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Insights and guidance for offshore CO_2 storage monitoring based on the QICS, ETI MMV, and STEMM-CCS projects

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ABSTRACT

Carbon Capture and Storage (CCS) is a collective term for technologies that allow society to unlock the benefits of energy intensive processes like fertiliser production and combustion of fuels (fossil or biologically sourced) without releasing the CO_2 to the atmosphere. Hence, CCS could assist in accelerating decarbonisation while society pursues a just energy transition. This paper aims to summarise the learnings of three research projects that all investigated aspects of marine monitoring for CCS from a CO_2 storage operator's perspective. The QICS (Quantifying and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage), ETI MMV (Energy Technologies Institute Measurement, Monitoring and Verification of CO_2 Storage), and STEMM-CCS (Strategies for Environmental Monitoring of Marine CCS) projects collectively represent over twelve years of dedicated research to assess environmental impacts and to develop technologies for detection, location, and quantification of potential leakage from offshore geological storage of CO_2. Each project used controlled releases in representative environments to test their methods and technologies. QICS as the first of the three projects, focused on the understanding of sensitivities of the UK marine environment to a potential leak from a CO_2 storage complex and tested technologies to detect such emissions. The ETI MMV project brought together research and industry partners to develop and sea trial an operational, integrated and cost-effective marine monitoring system for geological CO_2 storage. As a commercial project, these results have never been published before and this paper shares for the first-time insights from this work. In February 2020, STEMM-CCS, completed its quest to test techniques for environmental monitoring over a marine CO_2 storage site in the UK North Sea, further improved near seabed leakage characterisation capabilities, and delivered a first marine CCS demonstration level ecological baseline. This paper aims to summarise some of the key insights from the three projects and provides references where available for the interested reader. The key finding of all three projects is that the impacts of small to medium CO_2 leakages from large-scale storage are limited and localised. Technology capabilities exist for integrated marine CO_2 storage monitoring and their performance has been benchmarked at controlled release trials. Even small leakages of 10−50 L/min can be detected at unknown locations in a large area of interest. Finally, the first important steps towards automated monitoring data analysis have been made, including automated leakage signal detection from Side Scan Sonar data (ETI MMV project) and automated species identification from marine biology images (STEMM-CCS project). Some remaining challenges include missed/false alerts because of large variations in the background signal, the cost of monitoring large areas over long periods, and making real-time decisions based on big data. Continued work to reduce the cost of marine monitoring technologies and advancing automation of data processing and analysis will be important in order to support safe and efficient offshore CCS deployment at large scale.

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1. Introduction

Since the publication of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Carbon Capture and Storage (CCS) (IPCC, 2005), the technology has been identified as a major option for use in the large scale reduction of CO_2 emissions (Gale et al., 2015) based on modelling and scenario studies. Commercial-scale demonstration projects like Sleipner (North Sea, Norway, >20 Mt CO_2 injected) and Quest (Alberta, Canada, >5 Mt CO_2 injected) have shown that the technology is feasible and safe. Yet, CCS is still not as widely implemented as required to meet the ambitious targets set at the COP21 in Paris in 2016, largely for societal acceptance and economic reasons. Insufficient carbon pricing and a lack of regulatory drivers are preventing CCS from fulfilling its potential, rather than any major technological challenges. Nevertheless, it is critical for current and future CCS projects to demonstrate safe and efficient long-term storage of CO_2 in order to gain and maintain societal trust in this technology.

Site selection, characterisation and engineering designs are considered the prime means of ensuring confidence in the long-term security of a CO_2 storage site. Wide-ranging containment and environmental monitoring programmes are deployed to deliver the data to verify the site is performing as expected and to enable emission quantification and impact assessment in the unlikely loss of containment scenario. This has been demonstrated, for example, by the Sleipner project in Norway (Furre et al., 2016) and the Otway project in Australia (Jenkins et al., 2011) using quantitative verification of long-term storage and direct measurements of storage efficiency. Emerging storage operators verify CO_2 storage site performance using a comprehensive risk-based Measurement, Monitoring and Verification (MMV) framework (Bourne et al., 2014; Dean and Tucker, 2017). MMV is based on a bowtie containment risk assessment where potential mechanisms that could lead to loss of containment are investigated and mitigation options are identified. Barriers to reduce the likelihood of a hazard escalation (i.e. a leakage event) can take the form of monitoring technologies combined with corrective actions. Monitoring technologies in an MMV programme are comprehensive and cover all relevant phases (pre-injection, injection and post-injection) and domains (marine environment, geosphere, wells, etc.). Here, we focus only on technologies relevant in the marine monitoring domain, but it is important to recognise that loss of containment is likely indicated much earlier by in-well and subsurface monitoring data. This would trigger additional contingency monitoring (including environmental monitoring) and data analysis to re-assess all containment risks leading to corrective actions if indicated.

Given the current public acceptance challenges to onshore CCS, CO_2 storage in Europe will most likely be deployed in deep offshore geological storage sites utilising existing oil and gas technologies and where possible reusing existing infrastructure. Proven and effective industry monitoring technologies are available to monitor the subsurface and wells. However, over a decade ago potential offshore CO_2 storage operators recognised clear gaps in capabilities for CO_2 leakage detection, attribution and quantification in the marine environment above a storage site which are all regulatory requirements (EC, 2009). The marine environment is very challenging to monitor for an unknown leak at an unknown location given the significant natural background variability of sediment morphology, marine acoustics, chemistry and biology (Blackford et al., 2015). The QICS, ETI MMV, and STEMM-CCS projects have done much to fill these gaps and technologies are now available to support safe offshore geological storage of CO_2 and to manage unexpected emissions in a timely manner.

Challenges remain, such as making real-time decisions based on large data streams acquired and determining fit-for-purpose monitoring tactics that maximise true alerts while minimising false alerts and costs. Environmental monitoring plans will likely depend on site-specific risks (i.e. potential overburden leakage paths, pockmarks, abandoned wells, etc.) and relevant regulatory framework.

2. Motivation

The intention of this paper is to provide a summary of three projects that addressed gaps in marine monitoring capabilities as recognised by potential offshore CO_2 storage operators in collaboration with marine scientists and other stakeholders. Besides giving project summaries, technology options and information on data management, a recommended approach to marine CO_2 storage monitoring is shared based on the collective experience of the three projects. We would like to communicate the progress made to inspire deployment and further progression of the Technology Readiness Level (TRL) of marine monitoring and modelling tools to support large-scale deployment of CCS.

The former Peterhead CCS project (Spence et al., 2014) motivated much of the work done in the ETI MMV and STEMM-CCS projects. In fact, the STEMM-CCS project was to run in parallel with its final pre-operation phase. The intention was to contribute to the operator's environmental monitoring plan over the Goldeneye CO_2 storage site (Dean and Tucker, 2017). When the Peterhead CCS project was cancelled due to the UK government's withdrawal of funding in 2015, the decision was taken to continue with the STEMM-CCS project in order to benefit future CCS projects in the area.

The challenges and technology gaps identified when developing the Goldeneye CO_2 storage site as part of the former Peterhead CCS project included:

1 Marine baseline characterisation to enable CO_2 emission detection is very complex.
2 Attribution of emission events and avoiding false positives due to natural variation is difficult.
3 Cost of continuous, long-term (25 years) marine monitoring over a CO_2 storage site is very high.
4 Marine CO_2 emission quantification technologies do not exist, but are required by regulations (EC, 2012).
5 The impact of CO_2 emissions from a storage site is not well understood, although some work was done by the ECO2 project (Fritz, 2012).
6 Managing large offshore monitoring data streams and making real-time decisions based on them is difficult.

To address these challenges, experts in research institutes, technology providers and potential CO_2 storage operators have collaborated in three complementary projects. All projects performed controlled CO_2 release experiments in representative marine environments to test the performance of their technologies. The first project, QICS was a scientific research project led by Jerry Blackford of the Plymouth Marine Laboratory (PML). Industry did not play an active part in this project but was engaged as part of a broader community of stakeholders. As a result, some of the above listed challenges were more clearly defined and ideas for a future more active collaboration between industry and research institutes were formed. This eventually resulted in STEMM-CCS, an EU Horizon2020 proposal with industry as a participating partner. The STEMM-CCS project was mainly focussing on addressing challenges 1, 2, 4 and 5.

In parallel, a program of work was coordinated and funded by the Energy Technology Institute (ETI) UK, to develop an operationally ready, lower cost marine CO_2 monitoring system in collaboration with industry, research institutes and technology providers. This resulted in the ETI MMV project which due to its commercial nature has never published results externally. In this paper, we share for the first time results of the work at a level permitted by the nature of the project. The focus of the ETI MMV project was on addressing challenges 3 and 6, delivering an integrated efficient marine monitoring system ready for deployment at a marine CCS demonstration project. The scope included marine monitoring data acquisition, data transfer, processing and interpretation, and was demonstrated at harbour and sea trials with artificial leakage events (i.e. controlled releases of CO_2).

3. Project overview

The following sections provide brief introductions to the three projects with relevant references where available. As mentioned above, the ETI MMV project has not published externally as it was a commercial project and STEMM-CCS just finished in February 2020 and many publications have only just been submitted. However, the STEMM-CCS website (STEMM-CCS, 2020) includes an up-to-date list of all references.

3.1. QICS (Quantifying and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage)

QICS (Blackford et al., 2014) was a scientific research project operating between 2010 and 2013. Its objective was to investigate shallow sediment and water column dynamics of CO_2 dissolution and flow and improve understanding of the sensitivities of the UK marine environment to a potential leak from a carbon capture and storage (CCS) system. In addition, techniques to detect and quantify CO_2 flow were tested, and improved predictive models of CO_2 dynamics and impact were developed. The project consortium consisted of a range of UK research organisations, universities and risk management professionals. In addition, a group of Japanese scientists contributed to the QICS project in support of CCS demonstration projects in Japan such as the Tomakomai Project (Japan CCS, 2020).

The project injected 4.2 tonnes of CO_2 into sediments 11 m below the sea floor over a 6-week period, starting at 10 kg and increasing gradually to 210 kg per day. Injection was facilitated via a bespoke pipeline drilled from the nearby shore and the water depth at the injection point varied between 10–12 meters. A range of scuba, platform, boat and autonomous vehicle-based observations identified physical, chemical and biological perturbations to the system both during the release phase and subsequent recovery phase (Fig. 1).

The sediments between the injection point and the sea floor 11 m above comprised of a moderately complex stratigraphy which interacted with the development of the subsurface CO_2 plume, causing lateral spreading and retention of significant amounts of gas. Distinct chimney structures formed initially over an area of approximately 500 m^2 reducing to 100 m^2 during the release; gas flow at the sea floor consisted of approximately 20 separate and mobile release points, with bubbles seen soon after the gas flow was initiated (Blackford et al., 2014; Cevatoglu et al., 2015). From this it was concluded that CO_2 lateral spread could be a very significant factor in determining leak location and that quantification of leakage will need to account for shallow subsurface retention. Further, a significant amount of carbonate buffering was observed in the upper sediments (Blackford et al., 2014; Lichtschlag et al., 2015). Estimates of gas flow rate at the sea floor from both direct and indirect measurement suggested that 15 % of injected gas emerged from the seafloor in the gas phase, the majority of which dissolved in the water column. Contrary to expectations a few gas bubbles reached the sea surface, potentially due to bubble aggregation (Sellami et al., 2015). Although measurements of dissolved phase transfer across the sediment-water interface away from the bubble plumes were zero, models of the extent of the chemical signature of dissolved CO_2 in the water column (Maeda et al., 2015; Mori et al., 2015) suggested that approximately 50 % of the injected CO_2 entered the water column as either gas or dissolved phase, via the pore waters, indicating the challenge involved in quantifying flow. It is hypothesised that dissolved phase flow was spatially closely associated with gas phase flow. Imaging revealed at least a medium term retention of significant amounts of gas within the sediments. The differing carbon isotopic composition between the injected CO_2 and naturally occurring CO_2 was used to confirm the source of the observed gas in the pore waters and water column and indicated the utility of tracers for both attributing and quantifying CO_2 partition. Flow rates at the sea floor were also seen to vary with the tidal cycle, with higher flow rates observed at low tide, due to pressure differences (Blackford et al., 2014; Bergès et al., 2015).

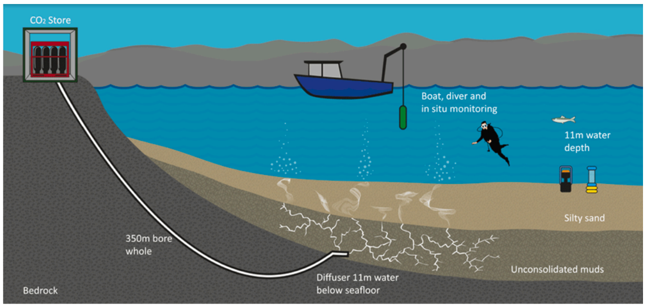


Fig. 1. Schematic of the QICS experiment (image courtesy of the QICS project).

A range of sensors were deployed to detect leakage signatures in the water column (Fig. 2). Chemical sensors were able to detect pH and pCO_2 signals in the vicinity of leakage (Atamanchuk et al., 2015; Shitashima et al., 2015; Taylor et al., 2015), with measurements highly sensitive to the positioning of the sensor in both the horizontal and vertical plane. Passive acoustic methods to detect bubble release were also trialled and shown to have potential to detect and quantify leakage, however these were sensitive to background ambient noise (Bergès et al., 2015).

Biological studies addressed the response of a range of benthic and bottom dwelling species. Whilst evidence of disturbance to bivalves and megafauna was absent (Pratt et al., 2015; Kita et al., 2015) impacts were seen in microbial communities (Tait et al., 2015) and microbenthic community structure (Widdicombe et al., 2015; Blackford et al., 2014). Besides performing pioneering baseline studies that accounted for natural variability of systems, the QICS experiment also demonstrated that biological systems recovered within a few weeks of exposure.

QICS was a ground-breaking experiment with a number of novel outcomes. Whilst such a deployment was challenging, it was shown to be tractable and informative. The QICS experiment revealed that complex physical and chemical processes determine the formation and dynamics of CO_2 flow even in shallow systems, demonstrating challenges for detection and quantification. Detection in the sediments and water column could be achieved via both acoustic and chemical methods, although the partitioning and fate of the CO_2 was very difficult to quantify. Because of the intermittency of bubbles and mobility of the

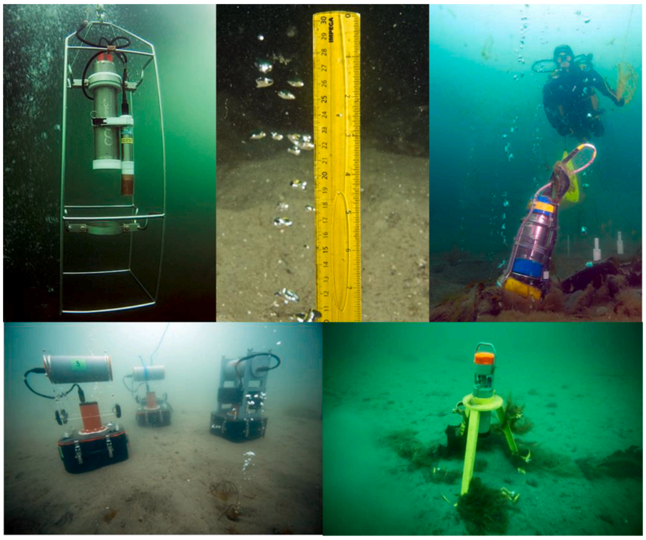


Fig. 2. Deployment of instruments during the QICS experiment. Clockwise from top left: Contros HydroC_CO_2 sensor, photographic measurement of bubble morphology, custom made CO_2 and pH sensor rig, Aanderaa RCM 9 current meter, benthic chambers sampling for gas exchange with the sediments (images courtesy of the QICS project).

CO_2 rich plume, no one detection method could be recommended as sufficient. Biological responses to a CO_2 release of this scale were shown to be both spatially restricted and temporary. Highlight results are summarised in Blackford et al. (2014) whilst a dedicated special issue (International Journal of Greenhouse Gas Control, vol. 38) details the range of biogeochemical and modelling development undertaken during the project.

3.2. ETI MMV (Energy Technologies Institute Measurement, Monitoring and Verification of CO_2 Storage)

The UK Energy Technology Institute led the ETI MMV project which started in February 2014 and successfully completed by February 2018. The involvement of technology providers like Fugro and Sonardyne in the project was part of a wider strategy to ensure that there was a commercially available monitoring service to support the White Rose and Peterhead projects that were in development as part of the UK carbon capture and storage competition at the time. As such very little has been published from the results of the ETI's work in this area as it was conducted with a commercial rather than academic aim. The project premise was that there are existing technology components which can detect CO_2 in a marine environment, but there are no integrated, cost-effective and commercially available systems which can reliably record and report CO_2 anomalies in the sea above a large CO_2 storage site as required by legislation such as the European Union's directive on CO_2 storage.

Current research and evidence shows that leakage is unlikely if a storage site is selected and managed according to industry standards and regulations. However, if CO_2 did escape, it would be difficult to predict with certainty where it would reach the seabed. Subsurface and in-well monitoring data may indicate a region where an emission would likely occur, however, areal marine monitoring would be required to locate the emissions. This is where mobile Autonomous Underwater Vehicles (AUV) are very useful, patrolling over large areas at relatively low cost. Higher risk areas, such as the injection point, might require constant monitoring from landers equipped with chemical and acoustic sensors, in addition to other MMV technologies like standard continuous pressure monitoring of the injection well tubing and annuli (Dean and Tucker, 2017).

The scope of the project included three phases (each one year long): Phase one was dedicated to the design of a concept of operations for an integrated, operational marine CO_2 monitoring system using state-of-the-art marine monitoring technologies (Fig. 3). The second phase covered factory acceptance testing of the subsystems and planning of the harbour and sea trials. The final phase included the harbour and sea trials which tested the integrated system with controlled release experiments in representative marine environments.

Prototype landers and AUV mounted sensors were benchmarked with controlled release trials in Portland Harbour, UK and the North Sea offshore Bridlington, UK. Side Scan Sonar (SSS) and chemical sensors were deployed on a long-range AUV provided by the National Oceanography Centre (NOC). Leakages were successfully detected and located with the SSS on the AUV and the active sonar lander system. The other two less mature lander sensors (chemical and passive acoustic) were also capable of detecting small leaks of 10−50 litres per minute at ranges of around 60 m. The future performance envelope of the passive acoustic sensing is unknown, and may well significantly exceed these levels, as early modelling indicated it should. The chemical sensor suite has not proven as sensitive as the sonar to small leak signatures, but still provides the essential role of establishing a wide area chemical 'baseline' and the potential to sense much larger leaks outside the view of the sonar. It also provides the possibility to classify leaks as a CO_2 emission provided the AUV carrying the sensors can be flown sufficiently close to the leak identified by the sonar. Based on the results of the Sea Acceptance Trial (SAT), the altitude of this fly-past may have to be significantly lower than the 7 m altitude tested in this experiment.

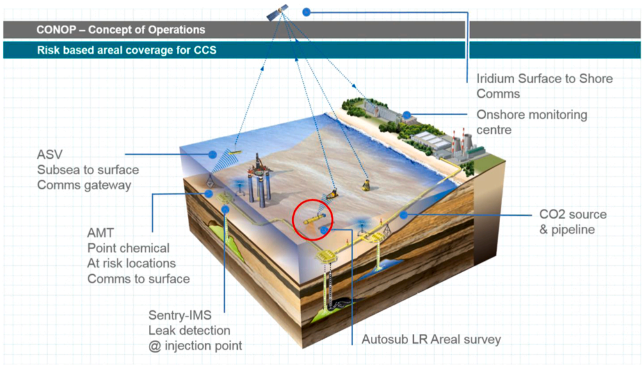


Fig. 3. The ETI MMV Concept of Operations: An integrated cost-effective operational system for offshore CO_2 storage (image courtesy of the ETI MMV project).

3.2.1. Acoustic sensors

Actively illuminating the plume (e.g. deploying active acoustic methods with sources) gives the advantage of being able to operate in the higher noise areas that may be expected around injection sites or for vehicle mounting, but this comes at the cost of increased complexity, power consumption and price. The concept of operations indicated that the injection point, and any other noisy, high risk area would have continuous monitoring from an active acoustic system. In the ETI MMV project, the Sonardyne Sentry sonar was chosen and results from the active acoustic lander tested in Portland Harbour are shown in Figs. 4 and 5. The lander-to-leak range was fixed for the five-week trial at 110 m and demonstrated on multiple occasions the successful detection of a 10 L/min leak. In quieter background scenarios passive systems can be used. These do not suffer from the disadvantages of active systems and, by integrating the signal from a leak source over several minutes, the signal to noise ratio can give effective detection ranges in excess of active systems.

In addition, as another element of a marine environmental monitoring plan, wide area periodic surveys by an active side scan sonar mounted on an autonomous underwater vehicle (AUV) was trialled. Testing of this concept gave high quality pictures of leaks with example imagery seen in Fig. 6. High risk areas away from noise sources (such as abandoned wells, old infrastructure, pockmarks and faults) could be monitored by a passive sonar (Fig. 6, right), which benefits from the reduced maintenance overheads of an active array.

3.2.2. Chemical sensors

The chemical sensors used were based on the patented lab on chip systems (LOC) developed over many years at the UK National Oceanography Centre (NOC) in addition to commercially available sensors like Satlantic SeapHox and SeaFET. These LOC systems employ standard wet chemical techniques on a miniaturised chip, with onboard calibration processes. The LOC systems used were for nutrients, nitrate and phosphate (Beaton et al., 2012; Grand et al., 2017; Clinton-Bailey et al., 2017) alongside a high sensitivity pH sensor (Rérolle et al., 2013).

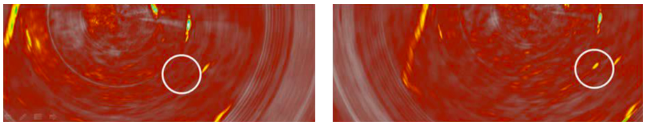
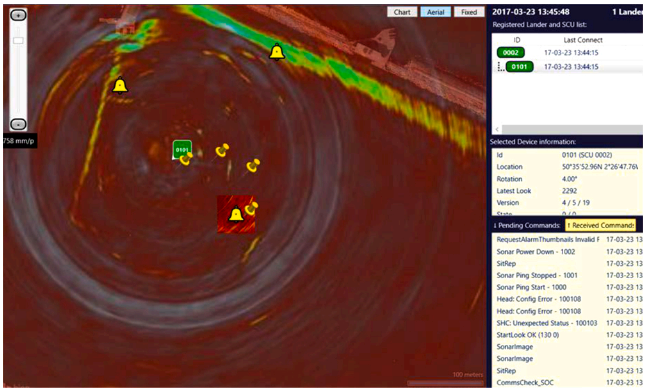


Fig. 4. The Active sonar processed imagery before (left) and after (right) the start of a 10 L/min carbon dioxide leak, 110 m from the Lander. Position of leak is circled.



2017-03-23 13:45:48

Registered Lander and SCU list:

ID	Last Connect
0002	17-03-23 13:44:15
0101	17-03-23 13:44:15

Selected Device information:

Id	0101 (SCU 0002)
Location	50°35'52.96N 2°26'47.76
Rotation	4.00°
Latest Look	2292
Version	4 / 5 / 19

↓ Pending Commands: ↑ Received Commands

RequestAlarmThumbnails Invalid F	17-03-23 13
Sonar Power Down - 1002	17-03-23 13
SitRep	17-03-23 13
Sonar Ping Stopped - 1001	17-03-23 13
Sonar Ping Start - 1000	17-03-23 13
Head: Config Error - 100108	17-03-23 13
Head: Config Error - 100108	17-03-23 13
SHC: Unexpected Status - 100103	17-03-23 13
StartLook OK (130 0)	17-03-23 13
SonarImage	17-03-23 13
SonarImage	17-03-23 13
SitRep	17-03-23 13
CommsCheck_SOC	17-03-23 13

Fig. 5. The view of the Lander Control Application showing a 10 L/min leak alarm with overlaid 'snippet' as seen in Fig. 4 (right). The pin positions show locations of the Landers and Buoy which was used to transfer data to the onshore monitoring facility. The two alarms on the breakwater are false alarms. Images courtesy of the ETI MMV project.

3.2.3. Platforms

Autonomous underwater vehicles

The mobile platform used was the Autosub Long Range (ALR) developed at NOC, building on many years of engineering development in the field of AUV technology. The ALR has a range of >1000 km or a three-month deployment time, depending on sensors used and types of operation selected. The ALR operates using a pre-programed survey pattern and can be deployed from either shoreside in a dock area, or from a vessel using a Launch and Recovery (LAR) system.

Landers

Two landers were designed and tested, one with an active sonar and one with a passive array and chemical sensors (see Fig. 7). The sensor heads were located at the correct position for operation without interference and to provide them with sufficient power for the planned deployment. The chassis design must also face more practical challenges such as ensuring it can survive in the environment above a CO_2 storage site and that it can easily be stored and deployed from a vessel.

Data transmission, management, analysis and display

There were several communications challenges related to the return of data from the point of collection to the decision makers (i.e. MMV operator). Firstly, as the information will be gathered at depth it needs to reach the surface for onward relay. This is most simply addressed in an AUV conducting a wide area survey where required surfacing gives an opportunity to make a GPS position fix and data upload. While this does take away from time on task the penalty is small in the reasonably shallow waters of the North Sea. For the seabed landers a surface relay station is needed with an acoustic data link. The use of buoys or an Unmanned Surface Vehicle (USV), which would conduct a data harvest of several locations, was examined by the project. A USV harvest can be the most cost-effective option for a field scenario with several locations in deep water, where buoy moorings would be costly, but naturally comes at a penalty of not providing constant surveillance. In the ETI MMV project, a buoy was successfully demonstrated as a surface gateway unit.

Field to shore transmission is only practical and reliable at the required bandwidth via satellite communications, resulting in higher costs, especially if providing constant monitoring for high resolution data. This drives the requirement for onboard processing of data from both lander and AUV units to automatically identify targets and transmit only the relevant data for expert interpretation. This capability and working method was one of the key ground-breaking advances made in

Fig. 7. Left: The active sonar lander prior to deployment on harbour trials in 2017, the red canister is the communications module for transmitting data to the surface unit. Right: The passive sonar/chemical lander prior to deployment on harbour trials in 2017. The passive acoustic array is seen on top of the lander and the chemical sensors are mounted below. Images courtesy of the ETI MMV project.

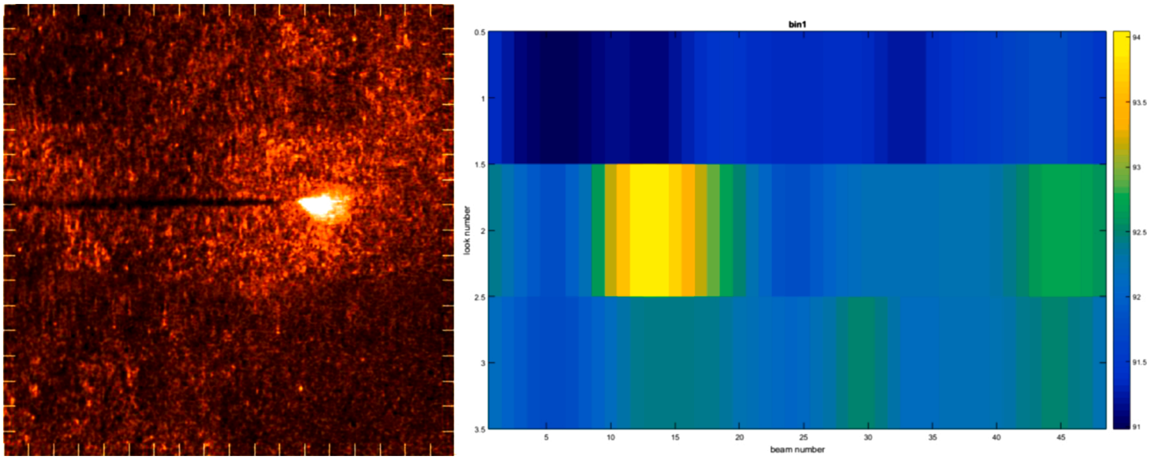


Fig. 6. Left: 18 m × 18 m image of a controlled CO_2 release (50 L/min) taken by an AUV mounted solstice side scan sonar using Multipath Suppression Array Technology (MSAT) to improve contrast. The image shows the CO_2 plume and associated acoustic shadow (black line) which was detected automatically. Right: Passive acoustic sensor results. Top row shows no leak, middle row 30 L/min and bottom row a 10 L/min leak detected from 60 m distance. Images courtesy of the ETI MMV project.

this project. The integration of the data streams allowed congruent data collection which is especially important when data is collected on AUV systems where issues around frequency of sampling must be overcome.

The amount of data produced by the seabed monitoring systems is very high. For example, the lander holding passive sonar and chemical sensors can generate 4GB (gigabytes) of data per day and the active sonar lander 21GB. The project applied onboard processing and target recognition algorithms and as a result turned this data into alert messages of 15KB/day and 400KB/day respectively. This reduced the cost of transmitting data to shore for analysis and increased the service life of the field units as it reduced the amount of power required to transmit large packets of data. If an alert was received the human-in-the-loop could then request further data and analyse the veracity of the detection from a focused data set. The AUV mounted sensors would similarly produce gigabytes of data per day. Using the same concept of data packaging, an AUV can transmit 20KB of survey and system information, with approximately 12 surfacings per day. Following a completed survey area, the AUV can then be re-tasked by an operator to investigate the targets identified of the highest concern.

Data can be easily integrated and displayed through several GIS (Geographic Information System) packages. For the ETI MMV project Fugro’s Metis system was selected as it provided a maritime focussed user interface with close project support from an involved partner.

These ETI MMV trials demonstrated the capabilities of an integrated marine CO_2 monitoring system made with commercially available components which could provide this service at an acceptable Technology Readiness Level (TRL). The expectation at the time was that the TRL would be progressed with successive deployments at industrial scale CO_2 injection operations. Unfortunately, this opportunity has not yet been realised, in part because both the White Rose and Peterhead CCS projects were cancelled when the UK government withdrew its funding for the CCS competition in 2015.

3.3. *STEMM-CCS (Strategies for environmental monitoring of marine carbon capture and storage)*

In February 2020, the STEMM-CCS completed its four-year project including a very successful sea trial near the CO_2 storage site of the former Peterhead CCS project. Drawing together expertise from across academia and industry, STEMM-CCS has benchmarked a set of tools, techniques and methods to support safe and efficient geologic CO_2 storage in the marine environment. Many of the activities led to the development or enhancement of sensing technologies, which also have applications beyond the CCS arena and may be suitable for commercialisation. Throughout the project there was a high level of engagement with policy makers and stakeholders to ensure the widest possible exchange of knowledge, including with countries outside Europe that are currently developing offshore CCS.

The aim of the project was to deliver a marine CCS demonstration level ecological baseline, i.e. comprehensively characterise the marine environment above a CO_2 storage site to enable leakage detection and impact assessment, and to test existing technologies in a realistic environment (Fig. 8). For example, an autonomous underwater vehicle (here the commercially available Gavia system from Teledyne) and a remotely operated underwater vehicle (ROV) for leakage attribution were tested. Another focus area was to progress leakage modelling capabilities and chemical lab on chip (LOC) sensors, as well as further developing the understanding of near-surface leakage paths due to geological features such as chimneys and pipes. In addition, innovative technologies for leakage quantification were tested like a marine eddy covariance system and machine learning for automated marine species recognition.

To collect baseline data, the project purchased a lander from Develogic in Germany which was deployed in October 2017 ahead of the main experimental phase of the project in May/June 2019. The design of the lander had pop-up beacons that would collect a sub-set of the data from the sensors and then be released to transmit the data via the Iridium telecommunications network. The landers had sensors for nutrients and pH and was augmented with hydrophones for measuring noise in the North Sea. Following further development between the ETI MMV and the STEMM-CCS projects, the suite of LOC sensors had been increased and the pH, and nutrient sensors were augmented with a newly developed TA (Total Alkalinity) sensor, besides the commercially available ISFET pH sensor.

The benchmarking of these technologies with a controlled release experiment near the Goldeneye platform (the CO_2 storage location of the former Peterhead CCS project) allowed the project to further reduce the uncertainties around detection, location, quantification and attribution of CO_2 leaks. The use of natural and artificial tracers in combination with direct measurement of the released gas were successfully demonstrated for quantification. Combining inert tracers with the reactive CO_2 allowed the determination of the proportion of CO_2 that had remained in the sediment, dissolved in the pore waters in the sediment or escaped to the overlying seawater. Whilst it has been shown that using artificial tracers for commercial scale CCS operations could be potentially expensive (Roberts et al., 2017), the project was able to test their efficacy in this small-scale experiment. In addition to added artificial tracers, the isotopic composition of the added CO_2 was used to trace its pathway from release to the seawater column, offering up evidence for such approaches in large scale CCS operations (Flohr et al., 2020). Using a bespoke advanced gas control system, the project was able to modify the flow of gas to simulate emissions at 2−50 L/min (4−200 g/min) well below suggested regulatory limits of 1 % of reservoir capacity loss in 100

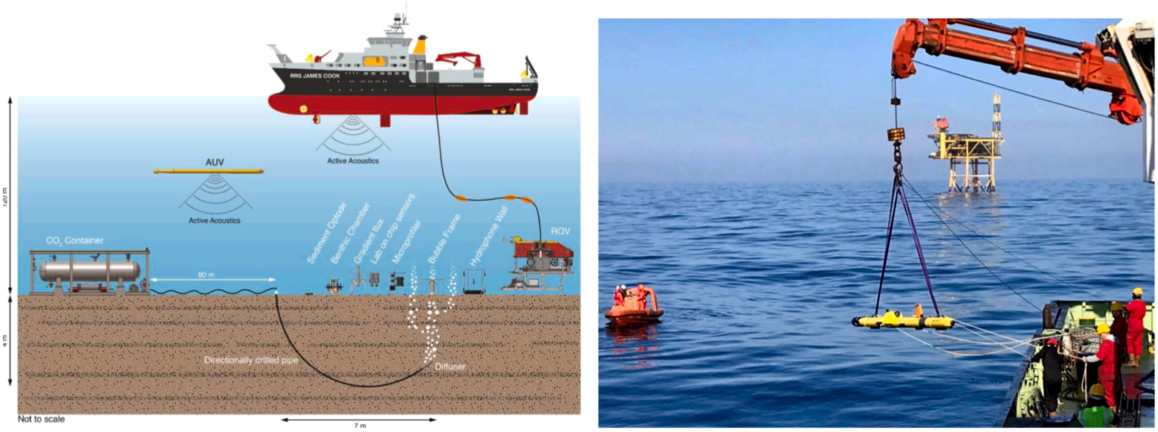


Fig. 8. Left: Schematic of the STEMM-CCS controlled CO_2 release experiment (image courtesy of the STEMM-CCS project). Right: Deploying the Teledyne Gavia AUV near the Goldeneye platform (image courtesy of Christopher Pearce, National Oceanography Centre).

years of a small (10 Mt) reservoir. The individual sensors developed as part of this project have demonstrated a high level of sensitivity and precision giving confidence that even very small leaks can be detected and quantified. The lab on chip sensors will be commercially available in the near future through a new company arising from the research and development at NOC.

4. *Marine modelling to supplement monitoring*

Whilst the development and testing of mobile and fixed platforms, sensors and data retrieval systems is crucial, there are at least two further requirements for effective monitoring offshore geologic CO_2 storage sites. The first is a requirement to understand the most efficient strategy of deployment in order to achieve desired assurance or detection efficacy, whilst minimising cost. Given that a leak location is a-priori unknown, reservoir complexes can have a horizontal footprint of several hundred square kilometres and leak signals may be small, monitoring requires a “smart” approach. Such an intelligent approach will likely be based on site-specific risks (i.e. potential overburden leakage paths, pockmarks, abandoned wells, etc.) and leakage modelling. Secondly, again given that leak signals may be small, especially if the sensor is not adjacent to a leak and that there is considerable spatial and temporal natural variability of CO_2 and its measurable parameters in the marine system, it is crucial to understand which signals indicate real anomalies and to minimise the chance of detecting false positives. Marine simulation models can help distinguish between signals caused by real leakage and natural variation.

Although the experimental releases undertaken during the QICS, ETI MMV and STEMM-CCS projects provide crucial evidence of how CO_2 releases manifest in the marine environment, they are restricted to specific locations, limited time frames and small volumes of CO_2. Further, data to adequately characterise natural variability of CO_2 parameters is sparse, especially at the sea floor and at the high spatial and temporal resolutions necessary to identify the small scale and changing footprint arising from leakage. However, simulation models provide an ability to detail spatial-temporal CO_2 baselines and simulate diverse scenarios of leakage and have been developed and applied as part of all three projects (Blackford et al., 2019).

Marine hydrodynamic (3D) biogeochemical models are ubiquitous research tools used for many applications and often include descriptions of carbonate (CO_2) chemistry and the bio-physical processes that influence the carbonate system. Hence with minimal development and suitable evaluation against real-world data these models can produce high frequency representative time series of observable parameters such as pH and pCO_2, and co-variables such as O_2 and nutrients, potentially at intervals of a few minutes over seasonal and decadal time scales (Artioli et al., 2012; Blackford et al., 2017). Spatial resolution varies according to the model and generally lies in the range of 1−10 km in the horizontal and 1−10 m in the vertical in shelf sea regions. The key outcome from these synthetic characterisations of natural variability is the understanding that simple thresholds have little chance of providing suitable anomaly criteria and that criteria may have to be seasonally and spatially bespoke (Blackford et al., 2015).

Hydrodynamic simulation models have also been used to investigate a wide range of leakage scenarios, using diverse model platforms (Blackford et al., 2013; Dewar et al., 2013, 2015; Phelps et al., 2015; Ali et al., 2016). In particular high-resolution systems such as the FVCOM (Finite Volume Community Ocean Model) tool allow for realistic simulations of plume dispersion and demonstrate that plumes are often advected back and forth under the influence of tidal flow. From this suite of model systems an understanding of potential impact footprint relative to leak rate can be derived, as well as an indication of the signals of leakage that appropriately placed or mobile sensors would be exposed to (Cazenave et al., 2019). Combining knowledge of leakage signals and natural variability enables the identification and crucially the assessment of anomaly criteria.

5. *Collective recommendations*

Environmental monitoring strategy for a CO_2 storage site should be closely linked to a subsurface containment risk-assessment investigating all potential site-specific leakage paths. This would be the premise for a comprehensive risk-based Measurement, Monitoring & Verification (MMV) plan which besides well and subsurface technologies includes environmental monitoring elements based on the assessed leakage risks, where the number and frequency of technologies deployed is proportional to the quality of barriers in place (e.g. number of subsurface seals, additional storage units, quality of plugs in abandoned wells, etc.) and the severity of potential impacts. It is important to remember that CO_2 storage projects rely on in-well (e.g. pressure and temperature) and subsurface monitoring data to identify a potential leakage event long before it reaches the overburden, seabed or overlying ocean. Should an unexpected subsurface migration occur, MMV data would trigger contingency monitoring and corrective measures which would rely on marine monitoring technologies and modelling techniques discussed in this paper. An environmental monitoring programme therefore needs to be designed holistically with the subsurface and wells in mind. Finally, to enable operational or contingency environmental monitoring, pre-injection or baseline data must be acquired. In some instances, environmental impact and site selection activities may generate sufficient data for this purpose.

The selection of suitable marine monitoring technologies will depend on the site-specific risks. Higher risk areas such as active pockmarks, poorly abandoned wells and injection wells may all be selected for continuous monitoring using landers equipped with chemical sensors (pH and pCO_2, O_2 and nutrients and salinity) and either passive acoustic (quiet areas) or active acoustic (noisy areas) sensors. This may be supplemented with AUVs performing aerial surveys using side scan sonar and or chemical sensors, over the CO_2 plume footprint at the seabed, potentially combined with routine pipeline inspection surveys. ROVs may be used for gas bubble detection using video, also potentially combined with routine platform inspection activities. Once bubble streams are detected, chemical analysis will be performed (including tracer analysis) for leakage attribution, followed by quantification of emissions and environmental impact assessment if warranted.

In addition to active acoustic bubble detection to identify leakage from a CO_2 storage site, two other criteria have emerged from the QICS/ETI-MMV/STEMM-CCS projects. The first, e.g. C_{SEEP}, (Omar et al., 2018) is based on recognising departures from natural stoichiometric relationships, while the second is based on marine hydrodynamic modelling and depends on observing gradients of change, steeper than those occurring naturally (Blackford et al., 2017). Tracers have been demonstrated to be useful for leakage attribution and important progress was made in leakage quantification using passive acoustic methods and eddy covariance systems.

Finally, work is beginning to address optimal deployment strategies for the minimum number of sensors or most efficient vehicle trajectory, for detection (Alendal et al., 2017; Alendal, 2017; Hvidevold et al., 2015; Gundersen et al., 2019), location and quantification (Oleynik et al., 2019) of leaks.

6. Conclusions and future work

Site selection, characterisation and engineering designs are considered the prime means of ensuring confidence in the long-term security of a CO_2 storage site. CO_2 storage operators deploy risk-based monitoring plans to deliver the data needed to verify the site is performing as expected and to enable emission quantification and impact assessment in the unlikely loss of containment scenario. This paper focuses on the marine monitoring element of such as an MMV plan and summarises the insights from projects that aspired to fill recognised technology gaps in the last decade.

The collective advances made by the QICS, ETI-MMV, and STEMM-

CCS projects resulted in increased capabilities for acquiring marine environmental baseline surveys and monitoring of high-risk seabed features. The technologies were tested with controlled release experiments which gives confidence that unexpected emissions to the environment can be detected and characterised in a timely and cost-efficient manner to limit escalation of unintended consequences. Whilst the models deployed have significantly improved our knowledge of monitoring strategies, many of these model systems are computationally expensive and in the lower half of application readiness scales. For these model tools to become generically useful requires the development of digital toolboxes of open-source software with high transferability between sites. Completion of these model enabled contributions requires the development of fast emulators that will allow large model ensembles and the application of machine learning and other techniques to identify bespoke costed monitoring strategies. The increasing use of autonomy (Wynn et al., 2014), combined with some of the technologies (chemical sensors, acoustics etc.) demonstrated through the projects discussed herein, offers a route to decrease the cost of offshore monitoring. In the near future we will be able to use AUV technology, probably launched from land, to perform offshore surveys over long periods of time which will support increased public confidence that we are able to detect leakage and enact mitigation strategies if needed.

Remaining challenges related to CCS deployment at large scale include not just the cost of monitoring large areas over long periods, made possible through autonomy, but making real-time decisions based on big data while minimising missed and false alerts. Future work should include integration of marine monitoring data with other MMV data (such as in-well temperature and pressure data) and testing of machine/deep learning methods to automate monitoring data processing and interpretation.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ijggc.2020.103120.

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