THE ROLE OF SITE SURVEYS IN CARBON CAPTURE AND STORAGE

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Abstract
To constrain the increase in atmospheric carbon dioxide (CO_2) concentrations, there are European and national drives to develop carbon capture and storage (CCS) schemes for the permanent geological storage of CO_2 from industrial sources in deeply buried strata. Currently, offshore sites are considered preferable to geological store in strata onshore. Although the target storage reservoirs, saline aquifers or former hydrocarbon fields are often at depths of 1km or more, knowledge of the shallow area is important. This is not only for the positioning of infrastructure, wells, pipelines, etc., but also in the monitoring of any potential leakage from the reservoir over the site's lifetime, which may span 25–50 years. Baseline and repeat surveys are necessary and may need to cover a considerably wider area than the expected plume extent in the reservoir, depending on the predicted gas leakage pathways. Hence a complete geological model is required from the proposed reservoir at a depth that is up to and includes the seabed.

1. Introduction

It is a recognised concern that carbon dioxide (CO_2) concentrations are increasing both in the atmosphere and the oceans, and that there are consequent adverse effects on the climate (Intergovernmental Panel on Climate Change (IPCC), 2007). The rising CO_2 concentrations are raising global temperatures because of their greenhouse gas effect, as well as increasing acidity in the world's oceans. Man-made contributions include CO_2 from the burning of fossil fuels for power generation and other industrial processes. Targets for reducing national emissions of greenhouse gases to the atmosphere have been set by legislation within the UK by the *Climate Change Act* 2008 and the *Climate Change (Scotland) Act* 2009. Plans to achieve the targets include greater efficiency in the use of electricity, decreased electricity use and implementation of low-carbon technologies for power generation, such as generation of electricity from renewable resources (wind, wave, solar, nuclear powered and hydro-electrical generation schemes). In addition, the capture of carbon dioxide emitted from fossil-fuelled power stations and other industrial sources, and its geological storage in deeply buried rocks known as carbon capture and storage (CCS), is another option to reduce CO_2 emissions to the atmosphere.

Energy generation from renewable sources is increasing, but many of the technologies are newly developed and, in the short and medium terms, are not yet sufficient to replace electricity generation by the combustion of coal and gas. Fossil fuel powered generation is also more flexible to meet sudden increases in demand for supply, unlike wind, wave and nuclear powered generation.

In the short to intermediate term (tens to hundreds of years), there will remain a need for electricity by coal or gas fuelled generation until targets for power from renewable sources are met. In the longer term, industrial processes such as the production of steel and cement for concrete will continue to produce CO_2. To avoid emissions to the atmosphere, methodologies are being developed, tested and refined to capture CO_2 at industrial point sources for transport by pipeline or by shipping it to a geological site suitable for the permanent storage of CO_2.

The method of injecting CO_2 into subsurface strata, piped from industrial sources, has been used to enhance recovery from oil fields onshore in the United States and Canada. For example industrially sourced CO_2 has been used to enhance recovery of oil from the Weyburn oilfield since 2000 and for geological storage of CO_2 (International Energy Agency (IEA), 2006). Investigations to identify geological sites suitable and feasible for CO_2 storage are being conducted in developed and developing nations around the world (Scottish Carbon Capture and Storage, 2011; Gammer et al., 2011).

Within the European Union (EU), regulations are in place for the implementation of CCS in member states with pilot and demonstrator plants in both onshore and offshore settings. There is an onshore CCS site within a depleted gas field at Lacq in southwest France (de Marliave, 2009) where injection commenced in 2010. Carbon dioxide within natural gas produced from the Sleipner field in the Norwegian North Sea has been re-injected and stored within sandstone in strata overlying the gas reservoir since 1996 (Chadwick et al., 2008). Concerns from the public in the vicinity of proposed storage sites onshore at Schwarze Pumpe, Germany, and at Barendrecht, the Netherlands, suggest that the public currently favours offshore sites within Europe.

2. Prospect of Global Need for Carbon Storage and Capture

International and national projections for the number of future CCS projects that will be needed to meet greenhouse gas emission reduction targets have been prepared. The Technology Roadmap by the International Energy Agency (2009) envisages 100 CCS projects globally by 2020 and over 3000 projects by 2050. Within Europe, its forecast is for 14 projects by 2020 and more than 300 by 2050.

The UK government states in its strategy for low carbon industry that one-third of industrial carbon emissions reduction will be from CCS. In addition, fossil fuel powered energy generation with CCS is expected to be cost competitive with other low carbon technologies in the 2020s (UK Government, 2011). The UK secretary of state for energy gave a commitment to support up to four commercial-scale CCS projects in 2010. Candidates for these demonstrator projects are applicants for EU NER300 funding and include sites offshore Scotland and England.

Offshore storage may be within depleted hydrocarbon fields and sandstones containing saltwater (saline aquifers). The CO_2 storage capacity offshore UK in depleted hydrocarbon fields that are very well known from the exploration and production of oil and gas is around 6500Mt (Department of Trade and Industry (DTI), 2006; Scottish Carbon Capture and Storage (SCCS), 2009). The potential storage capacity in saline aquifer sandstones is estimated to be between 25 000 and 66 000Mt of CO_2. This estimate is of major significance for Europe, as it approximates the storage capacity beneath the Norwegian sector of the North Sea and is greater than the offshore storage capacity of the Netherlands, Germany and Denmark combined (SCCS, 2009).

Geological storage for demonstrator projects will use depleted hydrocarbon fields, while commercial storage sites are anticipated to be within saline aquifer sandstones, as these have greater storage volumes. The requirement for site survey activities for offshore CCS project infrastructure will be similar to that associated with the production and transport of oil and gas. In addition, there is also a requirement to survey and monitor the injection site to demonstrate it is suitable for storage. This serves to establish a ‘baseline’ of observations prior to commencement of injection, and repeat surveys are conducted to confirm the injected CO_2 remains stored deep in the subsurface. Storage sites for CO_2 are required to demonstrate their performance and permanent storage of CO_2 with these baseline surveys and repeat surveys for monitoring decades after injection has finished and the store sites are closed. Monitoring surveys to verify the position and migration of injected CO_2 are currently undertaken by ship-borne seismic surveys, as at the Norwegian Sleipner Field (Chadwick et al., 2008). These are costly and the development of passive monitoring methods with systems installed on the seabed is the objective of technological research and testing.

3. Shallow Section Requirements for CCS

Site selection for CCS will be decided using deep-focused seismic data, such as 3D seismic surveys, to locate and model former reservoirs or saline aquifers. Optimum conditions include a porous reservoir and a competent seal above the reservoir (Chadwick et al., 2008). Faults that affect the cap rock need to be tight. In the absence of a completely tight cap rock, modelling of the zone above the potential storage site will be required to predict the fate of injected dense phase fluid.

It should be noted that the gas will have to be injected under pressure, and that will have an impact on pre-existing pore waters in the storage reservoir. This increase in pressure will advance far ahead of the injected fluid and may alter the physical properties of the storage site (Figure 1). For example, it may open up fractures, influencing the flow of the fluid. The reservoir pressure will drop rapidly immediately after injection ceases and will gradually return to just above normal over hundreds of years. As the pressure decreases the CO_2 density will change.

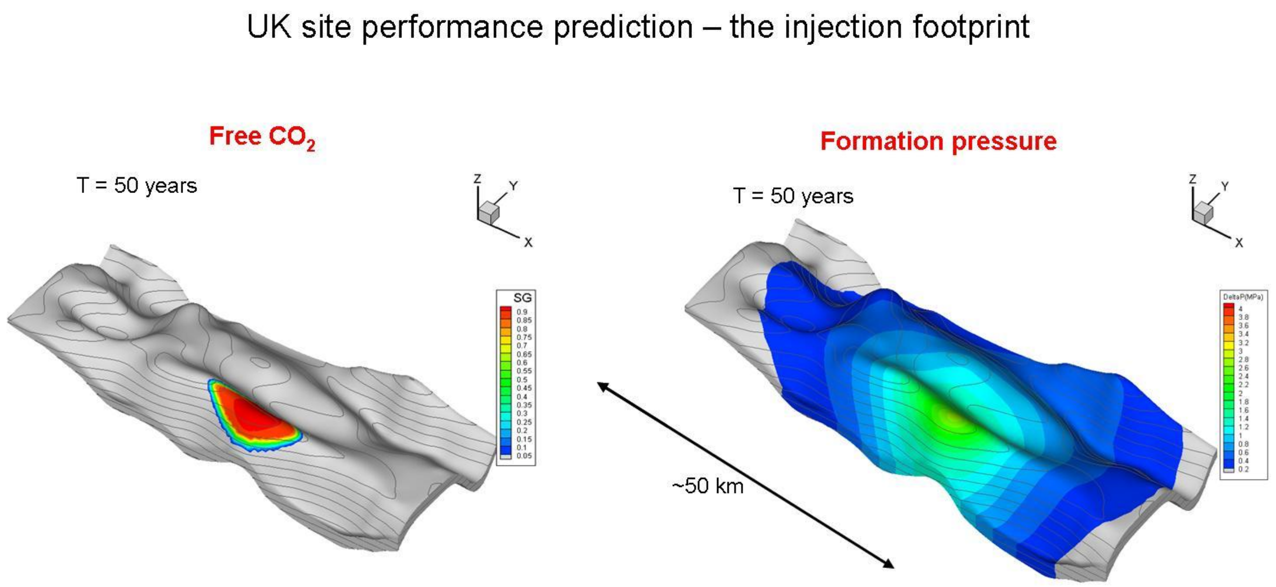

Figure 1: Modelled CO_2 and pressure footprints after 50 years of injection at a possible CCS site. Free CO_2 gas saturation and change in pressure is due to injection in MPa (courtesy of David Noy, Sam Holloway and Andy Chadwick, British Geological Survey)

To model the behaviour of the fluid and determine potential fluid leakage pathways, a detailed knowledge of the geometry of the overlying sediments will be required. This is particularly important in the shallow section with its greater permeability. Features that could influence migration pathways in the overburden include faults, pre-existing gas chimneys and stratigraphical features such as connected sand bodies. In the North Sea, and other areas previously subjected to glaciations, these include in-filled sub-glacial channels and buried iceberg ploughmarks, which can create potential high-permeability pathways with great lateral extent. Their presence would mean that surveys of the shallow section may have to cover a considerably larger area than that of the proposed storage site. Similarly, laterally extensive sand-filled bodies in the shallow section may exist in fluvial systems on continental shelves that have previously been sub-aerially exposed.

Proposed CCS developments will require site surveys to determine the ground conditions for any installations, such as an injection platform, pipelines to the site to transport the CO_2, and to establish the geological model for gas leakage. In evaluating the shallow section to create the geological model and to predict how any leaking gas might migrate, it is important to identify pre-existing evidence of gas migration. Usually this gas is methane of biogenic origin, but may be petrogenic and include higher hydrocarbons. Other gases, including CO_2, can be found as a natural gas seeping to the seafloor. These gases show up as acoustic anomalies or blanking on seismic survey profiles. Bedforms, such as pockmarks or lithologies including methane-derived authigenic carbonate cements, indicate previous fluid migration. Establishing baseline conditions is vital for future monitoring.

4. Site Surveys

A desk study is important as with any site survey. For CCS projects using depleted hydrocarbon fields, pre-existing data such as site surveys for wells drilled in the exploration and development of the field will equally be important. Likewise any environmental data collected as part of the original field development will provide essential long-term control on a subsequent baseline study. However, the surface area that will need to be included is likely to be considerably greater than that examined in the original field development (Figure 2), so site surveys of neighbouring wells will become useful. If a saline aquifer is to be exploited there is potentially an extensive dataset to be sought to provide the first assessment of the shallow geological conditions. Access to previous data may rely on how that data has been archived, particularly where the ownership of petroleum exploration and/or development licences have changed hands and are not coincident with CCS licence ownership.

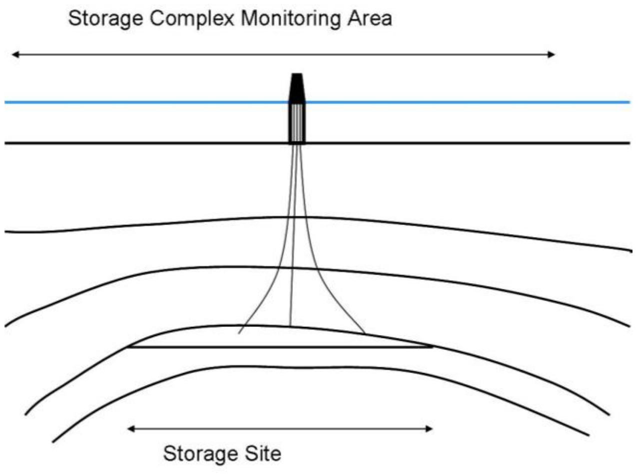

Figure 2: Diagrammatic depiction of lateral extent of CCS storage complex and site

Some of the necessary information for the geological sequence above the reservoir can come from pre-existing 3D seismic surveys if a former reservoir is being utilised. However, new data may well have to be gathered if the original survey's acquisition parameters were not appropriate for the shallow section. If new 3D data is being collected to model the storage reservoir, then the acquisition parameters should be tuned to give maximum resolution from seabed to the reservoir.

Seismic profiling is the traditional methodology to assess the shallow geology. These will include chirp or boomer systems for the very near seabed, and sparkers for slightly greater depths. Both sidescan sonar and multibeam echosounder will provide valuable information on the topography and the acoustic reflectivity of the seafloor against which change can be monitored.

To characterise the physical properties of the geological model, the pre-existing geotechnical data from the emplacement of any installations will be useful, along with well logs of the upper sections of any site investigation boreholes. If new boreholes are required for the installation of the CCS project infrastructure, then obtaining data on permeability will contribute to the geological model.

In establishing the baseline conditions, identifying active seepage sites such as pockmarks will need to include determination of the seepage rate. This may require visual inspection and could support the use of biological surveys to determine environmental conditions prior to any injection. Geochemical studies may be needed to determine fluxes. The results from any previous environmental or site survey can be utilised towards establishing the variability within a baseline against which future monitoring can be assessed.

5. Monitoring During the Lifetime of Carbon Capture and Storage

An important component of any CCS project is developing the predictive model of fluid flow and then monitoring the actual behaviour against its predictions. Correlating observed changes with those of predicted model is vital. This model may be updated as monitoring data is gathered. When fluid is injected into a storage site, it is necessary to show that it remains within the intended storage site strata. This requires regular surveys throughout the lifespan of the storage site. Even when injection ceases the CO_2 can continue to migrate within the store. Responsibility for the injection site can only be handed back to the licensing authority (i.e. the state) when agreed with the regulator and only when the licensee can demonstrate that the injected gas is in a stable location and that no leakage is occurring.

5.1 Seismic surveys

The usage of repeat seismic surveys to demonstrate the absence of changed conditions will require high confidence in positioning. As 3D seismic surveys will be run to monitor the storage strata, the acquisition parameters of the survey must be designed to maximise the resolution from the storage level and throughout the sequence above right up to the seafloor. The Sleipner CO_2 injection site has fortuitously had seven surveys (Figure 3) since it began in 1996 until 2008, where injection is planned until 2016 within the Utsira formation at around 1000m below seabed.

Past experience of mapping shallow gas with high-resolution seismic profiling, such as pinger and boomers, will be crucial. Although these systems can detect changes in gas close to the seabed, to detect leaking gas before it approaches the seafloor, seismic systems with greater penetration (albeit with lower resolution) need to be applied (such as a sparker). When running 2D surveys the replication of survey lines is important in recognising change in the migration of acoustic responses attributable to gas. It should be noted that shallow gas may be imaged on the seismic profile, but that alone does not confirm CO_2 migration. Marine sediments frequently have methane within them that could exsolve and appear as a zone of acoustic blanking.

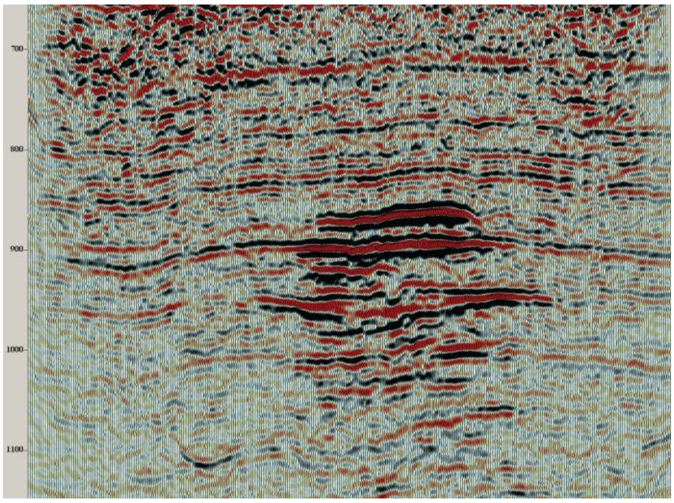

Figure 3: 2D high-resolution seismic line through the Sleipner CO_2 plume within the Utsira formation in 2006

It is possible to gain further information using multi-component seismic, as well as mapping reflectors and acoustic facies with single channel seismic. This would allow for both P and S wave values to be used to look at microfracturing, showing dilatency as pressures change that exhibit the first signs of leakage. However, obtaining S-wave values requires seabed seismometers, which obviously greatly increases the cost of the surveys and monitoring. Therefore, when planning a CCS store a decision has to be made on whether to lay out a network of seabed seismometers to be used in repeated surveys over the store's lifetime.

5.2 Gravimetric and electromagnetic methods

Fine-scale changes in the gravity field over the reservoir can support seismic interpretation of fluid emplacement within the storage site. Some surveys (such as those taking gravity measurements) require repeated returns to fixed locations to determine change. At Sleipner concrete benchmarks have been positioned to ensure repeatability of gravity measurements (Nooner et al., 2006; Alnes et al., 2008). This is done with a remotely operated vehicle (ROV) and provides a platform to monitor other aspects, such as video surveys at repeat sites. These gravity blocks also provide targets to act as controls on repeated multibeam bathymetry surveys.

In a similar way to gravity, electromagnetic (EM) methods complement seismic data to monitor changes induced by injection of CO_2. This requires variable electrical fields at the seabed to induce secondary fields giving information on the resistivity structure beneath. As CO_2 is resistive when it is injected into a saline reservoir, there will be a change in the EM properties as the conductive pore waters are displaced.

5.3 Environmental surveys for change from base-line

CO_2 emissions at the seabed may acidify the water, placing benthic communities under stress. Studies at natural CO_2 seepage sites (Hall-Spencer et al., 2008) indicate that biodiversity decreases. However, the dissolution of CO_2 into the water will lead to a rapid dispersement of the CO_2 as currents sweep waters away. Biological monitoring occurs at many levels, from identifying species communities to the health of individual organisms. The former involves assessing both the abundance and diversity, and how that might change from a baseline. However, the natural variation may be quite large and may need consideration when designing both baseline and monitoring surveys. For example, seasonal changes have to be recognised. In the event of seepage at the seabed, it can be expected that microfaunal communities will respond quicker than macrofaunal ones, and these could be initially detected by non-biological surveys. For example, bacterial mats could develop to be detected by acoustic methods.

While a CO_2 gas seepage could be recognised first from biological data (for example, by detecting changes in the behaviour of benthic fauna), it is more likely that biological studies will monitor the impact of a seepage site or event and provide information on recovery following any mitigation efforts. The range of changes that could be detected (abundance, diversity, physiology) should allow the impacts of seepage to be quantified. However, biological techniques are costly in respect of time, with results usually available some time after data acquisition. Ecosystem monitoring to provide information on CO_2 leakage is under development. Identification of the early response of particular species to elevated CO_2 levels and tolerance levels are being undertaken onshore (e.g. West et al., 2005) and offshore (e.g. Langenbuch and Portner, 2004; Ishida et al., 2005), as well as in the North Sea, as part of the CO_2ReMoVe project. Such studies include recovery and examination of physical samples collected by divers or camera-guided devices. Other samples are more randomly selected, such as those collected by box corers and grabs that are not guided to points of interest. There are also non-invasive techniques such as using video and stills cameras to survey the fauna of the seafloor.

Research on the response of specific marine organisms has included laboratory-based aquarium experiments (e.g. Langenbuch and Portner, 2004). Ishida et al. (2005) used a benthic chamber penetrating the seabed sediments, and following injection into the chamber of CO_2-rich water and monitoring the response of the contained organisms, concluded that calcium-carbonate organisms are likely to be the worst affected by elevated CO_2 levels. They also noted an increase in bacterial activity above 20 000ppm, which was believed to be an increase of bacteria adapted to high CO_2 levels.

A limitation of studying areas with natural CO_2 seeps is that the ecosystem has already adapted to increased CO_2 levels, so some early bio-indicators may not be obvious. In additional, this technique does not quantify the amount of CO_2 leakage. Marine observation requiring divers is also likely to be expensive and will have limitations on water depth. However, a study in the Aegean Sea where the naturally escaping gas is dominated by CO_2 showed a large diversity of microbial species with several new taxa documented. The epifauna abundance and diversity was also high compared with sites away from the seepage location, though no vent-specific species were found (Dando et al., 2000). Examination of a large North Sea pockmark attributed to a CO_2 blowout noted increased biological abundance and diversity, but attributed this to the geomorphology of the structure rather than the formerly escaping gas (Thatje et al., 1999). Many methane seepage sites have extensive bacterial mats that provide a conspicuous seafloor feature that can be recognised by video or sidescan sonar. CO_2 seepage with a low flux may not form a bedform, but may trigger a bacterial change in the seabed sediment that could be recognised on video or sidescan sonar.

5.4 Microseismic monitoring

Changes in pressure can induce mechanical failure resulting in microseismic activity. Injection of CO_2 gas and the resulting increase in reservoir pressure may induce similar events, as can the extraction of fluids from a reservoir. In microseismic or passive seismic monitoring, low-level seismic events are recorded using surface or downhole receivers. The events are measured and triangulated, and the main objective of this is to identify the position of failure events caused by the migration of the pressure front and the gas. This will contribute to the predictive model of the storage site and, in extreme cases, support or negate claims for any induced seismic hazard due to CO_2 injection.

The error of calculating the position of the microseismic events increases as distance from the monitoring borehole or seabed seismometer increases. It is also affected by the stratigraphy and seismometer's ability to conduct sound. The type of movement along the fracture that generates the microseismic event is also inferred from the geophone response, which is used to assess if the microseismic event is associated with CO_2 injection or other sources (e.g. oilfield operations). The technique can also be used to map the velocity structure of the subsurface using velocity tomography. By monitoring over time, this method could theoretically be used to map migration of the plume through induced fracturing or fracture reactivation.

A limitation of the technique is that it is a ‘passive’ seismic tool relying on natural or induced events. In addition, the geophone has to be powered and must collect high-density data over very long periods of time. Any receivers placed on the seabed will need to be tied back to a platform for real-time data transmission, or have battery systems replaced and data downloaded at regular intervals. Seabed instruments are also vulnerable to fishing activity. Even so, the technique is proven by the oil and gas industry where it is used to monitor hydraulic fracturing and structural imaging in mountainous regions. Most microseismic events in oilfields are of the magnitude –1 to –3 on the Richter scale, with slip vectors of a few microns (le Floch et al., 2008). Microseismicity has also been used for monitoring CO_2 injection for enhanced oil recovery (EOR).

5.5 Tiltmeters

Gas extraction has been known to cause ground subsidence, so it is logical that CO_2 injection may cause ground movement (Winthaegen et al., 2005). Tiltmeters can be deployed either at the surface or downhole to monitor small changes in strain in the reservoir, cap rock or overburden. This technique has been used in hydrocarbon extraction and is established in other fields of study such as monitoring volcanic sites and dams, but has not yet been proven for use with CO_2.

The pressure in the pore space will increase as CO_2 is injected, and this can result in small ground movements which could be detected using a sensitive tiltmeter. Such ground movements could indicate the areal extent of the pressure footprint, which will be larger than the injected CO_2 footprint (Figure 1). However, the cost of installation and providing real-time information offshore will be considerably greater than for onshore storage sites. Tiltmeters are currently being deployed on land at the In Salah CO_2 storage site in Algeria, but costs for downhole or marine tiltmeter surveys will be considerably higher than land-based monitoring.

6. Former Wells

Former wells will be of greatest concern, as they are potential conduits to the surface within the footprint of a storage site. The seal around the well has to be secure, but after cement plugging the well, the seal may degrade over time particularly when in contact with CO_2. Confirmation that the cement seal remains intact and no leakage is occurring may require high-resolution surveys around former wells and monitoring of wellhead locations even with permanent video or acoustic systems. Seal integrity may also be under threat when pressures rise in the storage level due to CO_2 injection. This may rely on wells and their seals working beyond the lifetime for which they were designed. However, if leakage is observed at a former well site, it will be necessary to show that it is coming from the CO_2 storage level and not from a different horizon, such as the well's target or from shallow gas in the upper section.

Seismic surveys would provide the main basis for establishing whether there is evidence of migration vertically up the outside of the wellbore and laterally into the overburden. These would be deployed in star-configuration over the wellbores and across any faults considered to be at risk as potential leakage sites. These 2D surveys could be integrated in a cost-effective manner with seabed imaging and bubble detection. Repeat multibeam or sidescan sonar surveys could be acquired over the seabed footprints of the wells located within the storage volume, particularly to identify the development of bubble streams should a well boring start to leak.

Abandoned wells can also contribute to the monitoring programme, as instruments could be placed at depth to record inter-borehole seismic activity. This will assist towards monitoring changes in the reservoir as injection takes place. They can also be used to run vertical seismic profiles to record changes about the well.

7. Conclusion

The developing CCS sector will place additional demand on the already busy offshore site survey industry. It will require multiple surveys to establish baselines, and regular repeat surveys to monitor injection and storage for decades at each site. It will also use both mainstream and innovative survey methodologies not normally in the package offered to oil and gas or marine renewable clients. However, it will be necessary to use a number of surveying techniques to have confidence in monitoring programmes. It will be necessary for them to demonstrate permanent storage of CO_2 or to have an effective detection and quantification of leaks at the seabed if they occur. With growing concerns about the effects of increasing CO_2 concentrations in the atmosphere and ocean, CCS will be increasingly seen as one of many ways to mitigate emissions, yet still allow fossil fuel based power generation in the immediate term as that from renewable sources increases. In the longer term, CO_2 captured from other industrial processes for decades or centuries into the future can be permanently stored in deeply buried geological strata.

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