data	Borehole GPR	Monitored water distribution in the subsurface and detected displacement of water by hydrocarbon gas vapours or biogenic gas accumulation in the area of CO_2 geological storage	53
Reservoir	Sensoric data	Borehole microgravimetry	Higher resolution monitoring of CO_2 movement around the well by measuring the gravity response of CO_2 layers in close proximity to the monitoring well	52
Reservoir	Sensoric data	Borehole seismic	Measured velocity and attenuation characteristics along a 2D profile between wells, yielding detailed, high-resolution velocity and reflection images of CO_2 in the subsurface	55
Reservoir	Sensoric data	Deep fluid chemistry	A CO_2 or fluid sampling system known as a U-tube sampler that allows samples to be returned to surface at reservoir pressures via a stainless steel tube that can be permanently or semi-permanently deployed in a wellbore	44
Reservoir	Sensoric data	Downhole pressure/temperature	Wellhead, bottom-hole and annular pressure and downhole temperature monitoring providing early evidence of CO_2 migration, reservoir pressure build-up, information on injectivity and cement and/or casing degradation or failure	53
Reservoir	Sensoric data	Electric Spontaneous Potential	Detected CO_2 migration in the subsurface by measurement and subsequent monitoring of self-potentials of storage sites. Coupled flow equations relating self-potential to fluid flux	54
Reservoir	Sensoric data	Geophysical logs	Measurement profile of various physical properties along borehole length, detecting presence of CO_2 which changed the physical properties of the borehole. Repeats for CO_2 monitoring	52
Reservoir	Sensoric data	Integrated tools: behind casing	Modular borehole monitoring (MBM) system designed to allow multiple monitoring technologies to be more easily and cheaply deployed in CO_2 storage site monitoring wells	57

Reservoir	Sensoric data	Microseismic monitoring	Monitoring of CO_2 storage to assess the geomechanical stability of the storage site and any induced seismic hazard due to injection. It may be possible to map the spread of injected CO_2 via induced fracturing or fracture reactivation	50
Reservoir	Sensoric data	Multicomponent surface seismic	A more complete picture of fluid behaviour, including improved imaging beneath gas accumulations, and improved discrimination of fluid pressure and saturation changes	55
Reservoir	Sensoric data	Seismic interferometry	A highly effective tool for monitoring changes in CO_2 saturation and pore pressure during and following CO_2 injection. Estimates of the propagation velocity of seismic waves in the subsurface, including the pore fluid	55
Reservoir	Sensoric data	Surface gravimetry	Detected mass changes, and possibly surface deformations, induced by the storage process or by possible CO_2 leakages into the overburden	59
Reservoir	Sensoric data	Tiltmeters	Assessed rock mechanical integrity of the reservoir and, in particular, the caprock during the injection process. Monitored changes in strain, useful where geomechanical models indicate that induced faulting may be an issue	55
Reservoir	Sensoric data	Tracers	Fluids with a distinct chemical property that gives the injected CO_2 a unique fingerprint, thereby distinguishing it from any other potential CO_2 sources	48

Table 2.2.2: Draft comprehensive inventory and ranking of geophysical and marine monitoring technologies.

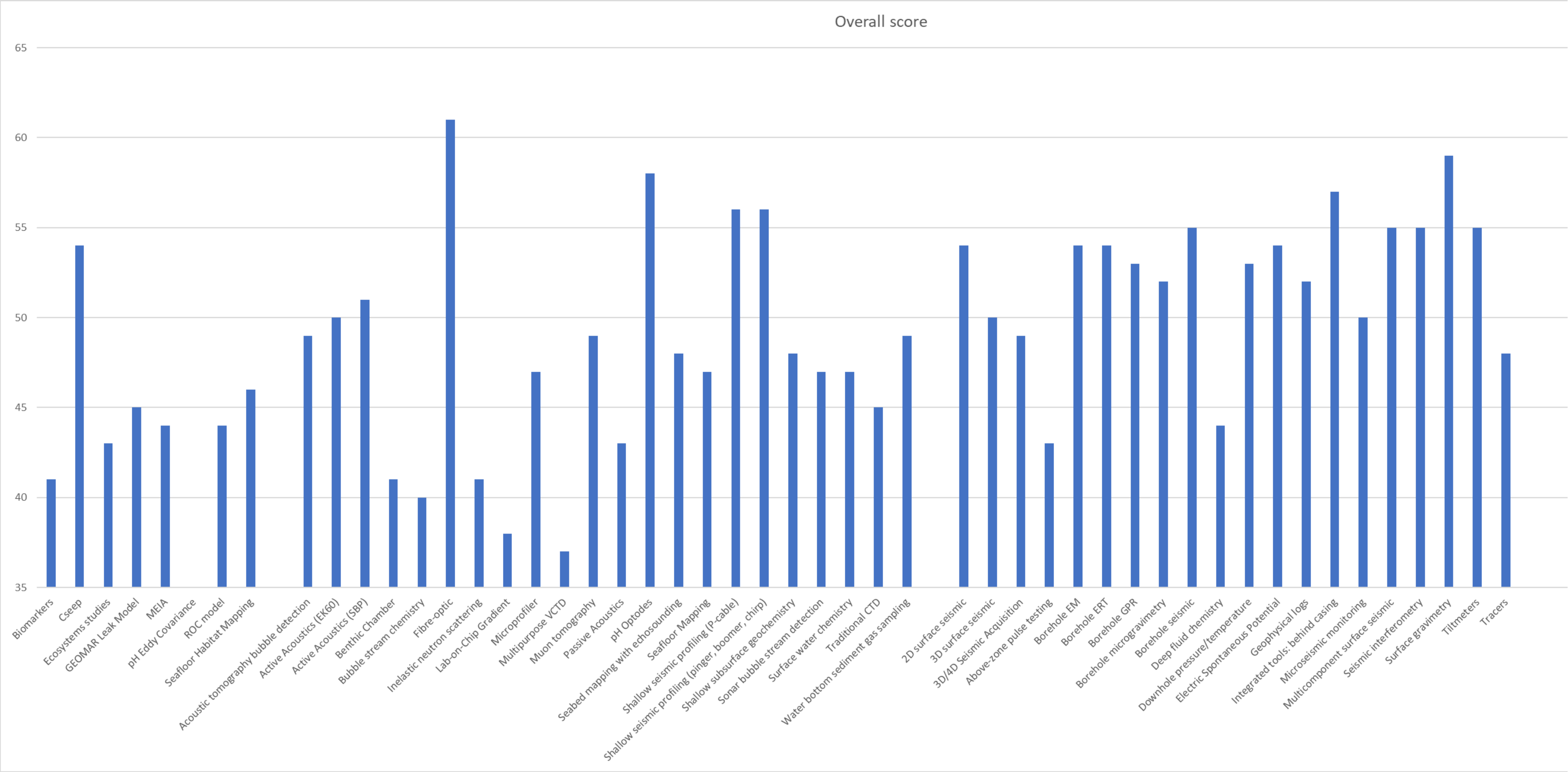

Figure 2.2.3: Visual plot of ranking results for all monitoring technology in Table 1.

When reviewing the plot of ranking results for all monitoring technology from Table 2.2.2 in Figure 3, at first glance, the overall optimal methods appear to be: a) Cseep, 2) fibre-optic measurements, c) integrated tools behind casing, d) pH optodes, e) 2D surface seismic, f) multicomponent surface seismic, g) seismic interferometry, h) shallow seismic profiling (P-cable, pinger, boomer, chirp), and i) surface gravimetry.

These overall optimal methods cluster into well-based/logging tools and seismic surveying, giving an indication of which methods can potentially be combined. An additional recommendation is therefore to assign extra ranking scores to methods that can be combined in one survey to save costs. Further ideas for improving the ranking table are to 1) include depth-relation: can certain shallow monitoring be ruled out/excluded by deep monitoring?, 2) include CO_2 flux detection threshold per method as a function of distance, time, site characteristics etc., and 3) further specify costs per method. The full table, including all nuances and criteria, is attached to this report.

2.3 Novel techniques

2.3.1 4D high-resolution surveying

In WP2, we will investigate how shallow subsurface geophysical information can be used to quantify risk spatially in task 2.3, thereby focusing the monitoring in a more efficient way. A feasibility study of the surveying techniques will establish whether their resolution, localisation, signal-to-noise and cost are suitable for the marine CO_2 monitoring strategies in this project. For this purpose, we will use an existing 3D high-resolution seismic data set, acquired by TNO near a foreseen storage location offshore of Rotterdam in the Netherlands. The acquisition parameters and geometrical layout of this 3D survey will provide input for a 4D seismic modelling study of all four methods and various CO_2 accumulation and seepage scenarios can be shared with other tasks in this project. The results of the 4D seismic modelling study will be compared with existing seismic modelling studies for other CO_2 storage locations, such as Tomakomai offshore of Japan and Smeaheia offshore of Norway, which is being investigated by Equinor. The milestone will be a map of geologically defined risk, uploaded to the GIS and informing the derivation of a monitoring strategy.

Already in WP1, we investigated what potential 3D high-resolution data have for upcoming CCS sites and our CO_2 simulation toolkit. Figures 2.3.1.1-2.3.1.3 show how the orders of magnitude of higher resolution in the P18 hi-res survey have revealed shallow gas accumulations and gas migration systems that conventional surveys have not been able to characterise.

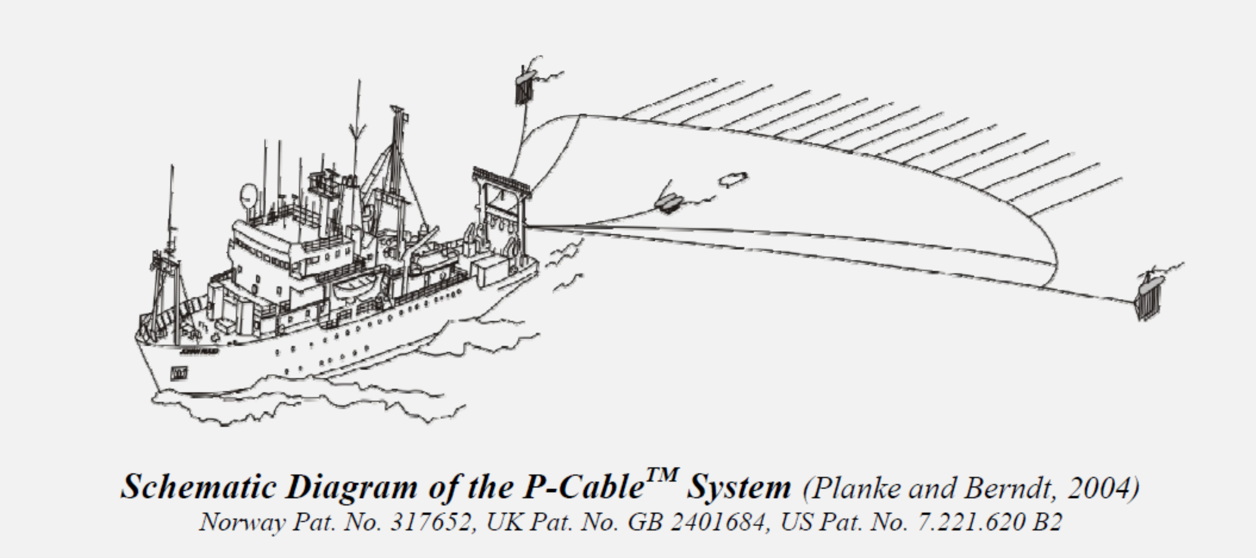

Figure 2.3.1.1: Sketch of the modified P-Cable system used for the P18 hi-res survey including patent details and patent ownership.

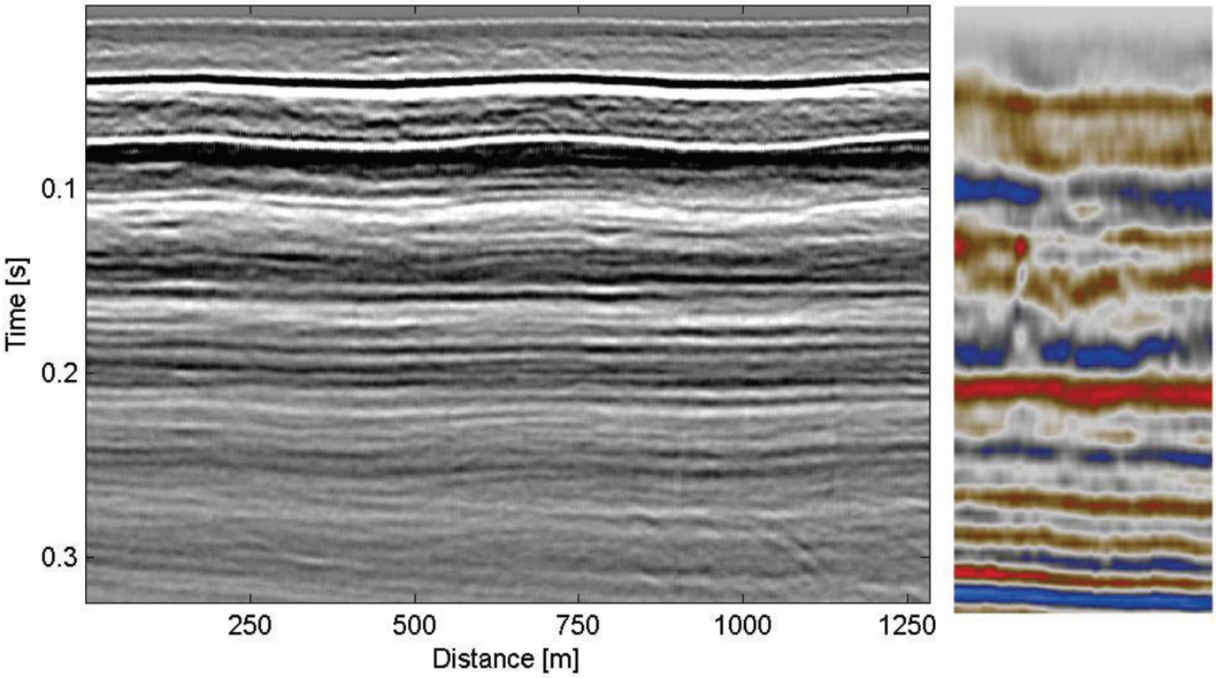

Figure 2.3.1.2: Comparison of P18 hi-res survey to a conventional co-located 3D survey.

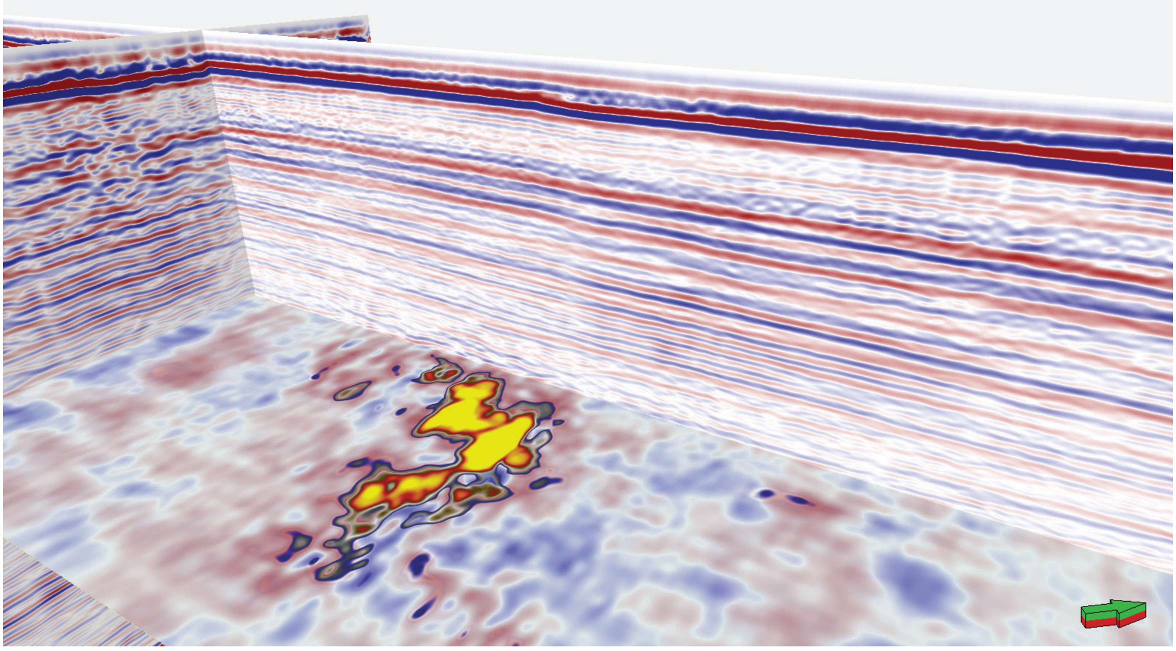

Figure 2.3.1.3: Indications of shallow gas bright spots in the P18 hi-res data and their possible migration systems are a good prospect for contributing to the WP2 toolkit.

2.3.2 Fibre-optic sensing

The potential of fibre-optic sensing was reviewed in an in-depth assessment of monitoring techniques. Figure 7 shows how a TNO proprietary Fibre optic DAS VSP dataset collected at a shallow geothermal site in Germany has added significant resolution to a co-located conventional 2D hi-res surface-based seismic survey. This is only a small part of the whole family of fibre-optic sensing methods. Distributed Acoustic Sensing (DAS) can track seismic velocity anomalies in the seawater column due to columns of rising CO_2 along the borehole. Distributed Temperature Sensing (DTS) can track temperature anomalies in the seawater column due to columns of rising CO2 along the borehole. Fibre Bragg Gratings (FBGs) on optical cables can sense CO_2 concentration anomalies. Distributed Strain Sensing (DSS) can sense flows of gas along the borehole. All of these applications will have to prove themselves in terms of sensitivity and feasibility.

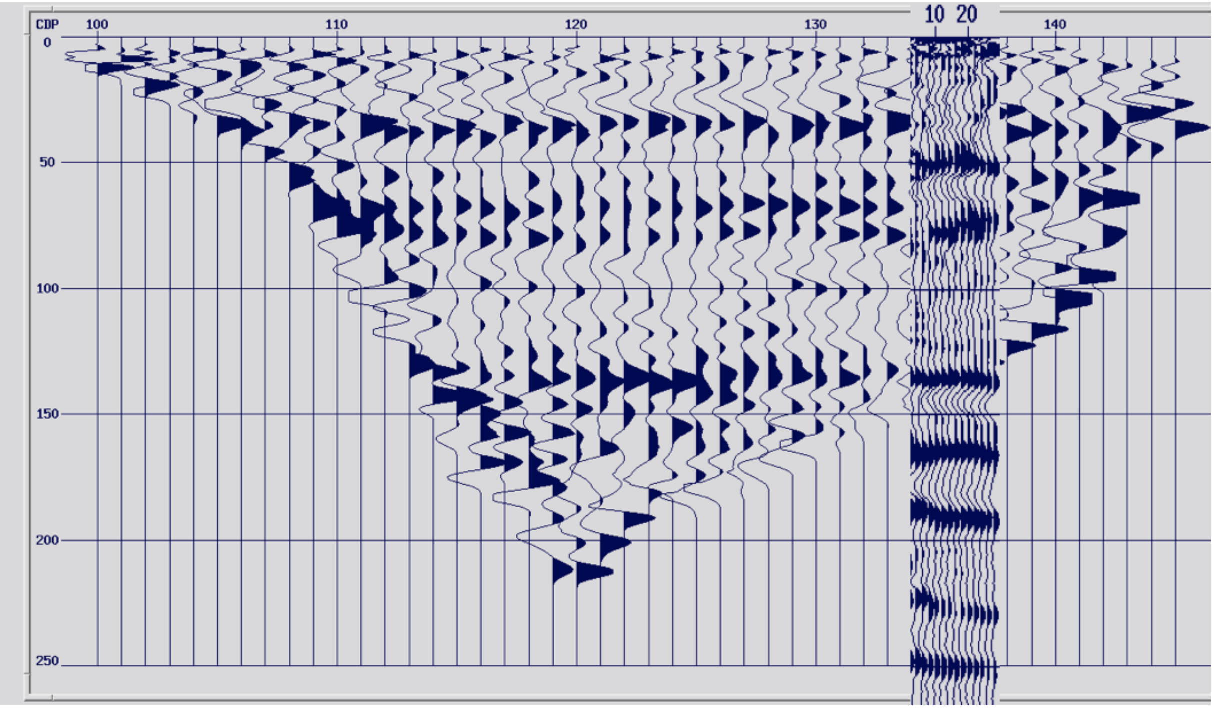

Figure 2.3.2.1: Fibre-optic DAS VSP (inset) has added significant resolution to a co-located conventional 2D hi-res surface-based seismic survey. Figure taken from Vandeweijer et al. (2018).

2.3.3 Interferometric imaging

As another potentially cost-effective CCS monitoring tool, Ambient Noise Seismic Interferometry (ANSI) was evaluated in depth. Figures 2.3.3.1 and 2.3.3.2 show simulation data and actual field data from use of the ANSI method. The figures show that in real-life noisy conditions, ANSI can be an attractive replacement for active-source 2D and 3D seismic surveying at a CCS site. However, the ANSI method still has some operational issues that must be solved before the method is really mature for timelapse CCS monitoring.

Figure 2.3.3.1: Results of timelapse simulation of an upwelling CO_2 plume in the subsurface (left) and the ANSI interferometric seismic timelapse signature (right). Figure taken from Eliasson et al. (2020).

Figure 2.3.3.2: Comparison of field data of ANSI result (left) for onshore geothermal exploration with co-located vintage active 2D seismic line (right). Figure taken from Boullenger et al. (2019).

2.3.4 Stoichiometric methods for the marine environment

Concentration-based monitoring methods aim to identify leakages from directly measured CO_2 concentrations. However, high variability in both biochemical activities (Artioli et al., 2012; Romanak et al., 2012; Botnen et al., 2015) and ocean current conditions (Alendal et al., 2005; Ali et al., 2016) is a challenge for such procedures. Romanak et al. (2015) pointed out that the concentration-based method has several drawbacks in the vadose zone, including high variability of in situ generated CO_2 that could mask a moderate leakage signal; inability of the background characterisation to, by itself, account for complete CO_2 variability from climatic, land use, and ecosystem variations over the lifetime of a storage project. Therefore, they recommended a process-based approach that uses stoichiometric relationships between major gases (CO_2, N_2, O_2, CH_4) to distinguish a leakage signal from natural variability of CO_2 in the vadose zone.

For the marine environment, a process-based stoichiometric approach called C_{seep} has been developed for the detection and quantification of CO_2 seepage dissolution into seawater (Botnen et al., 2015; Omar et al., 2020). When CO_2 dissolves and reacts with seawater, it forms carbonic acid (H_2CO_3), which rapidly dissociates into bicarbonate ions (HCO_3^-; Eq. 1), which, in turn, may dissociate into carbonate ions (CO_3^{2-}; Eq. 2) based on the following equilibrium reactions:

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \qquad (1),$$

$$HCO_3^- + H^+ \leftrightarrow CO_3^{2-} + H^+ \qquad (2).$$

This results in an elevated concentration of dissolved inorganic carbon (DIC = HCO_3^-+ CO_3^{2-} + CO_2; henceforth denoted as C) and of hydrogen ions (H^+), either of which could be used to detect CO_2 leakage signals (e.g. Alendal and Drange, 2001). However, defining anomaly thresholds for geochemical monitoring of the water column is challenging due to the complexity of the seawater CO_2 system. Natural processes, such as photosynthesis/respiration, biosynthesis/dissolution of calcium carbonate ($CaCO_3$) and changes in temperature and salinity, affect the seawater concentrations of C and H^+ which is normally reported as pH.

The C_{seep} method uses knowledge of the seawater CO_2 system, as well as the natural processes affecting it, in order to account for any signal arising from natural variability. The method assumes that there is a nearly constant theoretical baseline C concentration (C_b) in seawater, which is dictated by the history and physical properties of the sampled water parcel and over which fluctuations (ΔC) created by natural processes and/or CO_2 seepage are superimposed:

$$C = C_b + \Delta C \qquad (3),$$

where C is the measured concentration. Through baseline characterisation, a site-specific model that estimates the ΔC term is developed. Typically, this term is further decomposed into a biology-driven contribution (ΔC_{bio}), an air-sea exchange-driven contribution (ΔC_{ase}), a mixing-driven contribution (ΔC_{mix}) and impact of CO_2 seepage (C_{seep}). Furthermore, the first three contributions are ‘modelled’ from natural changes in nutrients, salinity, and total alkalinity (TA) relative to arbitrary reference values (e.g. annual means) using stoichiometric and empirical relationships as qualitatively described in Omar et al. (2018). Once the contributions of the natural variability are estimated, Eq. (3) is rearranged as:

$$C – \Delta C_{bio} – \Delta C_{mix} – \Delta C_{ase} = C_b + C_{seep} \qquad (4),$$

in which the terms on the left-hand side are known and those on the right-hand side are unknown. C_b is first determined by evaluating Eq. 4 for baseline measurements taken at a location with no seeps, i.e. with C_{seep}= 0. Now that C_b is known, Eq.4 can be further rearranged as

$$C – \Delta C_{bio} – \Delta C_{mix} – \Delta C_{ase} - C_b = C_{seep} \qquad (4a).$$

During the monitoring phase, new data are acquired and Eq. 4 is re-evaluated as Eq. 4a to determine C_{seep}. Thus, the central idea of the C_{seep} method is to estimate the natural variability and filter it out in order to facilitate easier identification of any seepage CO_2. This capability of the method has been tested in the northern North Sea, where the processes governing the natural variability of the seawater CO_2 system have been adequately modelled, allowing their influence on water column C measurements to be minimised, as depicted in Fig. 2.3.4.1.

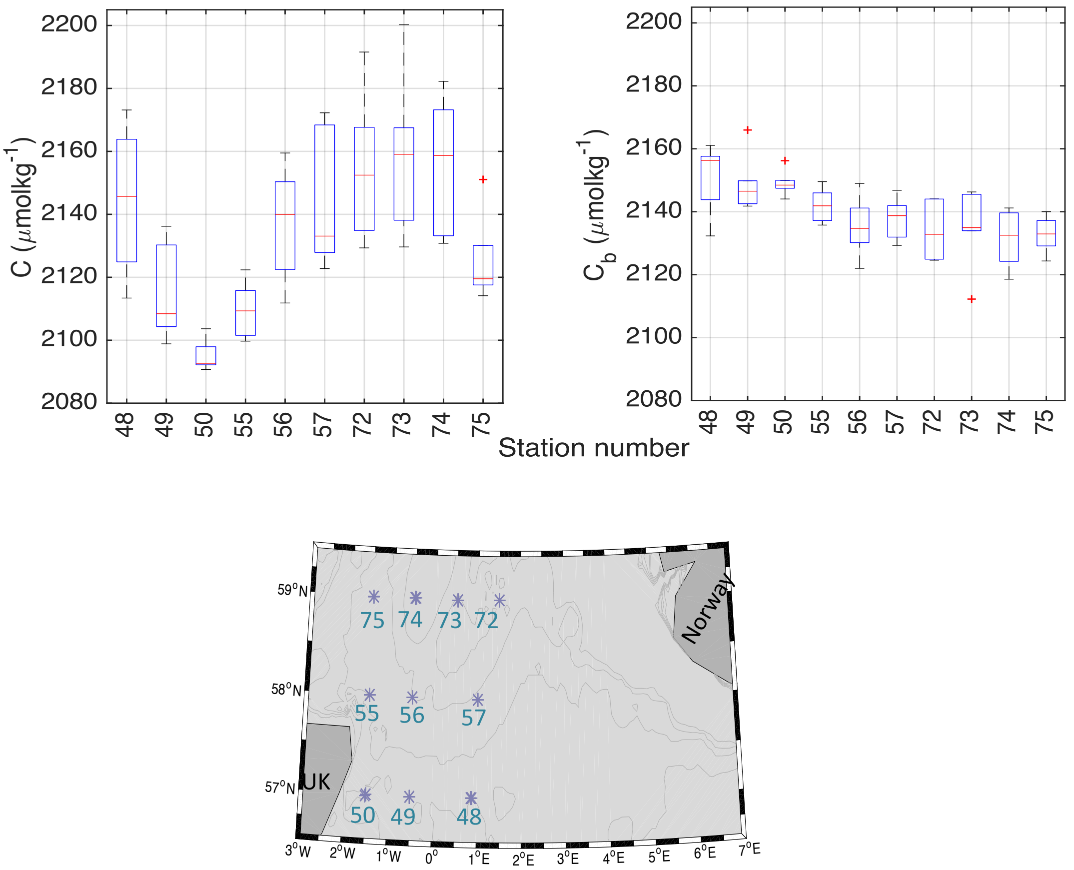

Figure 2.3.4.1: A box plot of measured background C (A) and computed baseline C_b (B), both as a function of sampling location station number. Based on historic data acquired from the north-western North Sea during six cruises in 2001, 2002, 2002, 2005, 2008 and 2011. Sampling locations and stations numbers are shown in (C). Each station was sampled six times and displays temporal variability. Panel B demonstrates how the C_{seep} methodology minimises the spatiotemporal variability arising from natural processes.

As can be understood from Eqs. 4 and 4a, uncertainties associated with the determination of natural derivers (ΔC_{bio}, ΔC_{mix}, ΔC_{ase}) and C_b all contribute to the total uncertainty in C_{seep} values. This total uncertainty is used to define a detection threshold. Monte Carlo simulations we carried out in WP1 showed that the main sources of uncertainty in the natural derivers and C_b include (i) errors in the stoichiometric ratios parameterising the C variability due to photosynthesis/respiration; (ii) errors in the freshwater TA; (iii) errors in the temporal trend in C due to oceanic uptake of anthropogenic CO_2 from the atmosphere (Omar et al., 2019); and (vi) measurement uncertainties. The latter uncertainties are usually relatively small, but inter-laboratory and/or inter-cruise differences may increase them substantially. A sound, site-specific characterisation with high spatiotemporal resolution is needed to accurately parameterise the drivers of the natural variability. Together with careful selection of appropriate data for the determination of C_b, this will contribute to reduced uncertainty in the computed C_{seep} values, thereby minimising the occurrence of false positives.

2.3.5 Rate of Change (RoC) Anomaly

Natural processes that affect the concentration of CO_2 in seawater tend to have particular temporal scales. For example, there are the daily and seasonal cycles of photosynthesis, depending on irradiance, while mixing depends on larger scale circulation processes, as well as the diurnal tidal cycle. Analysis of observational data augmented by comprehensive model results have enabled us to quantify the maximum expected natural change in CO_2 (expressed via pH) as a function of the time between samples (Fig. 7). From this, it is clear that, if sampling is frequent (less than 20 minutes apart), then a change in pH as small as 0.01 unit is very unlikely to be caused by a natural phenomenon. From the high-resolution models described in Blackford et al. (2017, 2020), we are able to understand the behaviour of small plumes of CO_2-rich water, as they oscillate via a tidal ellipse – the approximately ovoid trajectory that tidal processes impose on patches of sea water. As a result, a sensor is likely to experience a leak signal as a series of on-off events coherent with the tidal period (Fig. 8). Consequently we have identified a univariate anomaly criterion (a change of ≥ -0.01 pH unit in less than 20 minutes for much of the North Sea), which is achievable using current, off-the-shelf sensor technology and delivers a highly sensitive discriminator of a potential leak, thereby aiding long distance detection and or the detection of anomalies well below thresholds of environmental harm (Blackford et al., 2017).

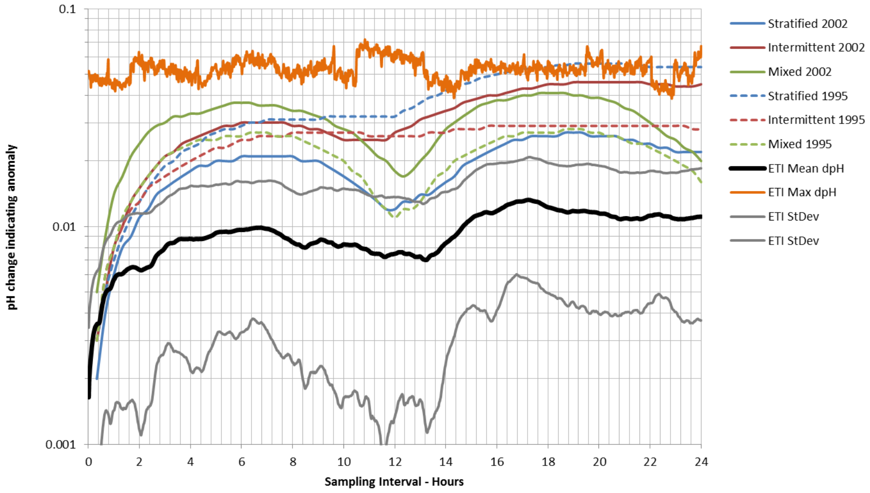

Fig. 2.3.5.1: Model-derived anomaly detection thresholds (red, blue, green lines representing different North Sea sites and solid-dash representing different years), expressed as the rate of pH change relative to the sampling interval. The black line represents the mean rate of change seen in a short-term observational exercise (range in grey). Orange lines represent an anomaly signal from a release experiment.

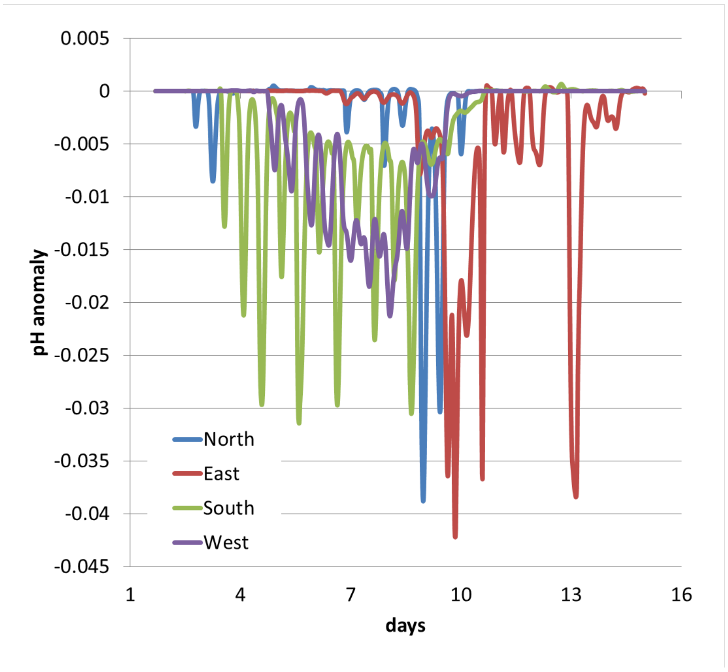

Fig 2.3.5.2: Signals of leakage seen by four sensors placed at cardinal points 1 km away from a leak event of 30T/d, derived from an in-silico simulation. The influence of the tidal cycle can clearly be seen.

2.3.6 Time series classification using machine learning technologies.

Machine learning techniques can be used to detect anomalies in time series, either by identifying outliers in unsupervised methods, or by classifying times series in classes through supervised learning.

Outlier, or event, detection in time series is frequently used in industrial settings to monitor changes in machines and structures to avoid breakdown and plan maintenance. One challenge when solely relying on outlier identification in environmental monitoring is that they can have many sources of origin, e.g. instrumentation failure or rare natural events. They will react to any unexpected characteristics in a time series.

In time series classification, through supervised learning, the machine learning framework needs data from the different classes. Gundersen et al. (2020) demonstrated the use of a Bayesian Convolutional Neural network to classify time series into two situations, leak/no-leak. The no-leak class, being the natural situation, could be covered by an environmental baseline. Multivariate time series would be preferred, enabling the framework to include correlation between variables in the classification. An example is the recurrence of pH drops with tidal current direction, as pointed out in a previous section. If the pressure drop occurs every time the current is in a certain direction, this would indicate a continuous CO_2 source in the upstream direction.

Very few time series are available for the leak situation, and they will be very expensive to produce. Data from a few release experiments are available (STEMM-CCS being one of them). So data for the leak situation will have to be taken from models simulating leak scenarios. Ocean General Circulation Models (OGCMs) that solve the fluid equation for velocity are often used to predict the transport of tracers. One use of the planned ACTOM simulation framework will be to utilise the produced velocity fields from these computationally demanding models to simulate more scenarios, thereby producing more data for the leak class in supervised learning.

2.3.7 A comment on monitoring strategy

Dean et al. (2020) summarised the findings from three projects investigating offshore monitoring of CO_2 storage projects. They describe the challenges of detecting, attributing and quantifying the flux of seeps of CO_2 through the seafloor. They also point to a challenge related to the lack of marine CO_2 emission quantification technologies that are required by regulations. Moreover, methods for analysing large streams of monitoring data for the purpose of detecting anomalies need to be matured. They conclude: *‘Some remaining challenges include missed/ false alerts because of large variations in the background signal, the cost of monitoring large areas over long periods, and making real-time decisions based on big data. Continued work to reduce the cost of marine monitoring technologies and advancing automation of data processing and analysis will be important in order to support safe and efficient offshore CCS deployment at large scale.’*

To reduce the cost, including the cost of false alarms, a holistic view needs to be taken of how uncertainties and inaccuracies propagate through the monitoring framework – from measurement errors via data analysis to decisions based on the information gathered. It will also be important to communicate capabilities to assure that regulations are not too demanding.

To achieve this, the monitoring programme will have to be designed so that it takes into account the site characterisation (where are the likely paths to the sea floor?), instrumentation (capabilities, uncertainties and synergies), data analysis (multivariate analysis, filtering, anomaly detection) and decision-making under uncertainty. A variety of measurement technologies can be used, the combination being site-specific, and the technology overview created here will be a valuable tool when designing monitoring programmes.

By viewing the marine monitoring programme as a component of the general marine surveying accompanying SDG14 (Life under water) and the UN’s marine decade, collaboration with other offshore activities could reduce the cost considerably. Many measurements will be common and there are obvious synergies. A collaborative monitoring programme can also be used to communicate that storage projects take environmental stress seriously and are part of sustainable ocean management, leading to higher public acceptance.

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