Industry review and recommendation of monitoring technologies with potential to reduce reliance on 4D seismic

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CO_2 Transportation and Storage Taskforce

EXECUTIVE SUMMARY

This report was prepared for the CCUS T&S Taskforce, by the Monitoring subgroup to screen monitoring technologies that could reduce reliance on 4D seismic and recommend those that could benefit from testing over the Track-1 & Track-2 stores. They may have additional advantages of improving resolution, reducing cost or environmental impact.

To assure conformance, the CO_2 plume and its migration need to be monitored and compared to the predictive models built by the storage site operator. The areal position of the plume and its evolution is traditionally observed with time-lapse 3D (4D) seismic surveys. While seismic will always be required for the characterisation of a carbon store prior to injection, the use of 4D seismic monitoring during the operational phase can add significant cost and complexity.

To address this, this study used a screening workflow to identify alternative monitoring technologies which have the potential to reduce the requirement for 4D seismic monitoring and assessed the applicability of these technologies to different store scenarios, including the UK Track-1 & Track-2 stores. These technologies provide areal data coverage of the CO_2 plume and provide an early indicator of irregularities, in the event they occur.

The technologies recommended by the Monitoring subgroup are:

1. Time-lapse surface gravity
2. Time-lapse surface seismic (2D)
3. Time-lapse S-DAS (Surface - Distributed Acoustic Sensing)
4. Time-lapse VSP-DAS (Vertical Seismic Profile - Distributed Acoustic Sensing)
5. Surface microseismic

These five technologies all demonstrate potential for monitoring of CO_2 storage sites and could warrant further testing at the Track-1 & Track-2 stores, following feasibility studies. It should be noted that they have different benefits and limitations, and therefore are individually more appropriate for some stores than others as outlined in this report.

The cost-benefit analysis outcome of suitable technologies could have a significant impact on their economic viability as an alternative/enabler of 4D seismic. As projects progress and their use cases become more concrete, the subgroup would be in a better position to comment with a greater degree of certainty on the economic viability of the recommended technologies.

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INTRODUCTION

This report was prepared on behalf of the CCUS T&S Taskforce by the Monitoring subgroup. Members of the subgroup comprise representatives from Taskforce members, including NSTA, OEUK, CCSA, Storegga, Halliburton, BP, Eni, and Shell. The work of the subgroup aimed to:

Provide an improved understanding of available monitoring technologies that have the potential to reduce reliance on 4D seismic as a core monitoring tool and could benefit from further testing and development over the Track-1 and Track-2 stores. The work also aimed to target technologies that may improve resolution, reduce cost or environmental impact of routine monitoring plans.

Under the UK Storage Regulations, monitoring plans need to demonstrate, amongst other things, both containment (no leakage) of the CO_2 and conformance (agreement of the measured data with the modelled data) within the CO_2 storage site and complex and the surrounding area(s). As such, the monitoring plan is a risk management tool that needs to be specific to the risk areas of a given carbon storage site. This means each monitoring plan should consider technologies that provide fit-for-purpose demonstration of containment and conformance, rather than striving for “best in class” as seen in the oil and gas industry.

The most effective monitoring plans will provide an early warning system for any non-conformance events that may lead to significant irregularities and leakage from the storage complex. As such, the recommended technologies from this study all aim to provide data to be used in assessing conformance.

Time-lapse seismic is traditionally used to provide this kind of data coverage in hydrocarbon exploration, development and production but has its own challenges for carbon storage monitoring. These include its cost, environmental impact (noise), and operational issues in areas congested by surface installations (e.g., offshore windfarms). It also has a lengthy lead time in acquisition and processing, so is very much a lagging indicator of potential non-conformance or significant irregularities. In addition, 4D seismic is not a universal monitoring solution, as its response is highly dependent on the rock physics properties of the proposed stores and their fluid content. For example, where saline aquifers are proposed as storage sites, 4D seismic is expected to provide a good image of the CO_2 plume due to the CO_2 displacing brine. However, depleted hydrocarbon fields pose a challenge as the 4D seismic is not usually able to detect differences between the injected CO_2 and the residual hydrocarbons in the formation water. Therefore, this study focussed on identifying alternative technologies that could provide the areal data coverage of seismic over a greater range of potential storage sites. Equally, where 4D seismic is the best technical solution, it may not be the optimised solution that balances data quality, speed of acquisition, cost, environmental impact etc.

METHODOLOGY

To identify potential technologies suitable for further testing at the Track-1 & Track-2 CO_2 stores, the screening workflow summarised in Figure 0-1 was adopted.

Figure 0-1: Screening workflow used by the Monitoring subgroup

First, an extensive list of monitoring technologies currently available was gathered both from the public domain and industry experience within the subgroup. The listing provided in the IOGP Report 652 (Recommended practices for measurement, monitoring, and verification plans associated with geologic storage of carbon dioxide) [1] was used as the basis for assessment as it provided a thorough suite of technologies and is sourced from an industry best practice document. The monitoring technologies have been classified by IOGP into six main categories:

1. Geophysical monitoring technologies
2. In-well monitoring technologies
3. Geochemical monitoring technologies
4. Marine monitoring technologies
5. Atmospheric monitoring technologies
6. Fluid metering and fluid quality monitoring technologies

The subgroup focussed mainly on the first category of the geophysical monitoring technologies as these provided the areal coverage required to be able to substitute 4D seismic. The IOGP list was supplemented by further technologies known to the subgroup through communications with service providers and/or research institutions in the development of their carbon storage sites.

It should be noted that as alternatives to 4D seismic, the identified technologies have currently mostly been used in the hydrocarbon industry and have not been tested over a wide range of CCS store types, to the knowledge of the subgroup. As such, would benefit from further testing through deployment at one of the first UK CO_2 stores to deepen the understanding of the technology limits across a wider range of geological scenarios.

The identified technologies were then ranked to determine which would be recommended for testing in the Track sites using the qualitative criteria in Table 0-1.

Table 0-1: Ranking criteria

Ranking Criteria	Qualifier
	The technology…
Technology readiness level (TRL)	…has a TRL of ~6 or above (technology demonstrated in a relevant environment).
Resolution	…has demonstrated capability of resolving CO_2 plumes.
Coverage	…provides sufficient coverage to monitor CO_2 plume conformance.
If the technology is already being deployed in a Track Cluster	…is not already being de-risked by deployment in a similar Track store.
Reliance on other monitoring data	…has the potential to be stand-alone (even if in the future) and doesn't require a dedicated monitoring well, which would add further cost/complexity to deployment.
Potential benefit/saving	…likely provides a cost saving, lowers environmental impact or provides additional benefits over 4D seismic deployment.
Nimbleness/detection speed	…can detect irregularities at sufficient speed to allow for timely deployment of corrective measures.
If the technology could reduce the requirement for 4D seismic	…could provide sufficient assurance of conformance to reduce the number of 4D seismic surveys during operations.

Finally, the technologies were qualitatively assessed for their efficacy in different geological scenarios to identify which Track store would be best matched to each technology. Note that a feasibility assessment, including field trials, will be required alongside existing (proven) techniques to confirm the efficacy of the technology at the site for its given development scenario, ahead of any widespread deployment.

RECOMMENDED TECHNOLOGIES: RANKING AND STORE SUITABILITY

The technologies recommended from the Monitoring subgroup ranking described in Section 0 are:

1. Time-lapse surface gravity
2. Time-lapse surface seismic (2D)
3. Time-lapse S-DAS (Surface - Distributed Acoustic Sensing)
4. Time-lapse VSP-DAS (Vertical Seismic Profile - Distributed Acoustic Sensing)
5. Surface microseismic

The rationale for the ranking is provided in Table 0-1 and the suitability of the recommended technologies to various geological scenarios in Table 0-2.

Time dependent on volume of CO_2 injected for the specific site – data resolution vs site. Nimbleness – weather/season restrictions

TIME-LAPSE SURFACE GRAVITY

Outline: Time-lapse surface gravity aims to detect changes in the gravitational field caused by a fluid of one density displacing pore fluid of a different density in the reservoir. The method has been deployed in hydrocarbon settings to monitor the movement of water flooding into previously gas-filled pore space. In a saline aquifer setting, it is lower-density CO_2 displacing water. Repeated measurements of the gravitational field are made at the same locations on the surface or seabed above a CO_2 store, typically at fixed concrete plinths to ensure repeatability. The gravity data can then be inverted and compared to pre-injection baseline data to constrain the distribution of CO_2 in the subsurface, as well as the total amount of free-phase CO_2 contained in the plume.

Positives:

Time-lapse surface gravity may provide benefits over 4D seismic in a) estimating CO_2 saturation and b) detecting CO_2 plumes in depleted fields where the 4D response is low.

Depending on seismic rock properties, even in cases where low saturations of CO_2 are expected to produce a clear 4D signal compared to brine, 4D seismic may be relatively insensitive to changes in the level of CO_2 saturation between, e.g., 20-80%. Conversely, time-lapse gravity data may provide a constraint on CO_2 saturation as well as its lateral and temporal variation within the plume. This may make it particularly suited to post-closure monitoring for CO_2 storage sites within structural closures where the maximum plume footprint can be expected to have been reached at the point of closure. If 4D seismic monitoring after this point is insensitive to saturation changes inside the existing plume footprint, as the CO_2 settles buoyantly towards the top of the storage site, gravity data may provide more information on the changing distribution of CO_2 within the plume footprint, as well as confirm containment of the total amount of CO_2 remaining in the free-phase plume.

For storage sites in which the seismic rock properties are not sensitive to CO_2 presence at all (e.g., some depleted fields with residual hydrocarbons in the pore space), gravity may also provide more information than 4D seismic on conformance within the palaeo-gas column.

Since time-lapse gravity data are sensitive to any difference in vertical elevation between measurements, seabed/surface deformation is a necessary dataset that is acquired simultaneously with the gravity data in order to be able to make any required corrections. If surface deformation is observed due to inflation of the storage site, this can be a useful dataset in its own right.

Gravity is included here for consideration because it is one of the few methods that provide full areal coverage of the plume and a gravity survey is typically much lower cost than a 4D seismic survey. Thus, even though the resolution of the plume image is much lower than with seismic, time-lapse gravity surveys may provide enough confidence that there are no significant irregularities or increasing risks to containment, such that the interval between 4D seismic surveys can be increased and the total number of seismic surveys over the life of the store can be reduced.

Negatives: Surface gravity inversion is significantly lower resolution than 4D seismic and solutions are non-unique, which are the main limitations of the method. Inversions are likely to be most effective if constrained by a depth structure derived from 3D seismic for the storage site (and other porous intervals in the overburden, in the event of suspected migration or leakage out of the storage site). A high-quality 3D survey would be expected as part of the Site Characterisation of the store, so this requirement for a depth structure should not be a constraint on the deployment of 4D gravity.

Technology Readiness: The method is technologically mature; the uncertainty is whether the site-specific conditions at UK carbon storage sites are amenable to its application. Therefore, site-specific studies are encouraged, to assess the likely signal strength from each store's CO_2 injection plans and the practicalities of implementation in the UKCS. Both signal strength and resolution will be reduced for deep stores.

Time to Detection vs 4D seismic: Data acquisition is potentially more flexible and less affected by sea conditions as measurements are typically taken at permanent concrete plinths on the seabed. 4D seismic has a relatively lengthy processing time, whereas gravity would enable earlier detection of any potential irregularities.

Cost-benefit: Gravity surveys typically have a cost in the region of one-tenth of that of a 4D survey. Multiplied over the life of the store this has the potential to introduce significant savings.

Co-location potential: Gravity surveys have a significantly smaller operational footprint than a 4D seismic survey, and typically involve visiting each measurement location in turn to deploy a single instrument module long enough to take a measurement before retrieving it and moving on. As such, it may be possible to design surveys that can be acquired within a wind farm, given sufficient spacing between turbines.

TIME-LAPSE SURFACE SEISMIC (2D)

Outline: For many CO_2 stores, 4D seismic surveys are likely to represent the best *technical* solution to monitoring CO_2 plume extent. However, the best technical solution (with correspondingly high cost) may not be required to achieve a sufficient level of confidence that the CO_2 is contained in the storage site. Time-lapse 2D surface seismic is considered here as an option that could represent a minimum viable specification of seismic acquisition that could still be capable of achieving the monitoring objective of tracking the CO_2 plume in the storage site. Carefully chosen 2D line locations could be used to 'pin' the edges of the CO_2 plume and/or to check that no CO_2 signal is observed close to critical locations, such as structural spill points.

Positives:

For relatively shallow stores, short-streamer site-survey vessels may be adequate to image down to the reservoir, with the added benefit of higher resolution shallow imaging than is typical with 3D surveys. This type of vessel is significantly lower cost than typical 3D survey vessels with wide-tow capability.

Negatives:

- As with any time-lapse seismic, the method is dependent on a sufficient change in seismic response when CO_2 is injected into the pore space, thus will not be effective for stores with a small expected CO_2 fluid substitution response (e.g., some depleted gas reservoirs).
- Spatial coverage is limited, which means needing to accept greater uncertainty in plume geometry than with 3D coverage.
- Repeatability is challenging for 2D towed-streamer, especially in settings with strong and/or variable currents. Depending on the seismic rock properties, this may not be a problem if the CO_2 signal is strong enough. It may be possible to use a 3D baseline survey acquired for site characterisation for the 2D baseline, if the CO_2 signal is strong enough.
- Smaller short-streamer or site survey vessels may struggle to image deeper stores adequately.

Technology Readiness: The acquisition technology is mature and is ready to deploy for testing. It may be possible to test the effectiveness of 2D monitoring during early-stage repeat 3D monitor surveys, if it is possible to extract pseudo-2D data to illustrate what information 2D acquisition would have provided. Operators should be encouraged to consider this sort of study to understand the potential to use lower-cost 2D surveys (or 3D swaths) for monitoring later in the life of the project. If confidence can be built in store performance during the early stages of injection, operators may be able to rely on 2D data to support extending the time between repeat 3D monitor surveys, or even to reserve full 3D surveys for triggered monitoring only if required.

Time to Detection vs 4D seismic: Similar to 4D seismic, time-lapse 2D has specific season and vessel requirements, to achieve acquisition repeatability. However, the mobilisation time for a 2D acquisition vessel may be faster than for a 3D vessel. The processing time for 2D is also faster due to the lower volume of data. Based on this the 2D may be able to detect irregularities in a shorter period compared to 3D.

Cost-benefit: Acquisition of 2D data is significantly cheaper than a full 3D survey, based on the time required to acquire 2D lines. The costs depend on the total amount of linear kilometres to be acquired and on the survey vessel used, but it can be said that the cost of a 2D survey is "£" compared with "£££" of a 3D survey.

Co-location potential: The operational footprint of 2D surveys, especially short-streamer surveys, is considerably smaller than a typical 3D towed-streamer survey. As such, it may theoretically be possible to acquire some limited orientations of 2D lines with very short streamers through a wind farm if turbines were spaced sufficiently far apart. However, this is still highly undesirable from an HSE/operational perspective, and the ability to acquire lines in the optimal positions for plume monitoring is unlikely to coincide with the limited possible line locations within the wind farm. Therefore, 2D towed-streamer acquisition is not considered a viable monitoring solution within a wind farm.

TIME-LAPSE S-DAS

Outline: Surface DAS (digital acoustic sensor) is an emerging technology that could offer the potential for low-cost, low-maintenance broadband seismic. The Net Zero Technology Centre (NZTC) has been supporting suppliers in development of this technology for CO_2 store monitoring since 2022. The technology requires deployment of a DAS fibre array on the seabed as a permanent monitoring solution and could monitor as a passive seismic solution (e.g., microseismic) and, with an appropriate source vessel, act as an active (i.e. seismic acquisition) seismic source.

Positives:

- Dual monitoring, in theory, of both active and passive sources.
- While it currently has a relatively low depth of penetration, it could be useful in stores that are at shallow depths, such as the proposed stores in the East Irish Sea, where a strong licence to operate is required, particularly given the public perception of induced seismicity. The Bunter saline aquifer stores in the Southern North Sea may also be suited to this kind of technology.
- Depth of penetration for active imaging is around 1500m, which may be sufficient for the Track 1 stores and a number in development.

Negatives:

- The technology has a strong directivity response so it may not image well in all directions (but it is likely this problem could be overcome).
- It has not been tested for 4D and the limitations on depth of penetration are around 500m for passive detection and approximately 1500m for active imaging, which may limit its usefulness in a number of proposed stores.
- As with VSP-DAS, any S-DAS will require a connection to land or a platform for the necessary cabling to provide a route for both power and data.

Technology Readiness: Relatively low, not yet ready for deployment. Potentially ready for trials.

Time to Detection vs 4D seismic: Not enough is yet known about the detection speed of S-DAS but in theory is similar to VSP-DAS (see below). For passive detection the time is short (days/weeks); for active detection the time would be longer due to the requirement for a suitable source to be mobilised and the more complex data processed.

Cost-benefit: Unknown, requires follow up with vendors.

Co-location potential: Laying of DAS cabling is thought to be compatible with wind farm operations, as no further activity on-site is required for passive seismic. For active seismic, an ROV/AUV could be deployed with the seismic source, again limiting the safety exposure in this area.

Time-lapse VSP-DAS

Outline: VSP-DAS is a proven technology in the oil and gas industry and has been successfully used at the onshore Quest CCS project in Canada. It involves installing a permanent fibre-optic cable in the well, typically this fibre stops just above the packer to avoid additional leakage risk from the store. The cable must be connected at the surface to receive the data. Typical usage is with active seismic sources from a small vessel, but the fibre could also be used for passive microseismic detection. However, for microseismic detection, the fibre must be installed in a dedicated monitoring well (i.e., one without injection), as the noise of the injection will create too much noise.

Positives:

- The receivers are already in place, so repeat surveys can be quick and cost-effective;
- If there are imaging challenges created by the overburden, these can be overcome with sensors close to the store;
- Resolution close to the well may be better than surface seismic and may provide a good image of early CO_2 injection, allowing the study of CO_2 migration in the reservoir.

Negatives:

- Installation in a sub-sea development is generally very expensive;
- DAS has a lower Signal-to-Noise ratio than geophones, so detection limits will be poorer;
- There is a limited cone of imaging, which is proportional to depth, so in shallower stores the CO_2 plume may out-run the imaging area quickly, leaving the technology less useful in later years of the project as the CO_2 migrates to the top of the reservoir;
- Injection will likely need to be stopped for a survey to be carried out if the fibre is in the injection well.

This means that DAS-VSP is currently favoured by onshore projects with deeper and limited extent stores and projects that already have a planned monitoring well. However, for offshore stores that have a platform, it could also be effective, especially if there is a need to learn quickly about early CO_2 migration patterns.

There have been many advances in DAS technology over the past few years and it is possible to get long sub-sea cables (100 km), if required.

Time to Detection vs 4D seismic: If used for passive monitoring of induced microseismic activity, detection using VSP-DAS is likely to be close to “real time”. If used for active monitoring of plume migration, acquisition and processing might take 2-3 weeks, versus 2-3 months for 4D seismic (plus the pre-survey permitting and mobilisation etc.). Additionally, a wide range of vessels with an attached seismic source could be used, compared to the few source vessels available for 4D seismic with long lead-times. Finally, there could be a longer window of season for acquisition as the seismic receivers in the well and thus results would be less affected by weather.

Cost-benefit: The cost-benefit is dependent on a number of factors, specifically whether you want to just image around the injector or if you want the VSP data to act as a larger 3D/4D for a larger project. If the goal is early imaging of specific injectors, and you have a platform to connect to, this could be a good option. It could also be advantageous if you have imaging challenges that would otherwise require significant undershoot, or other more expensive 3D acquisition. However, for a scenario where an image is required over a large area, this is not going to act as a replacement.

Co-location potential: This is largely not applicable as it requires a well, which is highly unlikely to be sited within a wind farm, as access to the wellhead will be required for potential remediation/workovers, any corrective measures, and decommissioning.

SURFACE MICROSEISMIC

Outline: Microseismic monitoring is an established and proven technology in the oil and gas industry for monitoring hydraulic fracturing and assessing the geomechanical stability and any induced seismic hazard due to injection. This methodology can be applied for both production and CO_2 storage and makes it perfectly suitable for monitoring CO_2 injection. The microseismic data allows analysis of the stress state of the entire storage system and, with accurate analysis, provides an understanding of leakage pathways being created or reactivated.

The installation of a permanent seismic network is required using sensors capable of recording low-level seismic events, either naturally occurring or induced by the injection process itself. Typically, geophones are deployed either at the surface, or if possible downhole and the seismic network design depends on the geological and seismic complexity of the area, as well as the logistic and environment characteristics, and by any regulatory requirements.

Positives:

- The microseismic monitoring is suitable both for depleted field and aquifer storage sites, whether onshore or offshore. The effectiveness of passive seismic techniques depends mainly on the level of both natural and induced seismicity and on the site's noise level.

Negatives:

- While data is collected continuously it requires extensive processing to extract meaningful results.
- Estimation of the plume location is challenging and may carry a high level of uncertainty, which may be above the tolerable level. However, it should be noted that passive seismic for subsurface imaging is further developing.

Time to Detection vs 4D seismic: Surface microseismic continuously detects for microseismic events and therefore is in "real-time" yet can take some time to process the data. It should be noted that this will be substantially quicker than detection via 4D seismic.

Cost-benefit: Indicative costs are estimated to be low "£" to moderate "££", depending on the network design, versus the 4D seismic "£££", Initial costs would be relatively high for network installation and design, but followed by much lower annual costs for long-term monitoring.

Co-location potential: A microseismic network is compatible with offshore wind and may even prove to be beneficial in providing valuable information on natural seismicity to the wind operator(s).

Table 0-1: Ranking of recommended monitoring technologies

Technology	TRL	Workover required?	Already being deployed in a cluster store?	Resolution and coverage	Reliance on other data	Potential saving/benefit	Reduces traditional 4D seismic?	Recommendation
Time-lapse surface gravity	Mature	No	Proposed for Hynet. Under evaluation for Endurance	Low resolution but good coverage	Seismic is required to determine structure to constrain inversions; early coincident 4D seismic may be needed for calibration.	Potential to displace higher cost seismic activity. May provide an advantage in depleted fields where no/low seismic signal.	May allow a number of seismic surveys over the life of development to be reduced, including a potential replacement for post-closure seismic survey.	Operators are encouraged to explore site-specific feasibility for surface gravity.
Time-lapse surface seismic (2D)	Mature	No		High resolution but moderate coverage		Could displace 3D seismic to triggered option, or compliment e.g. gravity	Localised but could mean 4D moves to triggered / contingent	Test alongside 3D in all possible projects (could process individual 3D lines as 2D to test)
S-DAS. Horizontal fibre optic on seabed	Still under development	Not well dependent		The signal-to-noise ratio is lower than traditional sensors but technology still developing. Depth of imaging	No specific reliance - if the seabed array is large enough then could provide information on	Could be used as regular monitoring and then decide based on results whether to	Potentially – if the technology is successful it could be a cheaper way to acquire 4D	Stores <1500m could be used to test, would be good to liaise with NZTC to understand plans and collaboration. Ideally requires a

				~1500m; depth of passive sensing ~500m.	fluid/pressure front movement	trigger additional monitoring		platform to reduce installation costs
Time-lapse VSP - DAS	Fully deployable	Installation required when well drilled, cannot be retrofitted	Hynet	Moderate resolution and coverage; containment/conformance only met for a limited time	No reliance on other data	Some scenarios may provide significant low-cost repeat monitoring, especially in the early years	If deployed in injectors and monitoring wells could provide wide coverage for deeper stores.	Likely only to be deployed on projects with a platform due to umbilical costs. Will be useful to see how more frequent/detailed early DAS-VSP data could help understand CO_2 migration and confidence in containment
Surface microseismic	Mature but with further development in using passive seismic for reservoir imaging	Network design and installation	Hynet. Endurance (under evaluation)	Low resolution and coverage	No reliance but synergy with ground deformation monitoring	Cost-effective monitoring of passive seismic for reservoir imaging (CO_2 plume conformance) once improved and tested.	Potentially may help to monitor conformance and relax intervals of 4D seismic surveys if reservoir imaging is improved.	Explore industry/BGS/ academia collaboration (e.g. BOPS) for future passive seismic imaging applications.

Table 0-2: Suitability of recommended technologies to store types

Technology	Shallow store (~1000m)	Deep store (~2000m)	Subsea Dev'mnt	Platform Dev'mnt	Good seismic signal - store	Poor seismic signal - store	Good seismic signal - overburden	Suitable for saline aquifers?	Suitable for depleted fields	Cluster store options for trials
Time-lapse surface gravity										Hynet, Endurance
Time-lapse 2D seismic										Endurance, Acorn
S-DAS. Horizontal fibre optic on seabed										Hynet, Endurance, Viking
Time-lapse VSP-DAS										Viking, Hynet
Surface microseismic										Hynet, Endurance

Legend: Ranking of the likely technology performance in various scenarios

Likely good performance	Performance possible but not best suited	Likely poor performance

3.6 Opportunities

The subgroup identified several opportunities that could provide benefits to the monitoring of CO_2 stores. These were:

- **Cost sharing:** Acquiring surveys in collaboration with other users of the seabed that require the same data. This could not only lower costs but also the environmental impact of acquisition.
- **Microseismic monitoring networks:** Using sensors from closely spaced stores in collaboration to create a microseismic monitoring network or deploying compact arrays onshore to improve detection thresholds and location accuracy by remote monitoring of microseismicity at offshore stores. For example, in the Southern North Sea where there are many contiguous carbon storage licences. This is something that the BGS is already exploring with a number of licensees and should be encouraged.
- **Data sharing:** Sharing of monitoring data, where possible, is integral not only to the success of the previous opportunities but also to the testing of the monitoring technologies recommended in this report. This will ensure the distribution of learnings to allow faster development and understanding of CCS monitoring technologies. Making funding available for technology testing could facilitate data sharing, as seen at Sleipner in Norway.
- **Cross-industry collaboration:** industry bodies such as OEUK or CCSA should work with their members to encourage sharing of proposed monitoring technologies to facilitate development of field trial opportunities as well as cost sharing opportunities.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

This report has identified five technologies which demonstrate the potential to reduce the requirement for 4D seismic within the core monitoring programme of CO_2 storage sites. While high-quality 3D seismic will always be required for the characterisation of a carbon storage site prior to development and injection, the alternatives to 4D seismic monitoring could offer significant cost benefits to the nascent CO_2 storage industry.

Based on the methodology described in Section 0, the following technologies are recommended for feasibility studies and field trials.

Table 3-1: Technologies recommended for feasibility studies and field trials

Technology	Cost	Areal coverage	Plume detection	Co-location flexibility	Time to detection	Technology readiness	Potential field trial
Time-lapse surface gravity			* Depleted fields * Saline Aquifers				Endurance, Hynet
Time-lapse surface seismic (2D)			*				Acorn, Endurance
Time-lapse S-DAS	unknown		*				Endurance, Hynet, Viking
Time-lapse VSP-DAS							Hynet, Viking
Surface microseismic							Endurance, Hynet

*Note the performance of time-lapse gravity vs 4D seismic regarding plume depends strongly on store type.

Legend: Performance relative to 4D seismic

Much better	Slightly better	Equal	Slightly poorer	Much poorer

RECOMMENDATIONS

Building upon the insights gained from our analysis, the following points have been identified to continue progress/assess the viability of the proposed monitoring technologies.

Desktop feasibility studies followed by field trials of the recommended technologies

A desktop feasibility study to first confirm the viability of the technologies at a specific store(s), followed by a field trial, is recommended to encourage testing and improve the readiness of these promising technologies. This would be complemented by a cost-benefit analysis which could have a significant impact on their economic viability as an alternative/enabler of 4D seismic.

The Monitoring subgroup recognises that there are multiple pathways to realise opportunities and these pathways may differ from technology to technology based on their TRL. For those with lower TRLs, it may be more suitable to consider Joint Industry Projects (JIP) to foster collaboration and collective learning. This could also consider the use of third-party infrastructure to make some aspects more effective and cost-efficient (e.g. shared passive seismic network and communications cables for S-DAS). Those more advanced could consider field testing for an improved understanding of their effectiveness in real-world scenarios.

Continue the conversation on future monitoring technologies

As monitoring technologies and CO_2 stores continue to be developed, further opportunities not included in this report may arise. As such, it is recommended to continue this work in the future to encourage development in these areas and reduce costs, which may include:

- **Installation of fibre in subsea wells.** Fibre is currently well tested in onshore hydrocarbon wells. However, it is not well understood in subsea developments. Fibre in subsea wells is currently being considered for use in several of the Track stores and hydrocarbon fields, which would provide useful insights if learnings could be shared.

- **Electromagnetic surveys.** This technology shows the potential to detect CO_2 via the difference in resistivity compared to brine and therefore could be considered in the future. It currently is challenged due to high costs, low spatial resolution and reliance on seismic data to calibrate the electromagnetic survey results.

To complement this, industry-wide engagement and education on non-seismic methods would be beneficial to move away from pure-seismic monitoring solutions. This could be championed by regulators to provide connections between various areas of the industry.

Any future work should continue collaborating with other Taskforces and working groups to ensure sharing of learnings and no duplication of effort.

Establish a framework for the sharing of data

Under the UK Storage Regulations, monitoring data gathered at CO_2 storage sites is to be reported annually to the regulator. The sharing of this data is critical to enabling learnings from monitoring technology (field trials of new technologies as well as more established methods) and deployment for the benefit of the CCS industry as a whole.

The NSTA launched a consultation on data reporting, retention and disclosure practices in Q4 2023. The outputs of this consultation will support the development of a framework for data sharing in the North Sea which, if successful, would aid cost reductions of monitoring operations in the North Sea and negate the need for repetition of seismic work. The subgroup encourages operators, and vendors, etc. to engage with the call for evidence. Simplification of data reporting across different regulatory bodies should be investigated to ensure a single repository for monitoring data. The methods and extents of retention and reporting of raw and interpreted data should also be considered, given the significant quantities of data expected to be acquired.

In addition, it is recommended that the method of interpretation should also be shared, alongside any reported monitoring data, to ensure a consistent industry approach and allow comparison and integration of the monitoring results. The use of AI and machine learning to aid interpretation efficiency and consistency should be encouraged.

FUTURE WORK

The Monitoring subgroup propose the following near-term and long-term future work, recognising the different maturities and possibilities for development of the recommended technologies.

NEAR TERM

A timeline to deployment for four of the recommended technologies in Track 1 and 2 stores is provided in Figure 0-1. These are:

- Time-lapse surface gravity
- Time-lapse surface seismic (2D)
- Time-lapse S-DAS
- Time-lapse VSP-DAS

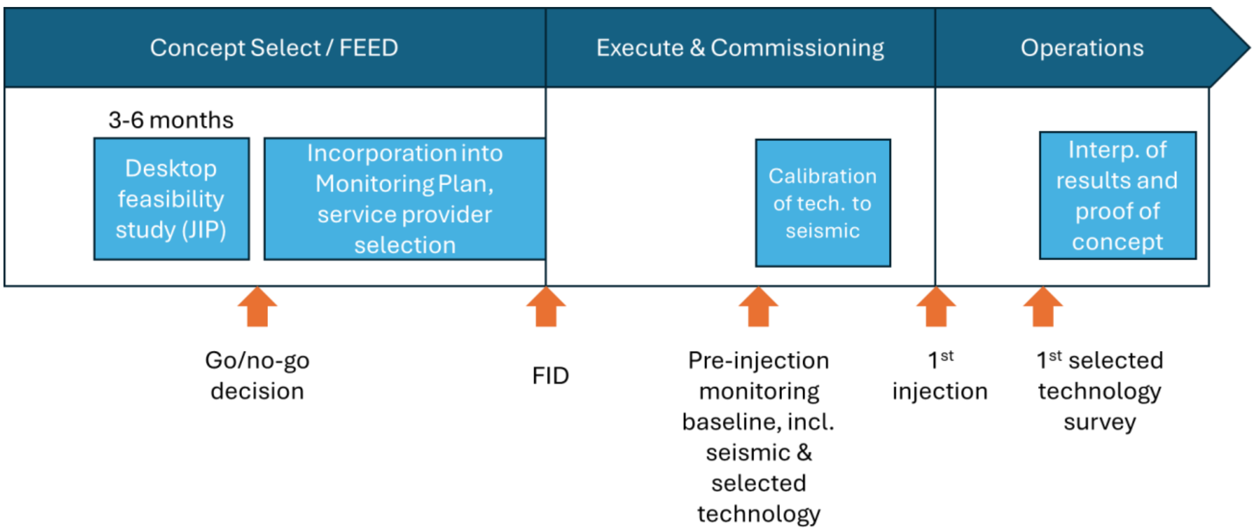

Figure 0-1: Proposed near-term deployment of recommended technologies

An initial 3–6-month desktop study is proposed to first determine viability of the technology in a number of geological scenarios, which should represent the stores proposed by Track 1 and 2 projects. Where the same technology is selected at various stores, a multi-store study could be completed via a joint industry project (JIP). Providing feasibility is demonstrated, the next step would be for the selected technology to be incorporated within the Monitoring Plan to incorporate field trials as appropriate, or directly towards acquisition of a baseline dataset. This could be part of the documentation submitted as part of the Storage Permit Application or within one of the periodic updates to the Monitoring Plan. In the former scenario, a pre-injection baseline of the technology would need to be acquired along with other monitoring data and calibrated against seismic or other suitable baseline data. In the latter scenario, the technology could be calibrated to the monitoring data acquired taken during operations. Results of the tested technology could then be analysed and a decision taken on whether it provides sufficient information to reduce the requirement for 4D seismic monitoring.

LONGER TERM

The fifth recommended technology, microseismic, is anticipated to require more time for development, particularly if considered in an onshore-offshore microseismic network, as described in Section 3.6, due to the complexity of such a project. As previously mentioned, this is currently being considered by the BGS who, as operators of the current onshore UK seismometer network, are well placed to complete the study. It is noted that a long baseline period (c.1 year) is likely to be required pre-injection to ensure robustness of signal and delineation of natural and induced seismicity, as well as an ability to demonstrate the source of any induced seismicity.

In the future, the subgroup could consider further monitoring technologies to continue their development, as recommended in Section 0, but would benefit from including licensees from the first CS licensing round rather than just Track 1 and Track 2 licensees. This would add breadth to the knowledge of the subgroup and also enable the testing of the technologies at a wider range of potential store scenarios than those noted in Table 0-2.

REFERENCES

[1] IOGP, "Report 652 (Recommended practices for measurement, monitoring, and verification plans associated with geologic storage of carbon dioxide)".