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Review of offshore CO_2 storage monitoring: operational and research experiences of meeting regulatory and technical requirements

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Abstract

Legislation for offshore storage has been developing over the last decade or so and is currently most developed in Europe. Although the large-scale operating sites in Europe were started prior to the regulations coming into force, any planned sites will need to meet these regulatory requirements. Our review of monitoring experiences from both the operating sites and research at experimental injection sites and in areas of natural CO_2 seepage suggest that broadly, the technical and regulatory challenges of offshore monitoring can be met. A full report reviewing offshore monitoring including tool capabilities, practicalities and costs is available from IEAGHG (released Q1 2016).

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Keywords: CO_2 storage sites; monitoring; challenges; regulations; Europe

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1. Introduction

The world's first large-scale dedicated CO_2 storage operation started at the Sleipner gas field in the Norwegian North Sea in 1996; this was followed by the Snøhvit project in 2008 (Fig. 1a). A pilot-scale project at K12-B, the Netherlands has been operating since 2004 and another, Tomakomai, recently started injection in Japan in 2016 (Fig. 1b). In addition, plans exist for large-scale storage projects in the North Sea Basin: Storage in the P18-4 gas field in the Netherlands, known as ROAD, is the first project to be awarded a permit under the EU Storage Directive; and in the UK, government sponsored CCS commercialisation competitions have yielded four Front End Engineering and Design (FEED) studies: for storage in the Goldeneye gas field (Longannet and Peterhead projects), the Endurance (5/42) saline aquifer structure (White Rose project), and the Hewett gas field (Kingsnorth project) (Fig. 1a).

The Tomakomai pilot aside, all offshore CO_2 storage is currently in Europe so it is perhaps not surprising that pertinent regulations are the most developed there. The focus of this paper therefore is on the technical and regulatory challenges relating to monitoring offshore at the European sites and how the monitoring strategies and results from operational sites meet the requirements. We also consider relevant research from experimental test injection sites and areas of natural CO_2 seepage (Fig. 1c).

The paper is based on a report for IEAGHG [1], published in January 2015 and publically released in June 2016. This includes more details on monitoring technologies deployed, considered in terms of their performance, capabilities, practicalities and costs. Note that the UK White Rose and Kingsnorth projects were not included because insufficient published information was available at the time the IEAGHG report was assembled. Also, since the report was published, the UK commercialisation competition was cancelled and funding withdrawn.

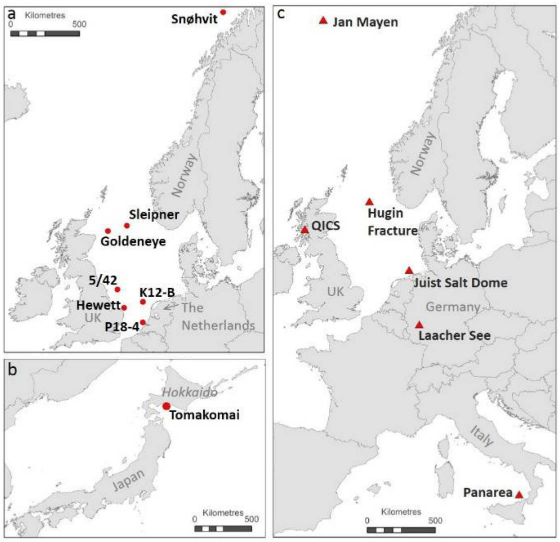

Fig. 1. (a) and (b) Offshore CO_2 storage sites operational or planned; (c) selection of European experimental or natural seepage sites offshore or in lakes.

2. Offshore storage regulations: monitoring requirements

International restrictions to the offshore geological storage of CO_2 were modified in 2007 with amendments to the London Protocol and the OSPAR Convention. Both of these have similar two-stage monitoring guidelines in place. 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 [1, 2, 3].

Since then, the global regulatory framework has been evolving, particularly in Europe where the European Commission developed a specific Directive for underground CO_2 storage in 2009 [4, 5, 6]. Even in Europe, which hosts all of the operational and currently planned large-scale offshore storage projects, it is recognised that precedents for the finer details of regulatory implementation have not yet been set. The Sleipner, Snøhvit and K12-B storage projects have been active for several years and predate the current legislation, whereas the planned ROAD project (Netherlands) and any UK North Sea projects will all be subject to European storage regulation.

Offshore storage regulations also exist and are developing elsewhere, notably in Japan, Australia and the United States (more detail is provided in IEAGHG, 2015 [1]). These are at various levels of detail, in a range of contexts, and at different stages of completion across the world. However, the regulatory documents from the different national jurisdictions generally emphasise the key role of monitoring and the range of objectives it should serve. We focus here on European sites under the European offshore regulatory framework which essentially comprises the European Storage Directive and the OSPAR Guidelines.

2.1. Monitoring requirements set by the European Commission (EC)

The EC Directive on the Geological Storage of CO_2 (2009) [4, 5, 6] applies to the territory and continental shelves of the member states for CO_2 storage exceeding 100 kilotonnes. It builds on the OSPAR principles and provides more detail of the practical implementation of a licensing regime. The Directive specifically addresses monitoring for the purposes of assessing whether injected CO_2 is behaving as expected, whether any migration or leakage is occurring, and if this is damaging to the environment or human health. Monitoring must be based on a monitoring plan which will be updated throughout the project lifetime as the risk profile changes and which takes into account improvements in scientific knowledge and best available technology. Monitoring deployments and results must be reported at least once a year to the Competent Authority (CA, the regulatory organization designated by each Member State).

To close the site, the operator needs to submit a post-closure plan approved by the CA. This must include: demonstration that the actual behaviour of the injected CO_2 conforms to the modelled behaviour; the demonstrable absence of any detectable leakage; and demonstration that the storage site is evolving towards a situation of long-term stability. These crucial closure-related criteria are critically dependent on the monitoring plan and its efficacy. Once a site is closed, any liabilities are transferred to the CA and monitoring may be reduced, but to a level that still allows identification of leakage or significant irregularities. If any such are detected, monitoring should be intensified as required to assess the scale of the problem and the effectiveness of corrective measures. The Directive indicates that anticipated monitoring costs for 30 years post-closure should be covered by financial contributions from an operator prior to site closure.

If leakage from storage is detected, additional monitoring is required by the EU Emissions Trading Scheme (ETS), to quantifying any actual emissions to a specified level of accuracy.

2.2. Overarching monitoring objectives distilled from the regulations

From a review of offshore storage regulation [1], two relatively consistent monitoring requirements have emerged: firstly to demonstrate that a storage site is currently performing effectively and safely; and secondly to ensure that it will continue to do so via the provision of information to support, and calibrate, predictions of future performance. These requirements can be distilled into a number of necessary actions (Fig. 2a), which fall within two main monitoring objectives, containment assurance and conformance assurance. A third category, contingency monitoring, might be required in the event that containment and/or conformance requirements are not met.

In terms of the types of monitoring tools used, it is convenient to categorise them as deep-focussed (providing surveillance of the reservoir and deeper overburden) and shallow-focussed (providing surveillance of the near seabed, seabed and water-column) (Fig. 2b). In general deep-focussed techniques are fairly well established offshore, as many have been matured for hydrocarbon exploration. Shallow-focussed monitoring for leakage detection is much less mature as it has much weaker industry drivers (excepting for military or hydrocarbon infrastructure maintenance related applications) and is therefore the subject of ongoing research and development.

a

		OSPAR	EU Directive	EU ETS	
Shallow-focussed monitoring actions	Verification of no leakage	✓	✓		Containment
	Leakage detection	✓	✓		Containment
	Emissions quantification	✓		✓	Contingency
	Environmental impacts	✓	✓		Other
	Testing remedial actions		✓		Contingency
Deep-focussed monitoring actions	Migration in overburden	✓	✓		Containment
	Containment integrity	✓	✓		Containment
	Migration in reservoir		✓		Conformance
	Performance testing, calibration and identification of irregularities	✓	✓		Conformance
	Calibration for long-term prediction		✓		Conformance
	Testing remedial actions		✓		Contingency

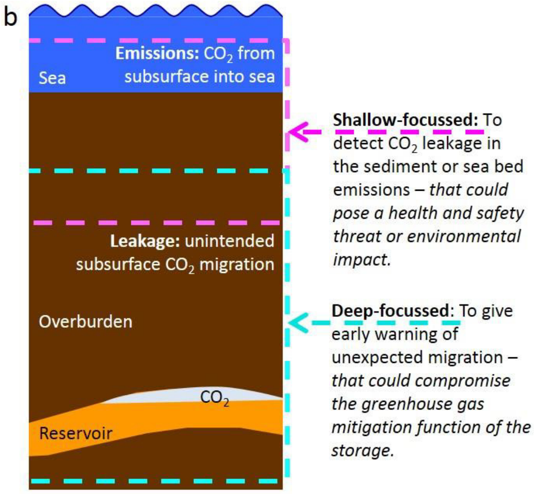

Fig. 2. (a) Key monitoring actions for offshore storage required under the European regulatory framework; (b) shallow and deep focussed monitoring regimes.

- Containment Assurance is the principal element of proving storage performance, demonstrating that the stored CO_2 is securely retained within the storage site such that it presents no hazard to health or the environment, and further, that the overarching greenhouse gas mitigation objectives of the storage are met. These objectives require both deep- and shallow-focused monitoring elements: deep-focussed to identify unexpected migration of CO_2 in the subsurface that might result in unintended leakage out of the storage volume i.e. to provide early warning of any potential CO_2 leakage and emissions; and shallow-focussed to detect CO_2 migration in the shallow subsurface and emissions at seabed. The latter should also address the possibility of other displaced fluids escaping from the storage site which might be precursors of impending CO_2 leakage. These could include shallow *in situ* pore-water or natural gases displaced across the sediment / water interface, or deeper subsurface fluids escaping from depth. It has the potential to detect small leakages and emissions that could not be detected by deep-focussed surveillance. However, natural variability may render the detection of emission signals above background challenging. A practical minimum requirement might therefore be that the deep-focussed monitoring system can reliably detect any leakage that is sufficiently large to compromise the greenhouse gas mitigation function of the storage i.e. with no gaps in spatial coverage and to a specified detection threshold depending on the amount of CO_2 stored; and that the shallow monitoring system should be capable of detecting any emission at seabed likely to pose a health and safety threat or environmental impact.

- Conformance Assurance is the second element of proving storage performance, showing that storage processes at the site are understood with a sufficient level of certainty to preclude the possibility that future deviation from expected storage behaviour would have significant adverse impacts. Conformance monitoring is primarily deep-focussed, aimed at imaging and characterising processes in and closely adjacent to the storage reservoir, such as temporal and spatial plume development or pressure evolution. Conformance can be demonstrated by verifying that models and observations agree within acceptable limits. Monitoring enables the testing and calibrating of models of current site behaviour, and forms the basis for reliable prediction of future site behaviour, long-term secure storage and satisfactory site closure. Non-conformance would be where observed site behaviour deviates from that predicted to a significant degree, for example, falling outside stated uncertainty ranges, or with the potential to lead to unfavourable outcomes. This would trigger suitable corrective actions such as additional (contingency) monitoring. Technologies deployed should therefore have sufficient resolution, sensitivity and / or quantitative capability to test the simulation models in a robust way.

- Contingency monitoring is for situations where assurance monitoring has detected significant deviation from planned performance. Additional monitoring might be required to track the deviation and assess possible consequences, to design corrective measures if necessary, and, should these be deployed, to confirm that they have been effective. An example might be where CO_2 is observed to be migrating into the shallower geological section, with a threat of future emissions. Contingency monitoring would be necessary to track the migrating CO_2 in the shallow subsurface, to assure that no emissions reach the water column and, if they did, to quantify them and assess environmental impacts resulting from leakage. It is likely that emissions measurement would require that the measurement accuracy of the monitoring system is known.

2.3. Regulatory requirements spatial scales and temporal frequencies

The monitoring aims require that monitoring of various parameters should be undertaken with a portfolio of techniques at a range of depths from the storage reservoir, through the overburden, to the seabed. The regulatory requirements also imply that monitoring will be required at a range of spatial scales: from the total footprint of the storage complex, including the area that might be influenced by the migrating plume or elevated pressure field, to detailed surveillance of specific pathways that might pose a higher risk of leakage. Monitoring will also be required on a range of temporal scales, from continuous (e.g. monitoring of downhole pressure) to surveys repeated at discrete intervals to meet the objectives through the injection period and if necessary, during the closure and decommissioning periods. Over these long periods, technologies available for monitoring can be expected to improve but should be selected on the basis of best available at the time. The ability to compare datasets acquired at different times, with different tools, should be retained. Establishing baseline conditions, which might require multiple measurements in dynamic systems of those parameters that are expected to evolve over the duration of project operation, is seen as fundamental. Such baseline conditions will be important inputs in defining normal, alert and threshold conditions.

3. Offshore storage technical challenges

Many technical challenges set by the objectives in the regulations (conformance, containment, contingency) are not exclusive to the offshore, but the nature of the offshore environment (3.1) introduces specific challenges, particularly for shallow-focussed surveillance. Once anomalies have been detected (3.2), further, more focussed techniques can be used to confirm leakage or emissions (3.3), attribute the source, quantify leakage and finally, assess impact (3.4).

3.1. Overcoming specific offshore-related factors relating to timescales and logistics

A number of natural and man-made factors can affect the efficacy and practicality of offshore monitoring. Notably these concern the timescales over which the seabed and water column can change and whether the monitoring tools can detect CO_2 related changes, particularly in the shallow-focussed region, over the timeframe of site operation. These factors will also dictate how long any *in situ* shallow monitoring technologies could potentially survive in the hostile environment, the necessity for sensor recalibration or replacement, and requirements for repeat baseline surveys to take natural variability into account. Meeting these challenges is an area of active research particularly in the shallow monitoring methods, taking test designs to commercially viable options. In practice these have to be operationally robust and built around a limited number of technologies of proven sensitivity, accuracy, and reliability. Health and safety is paramount and for commercial projects, protocols may dictate that only proven and “approved” methods be deployed.

- Water depths**:** Water depth and temperature will impact both on the logistics of deploying survey equipment and also on the nature of CO_2 emissions in the water column. For example bubble sizes and rate of bubble dissolution will be a function of water pressure, temperature, salinity etc.
- Water movement**:** Disturbance or stratification of the water column will determine the rate at which localised emissions of CO_2 or other fluids into the water column are dissipated into the wider marine environment. This will dictate the required sensitivity of instrumentation and/or its spatial coverage.

- Seabed type**:** The nature of the sediment cover at, and immediately beneath, the seabed will affect how upwardly migrating fluids escape to the water column. In general terms, fine-grained sediments would be expected to retard the upward migration of fluids, particularly gases, with episodic capillary sealing / breakthrough processes being manifest at the seabed as pockmarks. Sandy sediments would be expected to allow more continuous upward migration of fluids, with less physical manifestation of emissions in terms of changes to seabed topography. Other seabed features might affect monitoring strategies. For example, possible shallow plumbing features such as the Hugin Fracture in the North Sea might have the effect of 'focussing' dispersed leakage fluxes.
- Seabed renewal rate: Seabed permanence is a factor in determining time-lapse seabed survey efficacy. The seabed is recycled at various rates and by different processes. In shallow waters (down to storm wave-base) wave action is the primary process, with variations in sediment mobility dependent on lithology. Tidal mobilization is restricted to areas of high tidal flow which tends to control the lithology of the seabed sediments. Disturbance of the seabed sediments will determine the reliability of repeat time-lapse sea-bottom surveys as an indicator of leakage-induced change (for example pockmarks or algal growths might be short-lived). This might influence aspects of monitoring survey design such as spatial sampling strategy or repeat survey frequency for example.
- Anthropogenic effects: Trawling activity can have severe effects on the seabed, sufficient to modify or destroy subtle changes of the seabed that might be indicative of emissions. It will also destroy all but heavily protected *in situ* monitoring equipment. Wind-farms are an increasing component of offshore seabed infrastructure. The extent to which wind-farm development and CO_2 storage will ever be co-incident is uncertain, but the turbine installation and foundations might well compromise the logistics, coverage and quality of seabed monitoring surveys.

Compared to onshore, these logistical difficulties can make the monitoring operation very expensive, particularly if ship time is involved. On the other hand, onshore monitoring has its own access-related problems and in some cases the offshore location can provide some significant advantages for monitoring, both deep and shallow-focussed (Table 1).

Table 1. Selected examples where offshore storage could prove easier to monitor than onshore storage.

Onshore monitoring	Offshore monitoring
Major physical and chemical discontinuities are likely at the weathering zone, the water-table and the land-surface. Large seasonal (and human-induced) variations – can create monitoring repeatability issues	There is a "gradational continuum" from pore-waters to water column. i.e. this gives a spatially and temporally more stable shallow velocity structure - allowing improved 3D seismics quality and repeatability
Usually variable hydrostatic heads exist onshore, so there is often lateral and artesian water flow. CO_2 may be displaced laterally before emission. CO_2 denser than air, so above the water table in vadose zone it will spread laterally rather than rise buoyantly.	Generally small hydrological gradients compared to onshore (except in the vicinity of pressure transients resulting from e.g. hydrocarbon production) - lateral spreading less likely, and leakage pathways may be more predictable?
Need to protect of drinking water	Aquifers (above reservoir) generally saline and non-potable
	Possible to 'see' and 'hear' CO_2 bubble-streams using acoustic methods: to visualise the location, extent and shape of bubble plumes and to quantify gas flux through the acoustic emissions made when bubbles are formed.

3.2. Spatial coverage for large monitoring areas: shallow emissions detection

A technical challenge relevant to both on and offshore monitoring is the need to cover large areas corresponding to the footprint of a storage site (typically tens to hundreds of km^2 for likely North Sea options) and also allow accurate measurement and characterisation, possibly for lengthy periods, at specific leakage risk points such as the injection well, abandoned wellbores etc. Conversely, individual seabed emissions are likely to occupy very small areas (m^2 to tens of m^2).

None of the operating storage sites show indications of leakage, so research into emission styles, detection and quantification methods is largely carried out at research sites. Ideally deep-focussed monitoring of the storage reservoir and overburden would provide an early warning of any such leakage and emissions (see section 3.3), and site characterisation and risk assessment processes would provide an understanding of potential leakage pathways which would narrow search areas and give pointers to where seabed egress could occur. However, at the QICS experiment site (Fig. 1c), where CO_2 was deliberately released 12 m beneath the seabed, some of the CO_2 bubble-streams were displaced several metres laterally from the injection point. This suggests that on a site-wide scale, determining seabed egress points will not be straightforward. In addition, dissolution of any bubble-stream will occur rapidly and dispersion of dissolved CO_2 from an emission point will take place via physical mixing by tidal action, waves and currents. Although this initially means that the dissolved CO_2 plume is enlarged (facilitating possible detection), associated dilution and dispersion makes detection above ambient background levels increasingly difficult.

The form of leakage or emission has been observed to vary in terms of sediment type, water depth, flux rates and so no single monitoring approach is likely to deliver a full set of requirements [8]. A hierarchical approach might be appropriate, similar to those proposed onshore [9] where techniques with wide aerial coverage were used to detect anomalies which triggered more detailed 'ground-truthing' methods. Currently, wide area coverage offshore could be achieved using either active or passive acoustics which respectively 'image' or 'listen' for bubbles, or using chemical detection methods (pH, pCO_2 etc). Active acoustic bubble detection ranges might be of the order of a couple of hundred metres, although range could be increased for lower resolution. Chemical sensor ranges will depend on the speed and direction of water currents, and hence the rate of signal attenuation. Down-current of an emission point an Eh sensor could detect a release of a reduced species over hundreds of metres, and a pH sensor on the order of tens of metres.

Current research on emissions detection is mainly via passive acoustics (listening for bubbles) or chemical detection (pH). The development of deep sea hyperspectral imaging systems also shows promise: these can be configured to do wide aerial surveys of biological communities and seafloor substrate features (natural and man-made) for both baseline surveys and periodic monitoring. Only research-based shallow-focussed monitoring has so far been deployed offshore, but this will change once new regulated projects come on stream.

3.3. Confirmation of leakage or emission signatures above background variation

In addition to the challenges outlined in section 3.1, a significant issue that makes detection of leakage or emission signatures more difficult offshore compared to onshore is the relative lack of information on background variability. For example, even in well studied waters such as the North Sea there is a dearth of information on near seafloor biochemistry, although model systems can provide some insights. Generally signals at the epicentre of the emission point will be distinct, but the natural heterogeneity of the marine environment, along with other anthropogenic signals might overwhelm signals as the distance from leakage increases. To maximise detection efficiency and to avoid both false positives and false negatives a thorough understanding of the marine baseline is required [9].

Onshore the value of reference sites has been proven [10] and offshore these were used in conjunction with the degree of baseline characterisation that has been implemented during repeat cruises for the extensive shallow-focussed monitoring research deployments in the ECO2 project at Snøhvit and Sleipner [11, 12]. These involved various chemical measurements in the water column and sediment via probes and samples, benthic chamber measurements of seafloor CO_2 fluxes, biological surveys and numerous imaging (video, sidescan sonar, multibeam echosounding) surveys to detect changes of seabed morphology or to detect bubble-streams in the water column. All encountered normal seabed conditions throughout. Research into these and other tools for the detection of shallow leakage and CO_2 emission at the seabed continue to be developed and tested at natural and artificial emission sites (Fig. 1c). Biological methods that examine changes in the ecosystem that might occur in response to changes in CO_2 emissions are still in their infancy, and reliable practical methods have yet to be developed [13].

In the deep-focussed regime, background conditions are generally less variable offshore than onshore (Table 1) and seismics can be used to identify potential leakage pathways through the overburden. A study of deep-focussed detection thresholds at Sleipner using time-lapse 3D seismics has shown that CO_2 in the overburden becomes more detectable as it rises to shallow depths because it becomes more reflective on seismics as it enters the gas phase. A spatial-spectral methodology [14] combined with conservative assumptions of CO_2 saturations, indicates that at the top of the Utsira reservoir, CO_2 accumulations of around 2100 tonnes would be detected (lower saturations would convert to lower mass detection thresholds). Within the overburden the analysis indicates that the detection threshold falls to less than 1000 tonnes of CO_2 at 590 m depth, and to less than 500 tonnes at shallower levels in the overburden where the CO_2 is in the gas phase.

Were any anomalies to be detected at the seabed, further, more focussed or point sampling techniques can be used to confirm and establish the source of the CO_2 (for example, is it of near surface biogenic origin or deeper leakage from the storage formation?). Confirmation and attribution will be facilitated by direct sampling, development of tracer techniques (naturally occurring or artificially introduced); gas ratio techniques (as deployed onshore [15], might also be useful). This attribution process was initiated at the Hugin Fracture site (Fig. 1c), where long sediment cores were found to be particularly helpful in characterising shallow gas fluxes [1].

3.4. Quantification and impact assessment

If emissions do occur, quantification of the amount of gas is required, and possibly the assessment of environmental impact [9]. Quantification is likely to be challenging. Passive acoustics, tracers, reverse engineering of model simulations and direct capture of gas will all aid quantification, but research addressing the consistency of various methods is necessary and will likely require controlled release experiments. The determination of CO_2 concentration in bubble-streams using acoustic methods and subsequent mathematical analysis is rapidly developing [16, 17]. More *in situ* ground-truthing experiments are required and there are a number of studies preparing to do this. The detection and quantification also needs to include a characterisation step, to analyse the gas in the bubbles to ensure it is CO_2.

It is not yet clear whether large dissolved CO_2 leakage fluxes will occur - there is a strong argument that any significant long-term offshore leak will saturate the pore-water in its pathway and soon be emitted at seabed as a gas in any case. Nevertheless the quantification of any dissolved leaking CO_2 is challenging. The use of landers and benthic chambers has shown some promise but one of the main challenges is the suitability of sensors. Current off-the-shelf sensors for CO_2 and pH are only suitable for short-term deployment due to biofouling and interference issues. Benthic chambers are generally deployed for short periods by ROV, which is expensive. Also there are issues around how representative they are of the virgin environment. The chambers effectively seal off a section of seabed from the normal environment and care must be taken with the interpretation of data for such a system. Leakage of dissolved CO_2 might be widely distributed and any use of chamber or lander based technology must be assessed with regard to this spatial inhomogeneity. Investment is needed to develop more sensitive, cheaper, fouling-resistant sensors for use in the benthic chambers to allow longer and more widespread chamber deployments.

Impact assessment will require integration of detailed biological and biochemical surveys, whereas many of the current methodologies establish these individually [18].

4. Introduction to offshore storage regulations: Monitoring requirements & regulatory challenges

Taking into account the technical and regulatory challenges outlined in sections 2 and 3, we examine the efficacy of current and planned offshore monitoring plans with respect to the relevant regulatory requirements.

4.1. Sleipner

The Sleipner project commenced prior to the European Storage Directive coming into force and the monitoring programme was not designed to meet its regulatory requirements. Sleipner operates under Norwegian offshore petroleum regulations and its initial monitoring programme was designed to address a number of identified storage risks. These principally relate to migration of CO_2 out of the Utsira Sand reservoir, either laterally into adjacent licence areas or vertically through the overburden, via geological pathways or wellbores [19].

A number of associated research projects have augmented the operational monitoring programme at Sleipner, primarily aimed at demonstrating and developing a range of monitoring tools, and carrying out detailed assessments of conformance and containment (Fig. 3).

Monitoring technique	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
3D surface seismic	✓					✓		✓	✓		✓		✓		✓		✓		✓	
2D surface seismic (hi-res)													✓							
Seabed gravity									✓			✓				✓				✓
CSEM															✓					
Wellhead pressure			continuous																	
Seabed imaging (ss sonar, multibeam, pinger)													✓					✓	✓	✓
Sediment sampling				✓			✓			✓			✓					✓	✓	✓
Water column sampling, bubble stream chemistry																		✓	✓	✓
Cumulative CO_2 injected at survey (Mt)	0.00		injection starts			2.35		4.25	4.97(s) 5.19(g)		6.84	7.74	8.40		10.15(s) 10.38(e)	11.05	12.1			~14

Fig. 3. Monitoring surveys deployed at Sleipner from 1994 to 2013. (Research-based monitoring tools are shown in italics, with colours denoting the types of techniques: green denotes deep-focussed techniques that operate from the surface; yellow denotes well-based techniques and blue denotes shallow-focussed techniques. For years with more than one survey, the amount of CO_2 injected for each specific survey is stated: thus "s" denotes "seismic", "g" gravimetric, and "e" electromagnetic surveys).

Containment Monitoring: The detailed repeat 3D seismic surveys have been effective at demonstrating that the migration of the CO_2 plume can be tracked. Results have clearly shown that CO_2 has been contained within the storage reservoir and is not currently threatening any identified containment risk. There is no evidence that CO_2 has migrated into the topseal or the shallower overburden, subject to preliminary quantitative detection thresholds. In addition to the deep-focussed monitoring a number of shallow-focussed research surveys have been undertaken (by the CO2STORE, CO2ReMoVe and ECO2 projects) to test monitoring tool efficacy and develop integrated shallow monitoring strategies. So far as we are aware, no systematic shallow / environmental baselines were established at Sleipner prior to injection, but it is clear that the research surveys have not found any evidence of anomalous seabed or seawater conditions.

Conformance Monitoring: This has been a prime objective of the research at Sleipner, with monitoring data being repeatedly matched against simulations both of current CO_2 plume migration and of predictions of future plume migration and dissolution. Although discrepancies have been identified between observed and predicted behaviour, it is argued that these are due to minor uncertainties in the geological model and fluid flow properties. Crucially the uncertainties currently seem to be small enough to preclude, at least with current injected amounts, the possibility of unpredicted future behaviour leading to significant adverse future outcomes. Thus, lateral migration of the CO_2 is constrained by the known topseal topography, such that the plume of free CO_2 will not reach any old wellbores or seismically-detectable faults. In addition the maximum thickness of buoyantly-trapped CO_2 will not be sufficient to exceed the expected topseal capillary entry pressure.

4.2. Snøhvit

As was the case at Sleipner, Snøhvit preceded the European Storage Directive and was licensed under Norwegian offshore petroleum regulation. Two monitoring aims have been defined: firstly to ensure reservoir pressures do not exceed the fracture threshold in order to reduce the risk of subsequent unwanted CO_2 migration that might lead to leakage; and secondly to monitor the CO_2 plume migration in order to avoid impinging on the overlying natural gas reserves [20] (Fig. 4).

Monitoring technique	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
3D surface seismic	✓						✓		✓	✓	
High resolution 3D seismic (p-cable)									✓		✓
Seabed gravity					✓				✓		
Downhole pressure						continuous					
Wellhead pressure						continuous					
Multibeam echosounding									✓		✓
Conductivity - temperature - depth profiles									✓		✓
Sediment sampling											✓
Water column sampling											✓
Cumulative CO_2 injected (average, Mt)	0					injection starts	0.5		1.0		

Fig. 4. Monitoring surveys deployed at Snøhvit from 2003 to 2013. (Italics and colours as per Fig. 3).

Containment Monitoring: 3D time-lapse seismic surveys of the deep reservoir and the overburden have confirmed that the storage site provides secure containment of the CO_2. A baseline survey was undertaken six years prior to the start of injection and subsequent surveys have confirmed an absence of migration out of the storage reservoir. Continuous pressure downhole measurements have demonstrated that reservoir pressures did not exceed the fracture pressure, so no induced leakage pathways have been formed.

Leakage to the seabed is considered to be a very low probability risk, due to the depth of the storage reservoir and the nature of the overlying seals. To the best of our knowledge no systematic shallow / environmental baseline surveying was carried out. Recent environmental seabed and water sampling for the ECO2 research project has found no evidence of anomalous features or conditions.

Conformance Monitoring: Downhole pressure and time-lapse 3D seismics have proven to be key diagnostic tools for conformance monitoring at Snøhvit. The downhole pressure measurement was able to show non-conformance as reservoir pressure increased more rapidly than expected. The time-lapse seismic contributed additional insights by showing that the faults which cut the reservoir were acting as barriers to fluid flow, and were, in all likelihood a significant factor in the pressure build-up.

In response to the non-conformance, Statoil set in train the established remediation plan which involved re-perforating the tubing at a shallower reservoir unit and continuing CO_2 injection in the Stø Formation. Pressure and seismic monitoring of the new reservoir since the corrective actions have shown that the operation is now in conformance.

4.3. K12-B

As a pilot–scale project storing less than 100 ktonnes of CO_2, K12-B is not required to meet the conditions of the European Storage Directive, and its monitoring programme was designed principally for research purposes. Nevertheless the monitoring programme can be reviewed in the light of relevant regulatory requirements [21] (Fig. 5).

Monitoring technique	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Downhole pressure and temperature		✓	✓		✓			✓			
Wellhead pressure		continuous									
Well integrity			✓	✓	✓		✓				
Chemical tracers			✓	✓	✓	✓					
Downhole fluid sampling								✓			
Cumulative CO_2 injected (average, Mt)		injection starts	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	

Fig. 5. Monitoring surveys deployed at K12-B from 2003 to 2013. (Italics and colours as per Fig. 3).

Containment Monitoring: The excellent sealing quality of the thick Zechstein evaporite reservoir topseal effectively eliminates the possibility of leakage along geological pathways. In addition, faults which cut the reservoir act as lateral seals, producing hydraulically isolated storage compartments. These behave effectively as ‘tanks’ with minimal fluid flow across their boundaries. The principle risk of leakage is therefore considered to be via the wellbores, so well integrity was a key focus of the monitoring programme.

In these circumstances continuous downhole pressures can perform a containment monitoring role. Measured values were consistent with a lack of fluid loss from the storage compartment, though not uniquely diagnostic of this.

No shallow / environmental surveys have been described at K12-B.

Conformance Monitoring: K12-B is interesting in that plume migration tracking by 3D seismic is seemingly not an option. This is because the storage reservoir lies beneath a thick salt seal and also because of the presence of residual gas in the reservoir, both of which markedly reduce the ability of surface seismics to image changes in fluid saturation. The main conformance tools therefore were downhole pressure monitoring and fluid analysis, together with tracers (Chapter 3). These were used via history-matching to progressively refine the reservoir flow model.

4.4. Goldeneye

The monitoring programme at Goldeneye has been designed to meet the requirements of the storage permit under the European Storage Directive. The programme was developed from a comprehensive risk assessment and as such is designed to address those 'residual risks' which must be monitored during and after injection. The Goldeneye monitoring programme includes the establishment of baseline conditions followed by a detailed plan of operational and post-closure monitoring, as well as plans for contingency monitoring that would be deployed in the event of a significant irregularity (Fig. 6). It is designed to meet all relevant regulatory monitoring requirements and is the most comprehensive offshore monitoring programme published to date [22].

Monitoring technique	Mode	Baseline	During injection	Post injection
Surface seismic - Streamer 3D	Time-lapse	✓	~5 years	1 year and 6 years
Surface / downhole seismic - OBN/VSP	Time-lapse	✓	~5 years	1 year
Surface seismic - high resolution p-cable	Contingency			
Broadband seismometer beneath platform		continuous		
GPS on platform		continuous		
Downhole pressure & temperature		✓	continuous	for 3 years
Downhole saturation and porosity logging	Time-lapse	✓	annual, years 5-10	
Well log integrity		✓	every 3 years	
Downhole fluid sampling	Time-lapse	✓	annual, years 5-10	
Seabed bathymetry and imaging	Time-lapse	✓	year 5 (targetted)	at 1 year
Sediment sampling	Time-lapse	✓	year 5 (targetted)	at 1 year
Water column sampling	Time-lapse	continuous		
Cumulative CO_2 injected (Mt)		0		10-20

Fig. 6. Monitoring programme proposed for Goldeneye [21]. (Colours as per Fig. 3).

<u>Containment Monitoring</u>: The storage is within a depleted gas field with sub-hydrostatic reservoir pressures throughout the injection period, so leakage is considered to be very unlikely. Nevertheless containment monitoring is addressed by time-lapse 3D seismics, possibly augmented by 3D VSPs, to repeatedly image the reservoir and overburden, as well as high-resolution p-cable surface seismic for monitoring of the shallow overburden. It is expected that imaging the plume within the original gas-water contact might prove problematical due to residual gas, but the seismic will cover possible lateral egression of CO_2 outside of the gas-water contact and also any migration of CO_2 into the overburden.

Detection of possible shallow leakage and emissions at seabed is addressed by a comprehensive surface monitoring programme. The shallow-focussed monitoring is designed to detect emissions, but it is stated that contingency monitoring for emissions quantification might require additional technologies not currently available.

<u>Conformance Monitoring</u>: The main conformance monitoring tool will be downhole pressure measured in a number of injection wells and a possible monitoring well, plus fluid sampling and saturation logging. 3D time-lapse seismics will provide additional constraints on lateral plume migration.

4.5. ROAD

Although ROAD has been granted the first storage permit in Europe, the monitoring programme has yet to be finalised. An initial concept has been developed by assessing key risks at the site (Fig. 7). As the geological situation is quite similar to K12-B the main risks are considered to be very similar i.e. leakage via poorly abandoned well-bores. Additional risks associated with unacceptable pressure build-up and fault leakage will be addressed by the fully developed monitoring plan. This will have to meet the regulatory requirements in order for injection to start, and will be reviewed repeatedly during injection [23, 24].

Monitoring technique	Mode	Baseline	During injection	Post injection	Post closure
Shallow focused 2D or 3D seismic	Contingency		(✓)	(✓)	(✓)
Microseismics		continuous			
Well head pressure and temperature		continuous			
Downhole pressure and temperature		✓	✓	✓	
Downhole pressure in adjacent reservoir	Contingency		(✓)	(✓)	(✓)
Downhole saturation logging		✓	✓		
Downhole fluid sampling		✓	✓		
Well integrity logs		✓	✓	✓	
Seabed bathymetry, imaging and bubble detection		✓			✓
Seafloor gas/sediment sampling	Contingency		(✓)	(✓)	(✓)
Cumulative CO_2 injected (average, Mt)		0		8.1	

Fig. 7. Monitoring programme proposed for ROAD (Note that a final pre-injection monitoring plan update is expected 6 months prior to injection start) [23,24]. (Colours as per Fig. 3).

Containment Monitoring: This monitoring requirement will be met by downhole pressure and temperature measurements to assess geomechanical responses to injection and to monitor the injection progress. As with K12-B, imaging of the CO_2 plume within the reservoir is thought to be challenging.

Leakage detection could be achieved through 3D seismic surveying of the overburden above the evaporite seals, combined with well integrity measurements to assess the potential for the boreholes to act as leakage pathways. Environmental surveys will include imaging of the seabed and acoustic bubble detection if leakage is suspected. No contingency monitoring for emissions quantification is currently included in published plans, although this would be required.

Conformance Monitoring: Conformance assurance is provided principally by history-matching numerical simulations of reservoir pressure and temperature with downhole measurements.

5. Conclusions

The Sleipner, Snøhvit and K12-B projects commenced prior to implementation of the EU Storage Directive and their monitoring plans are designed to address particular site-specific objectives. The monitoring programmes at Sleipner and Snøhvit were both risk-based and meet many of the high-level principles of the current regulatory requirements, notably for containment and conformance. At both sites, the time-lapse 3D streamer seismics proved strikingly effective for these purposes. At Sleipner, monitoring data have been used mainly for history-matching and leakage detection. At Snøhvit, two key deep-focussed tools, downhole pressure and 3D seismics have proved notably successful in rapidly identifying and characterising a significant deviation from predicted behaviour. The deviation was identified before adverse any impacts occurred and the situation was successfully corrected.

The main area where the plans for these two sites might be deemed to have been initially lacking in terms of current legislation, is in the shallow-focussed, environmental monitoring component with the absence of a robust baseline. In fact a series of research surveys have plugged many of the gaps here, and have shown that the sites are performing as designed at all levels.

K12-B has an excellent geological seal and sub-hydrostatic pressures, so the rather simple containment monitoring programme is probably fit-for-purpose. Downhole pressure proved to be the key tool for conformance history-matching. If required it could be further improved by 3D seismics to provide surveillance of the overburden and shallow-focussed monitoring deployed principally around the wellbores.

Goldeneye and ROAD are being developed within the European offshore regulatory framework (EU Directive and OSPAR) and their monitoring plans will be compliant with this. The provisional monitoring plan for ROAD incorporates many of the elements required to meet the regulations, but additional detail will be required. The Goldeneye monitoring plan is extremely comprehensive and provides a programme of risk-based monitoring actions, focussed on containment and conformance assurance, from baseline through to post-closure.

This review has highlighted that regulatory and technical challenges can largely be met in terms of storage site monitoring. Deep-focussed monitoring has been proven to meet the containment and conformance objectives and, for seismic surveys, the offshore environment can offer more favourable data quality compared to onshore. Shallow-focussed monitoring has so far only been deployed for research purposes offshore. Despite this, appropriate techniques are available for demonstrating containment at large-scale sites, although continued research to enhance some aspects would be beneficial. Focus areas include improving aerial coverage of remote systems, longevity and calibration issues of sensors and landers (trawler and biofouling proofing), and growing useful baseline datasets. In terms of contingency monitoring, robust accurate quantification of seabed emissions, particularly by remote (acoustic) methods still requires development. Other more generic challenges remain, notably in remote data transmittal for real time monitoring, power supply and consumption for remotely operated monitoring platforms, and in the general reduction of monitoring costs and its environmental impacts. Dialogue between site operators and regulators are needed to discuss issues on leakage or emissions within realistic monitoring detection thresholds and cost-effective spatial sampling options, particularly during any post-closure monitoring and associated financial liabilities.

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