

Review

# Marine Monitoring for Offshore Geological Carbon Storage—A Review of Strategies, Technologies and Trends

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**Abstract:** Carbon capture and storage (CCS) could significantly contribute to reducing greenhouse gas emissions and reaching international climate goals. In this process, CO<sub>2</sub> is captured and injected into geological formations for permanent storage. The injected plume and its migration within the reservoir is carefully monitored, using geophysical methods. While it is considered unlikely that the injected CO<sub>2</sub> should escape the reservoir and reach the marine environment, marine monitoring is required to verify that there are no indications of leakage, and to detect and quantify leakage if it should occur. Marine monitoring is challenging because of the considerable area to be covered, the limited spatial and temporal extent of a potential leakage event, and the considerable natural variability in the marine environment. In this review, we summarize marine monitoring strategies developed to ensure adequate monitoring of the marine environment without introducing prohibitive costs. We also provide an overview of the many different technologies applicable to different aspects of marine monitoring of geologically stored carbon. Finally, we identify remaining knowledge gaps and indicate expected directions for future research.

**Keywords:** CCS; GCS; CO<sub>2</sub> storage; marine monitoring; monitoring technologies; acoustic sensors; chemical sensors; environmental monitoring



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## 1. Introduction

Carbon capture and storage (CCS) is recognized as a key technology for accelerating global decarbonization and reaching international climate goals as set out in the Paris Agreement [1,2]. The CCS process involves capturing CO<sub>2</sub> from energy-intensive industries, such as waste-to-energy plants, cement- and fertilizer production, and fossil fuel combustion, and injecting it into suitable geological formations for permanent geological carbon storage (GCS) instead of releasing it into the atmosphere. A significant portion of the global storage potential lies in off-shore geological formations along continental shelves [3]. The ongoing Sleipner project was the world's first industrial-scale offshore CO<sub>2</sub> storage project, with more than 16 Mt CO<sub>2</sub> injected since 1996 [4]. Since then, commercial implementation of CCS has gradually increased, and as of 2019, 26 CCS facilities are in operation and 33 sites are under development [5]. Once injected into a properly selected geological storage formation, the risk of CO<sub>2</sub> escaping the reservoir and entering the overburden and ultimately the marine environment is considered low [6]. Multiple natural barriers, including at least one non-permeable caprock layer and natural sealing processes, are expected to ensure that the injected CO<sub>2</sub> stays in place. Still, monitoring is required to verify long-term storage, and to detect and quantify leakage if it should occur [2]. Primary monitoring methods for offshore CO<sub>2</sub> storage include in-well measurements of pressure and temperature, and seismic imaging targeting the reservoir and overburden [4,7,8]. The spatial extent and evolution of the CO<sub>2</sub> plume inside the reservoir can be mapped using time lapse seismics, as demonstrated for the Sleipner site [4]. However, the limited sensitivity and accuracy of seismic methods implies that small- to medium-sized leaks may pass undetected [9]. Marine monitoring of the seabed and water column above the storage reservoir is therefore

recommended as a complementary monitoring method, intended to ensure that there are no indications of CO<sub>2</sub> reaching and potentially harming the marine environment.

Monitoring the marine environment for indications of CO<sub>2</sub> leakage or to verify a lack thereof, is a challenging task for several reasons. Firstly, the marine environment is highly inhomogeneous and subject to significant spatial and temporal variability, making it difficult to differentiate between natural processes and potential leakage. Direct indications of leakage include CO<sub>2</sub> bubbles emitted from the seabed, and locally elevated levels of dissolved CO<sub>2</sub> in the water column. Features on the seabed, such as pockmarks, bacterial mats and local depression or upheaval, may also indicate fluid flow. However, naturally occurring bubble seepage, fluctuations in seawater CO<sub>2</sub> levels, and the presence of fluid flow related features on the seabed are all common in the marine environment, and their presence is sparsely mapped. Leak scenarios established through models and supported by controlled CO<sub>2</sub> release experiments suggest that the flux and spatial footprint of expected leak-related anomalies are well within the natural variability in the marine environment. Another challenge that a marine monitoring program needs to address is that the area to be monitored is potentially very large, in the order of tens to hundreds of square kilometers, while experience from controlled CO<sub>2</sub> release experiments, natural leakage analogues, and simulations of hypothetical leak scenarios suggest that the spatial footprint of a leak is limited to a few tens of meters [10]. Considering these challenges, meaningful marine monitoring of an offshore CO<sub>2</sub> storage site involves several key components:

- **Understanding the marine environment and recognizing anomalies.** Given the significant natural variability in the marine environment, detecting and reliably attributing an anomaly related to an ongoing GCS project without introducing false alarms requires a strong understanding of the marine environment. Observational data are limited, and advanced ocean models, therefore, play a significant role in marine monitoring, coupled with accurate simulation of potential leakage scenarios.
- **Selecting and combining sensors and platforms** to detect, attribute and quantify potential leakage, and conversely, to document the lack thereof. This includes sensors capable of detecting and characterizing different aspects of potential leakage, such as bubble seeps, chemical changes in the water column, and features in the marine environment, such as pockmarks, bacterial mats or gas-saturated sediments. Platforms on which these sensors may be mounted include surface vessels/ships, AUVs, gliders, and stationary templates. A strategy for how to use and combine these technologies should ensure adequate and practically/economically feasible monitoring.
- **Extracting key information.** Depending on the monitoring strategy, the amount of data quickly becomes unmanageable and human interpretation impractical. Dedicated data analysis is required to extract key information from significant and diverse data sets. Machine learning may play a significant role in differentiating between natural variability and potential leakage.

Regulations for marine monitoring of offshore CCS are set out in the CCS directive [2] from 2009, and were revised in 2015. These regulations define a minimum of required marine monitoring, but they do not specify the details of how to establish a meaningful monitoring program. While member states are required to report to the European Commission on the implementation of the directive every four years, there is no provision for continuous updates of the CCS directive. Consequently, the monitoring requirements may not be sufficiently up to date and reflective of recent technological advancements.

In this review, we condense recommendations and knowledge about marine GCS monitoring obtained through several research projects and many years of commercial CCS operations. Recommended strategies for marine monitoring are generally well aligned between the research projects considered here (ECO2, QICS, STEMM-CCS, ACT4storgae, ETI-MMV), and key components of these are described in Section 2. It is worth noting that these projects have had significant industry participation, indicating that the recommendations are aligned with industry perspectives.

In Section 3, we provide an overview of the most relevant technologies for marine GCS monitoring, including which sensors are applicable to different monitoring tasks, and the variety of platforms (ships, autonomous underwater vehicles (AUVs), stationary monitoring stations) that these sensors may be mounted on, depending on monitoring needs. Finally, we identify knowledge gaps and indicate future directions of research in Section 4.

## 2. Strategies for Marine GCS Monitoring

A number of research projects have addressed strategies for marine GCS monitoring, providing guidance about how to monitor the marine environment in sufficient detail without prohibitive costs [4,7,11–15]. Considering that the probability of leakage from a well-planned CO<sub>2</sub> storage site is considered low [5,6], it is generally not necessary or economically sound to monitor the entire region in detail over an extended period of time. A meaningful strategy combines sparse mapping of regions where there are no identified risk zones, with more resource-intensive monitoring either near risk structures, such as infrastructure (wells) and natural migration paths (faults, channels, pockmarks), or triggered by observations, such as deviations between models and measurements. In this section, we condense the recommendations provided by five major research projects carried out between 2011 and 2019; QICS, ECO2, ETI-MMV, ACT4storage, and STEMM-CCS. While there are slight variations in the viewpoints presented through these projects, the high-level recommendations for marine monitoring strategies are very much aligned.

### 2.1. Cite Characterization—Understanding the Baseline

All evaluated projects highlight the importance of obtaining a strong baseline, sometimes also referred to as site characterization, prior to injection of CO<sub>2</sub>. The motivation for cite characterization is to obtain an understanding of the marine environment in the area, including natural variability. A strong understanding of the marine environment and its variability, both spatially and over considerable time scales, makes it easier to identify anomalies potentially related to CO<sub>2</sub> leakage. Further, these insights can prevent falsely attributing naturally occurring events to the ongoing CCS project. While there is agreement about the benefits of obtaining a strong baseline, there are different viewpoints related to the required level of detail as well as the timeline for building the baseline. Hypothetical leakage scenarios span from integrity issues with the injection well resulting in immediate leakage, to gradual migration of CO<sub>2</sub> from the reservoir along a geological risk structure, which would take several years to reach the marine environment [16]. Thus, the characteristics of a leak, including the delay from injection until an anomaly may be detectable in the marine environment, is complex and related to the geological conditions in the area as well as the presence and state of the infrastructure. In [12], the authors provide an overview of monitoring methodologies and recommended spatial and temporal sampling criteria for a baseline study. The specific requirements for a baseline study are related to a site-specific risk assessment, including potential risk structures and associated hypothetical leakage scenarios.

### 2.2. Using a Risk-Based Approach

A risk-based approach is recommended to focus monitoring efforts where they are most needed. Three-dimensional seismic data, either acquired as part of the site characterization of the reservoir or available from previous exploration activity, are used in the risk analysis to identify potential natural risk features, such as chimney structures, faults intersecting the reservoir, and subsurface channels. Marine surveys may reveal indications of past or ongoing fluid flow at the seabed, such as pockmarks, bacterial mats, or gas seepage. Additional risk structures include infrastructure—in particular, legacy wells. An initial risk analysis is intended to identify these structures and evaluate the risk of leakage as well as estimate the resulting environmental impact. Subsurface and ocean models combined with simulations of potential leakage scenarios may be used to predict the envi-

ronmental impact related to identified risk structures. The risk analysis is a cyclic process, with new knowledge continuously being taken into account to adjust the current risk level. At CCS sites with no significant risk structures, resource-intensive marine monitoring may be recommended only as part of a contingency plan, to be triggered if an anomaly is encountered in, for example, seismic time-lapse data or in-well pressure measurements. In cases where risk structures are present, dedicated marine monitoring may be necessary to verify that there is no leakage through these structures, and to ensure that potential leakage is promptly detected such that corrective actions may be taken. The bowtie method, based on the barrier approach to risk management [11,17], provides a framework for a systematic risk assessment, including identifying risks and proposing proportional monitoring efforts. Figure 1 illustrates a risk-based approach to marine GCS monitoring, where an initial monitoring scope is set based on available information and an initial risk assessment, and is continuously re-evaluated as new information becomes available.



**Figure 1.** In a risk-based and flexible GCS monitoring strategy, an initial monitoring scope is based on available information, and adjusted continuously as new information becomes available.

### 2.3. A Site-Specific and Flexible Marine Monitoring Program

The marine monitoring program should be tailored to the specifics of the location and, in particular, related to a site-specific risk analysis. The monitoring program should also be designed to adapt to changes in the risk level, for example, initiated by anomalous measurements (increased risk level), or added confidence in storage containment (reduced risk level). Additional factors that may influence the optimal approach to marine monitoring include the available infrastructure, water depth and ocean currents, and characteristics of the overburden. If shallow risk structures are identified in the overburden, a marine monitoring program can be designed to detect potential precursors of leakage based on expected changes in sediment or seawater geochemistry. The number of wells and the state that they are in will affect the need for detailed and potentially continuous monitoring. Finally, relevant data already available from the site, such as previous seismic surveys, bathymetry maps, and sediment and water samples, should be used as part of the site characterization process.

## 3. Overview of Marine Monitoring Technologies

Because of the complexity of the marine environment and the range of processes potentially indicative of CO<sub>2</sub> leakage (gas bubbles in the water or sediments, excess levels of dissolved CO<sub>2</sub> in the water column and related geochemical disturbances, excess fluid flow, etc), there are a variety of sensor technologies that are applicable to marine GCS monitoring. Generally, a combination of several sensor technologies is required to adequately

describe the marine environment and detect or document the lack of potential leak-related anomalies. The two most widely used classes of technologies for marine GCS monitoring are acoustic sensors (aimed at detecting bubbles in the water column, mapping the seabed, and providing quantitative estimates of bubble emissions), and chemical sensors (aimed at detecting and characterizing chemical anomalies in sea water, and establishing baseline chemical seawater conditions). These may be complemented by additional sensors, such as CTDs, ocean current meters, and optical and turbidity sensors, for more complete mapping of the ocean environment.

Selecting an appropriate combination of technologies to be used in a site-specific monitoring campaign is non-trivial. A recurring challenge is how to achieve the required area coverage with satisfactory spatial and temporal resolution, and without prohibitive costs. On the one hand, in many cases, the large area to be covered suggests the use of survey vessels or autonomous underwater vehicles (AUVs) to achieve the required area coverage rates. On the other hand, the spatial footprint as well as the temporal duration of leakage events is expected to be limited (in the order of tens of meters and hours to days in duration [10]), requiring more focused and sometimes long-term monitoring to capture these events. Table 1 summarizes different potential monitoring objectives and corresponding sensors and platforms that may be used to reach these objectives. These technologies and their capabilities for marine GCS monitoring are elaborated on in the remainder of this section.

**Table 1.** Overview of relevant marine GCS monitoring objectives, and sensor technologies and platforms with corresponding capabilities.

Monitoring Objective	Sensor Technology	Platform
Detect bubbles in the water column (single bubbles, seeps or plumes)	MBES, SBES, sidescan sonar, SAS	Survey vessel, AUV, stationary template
Identify seabed features related to fluid flow	MBES, SAS, sidescan sonar	Vessel, AUV
Identify sub-seabed features including shallow gas accumulation	SBP	Survey vessel, AUV
Quantify gas-phase CO <sub>2</sub> emission from seabed	SBES, direct measurement	Survey vessel, stationary template, AUV
Identify anomalous chemical signature in water masses	pCO <sub>2</sub> , pO <sub>2</sub> , pH, CTD, other chemical	Stationary template, glider, AUV, survey vessel
Quantify amount of excess CO <sub>2</sub> in the water masses	pCO <sub>2</sub> , pO <sub>2</sub> , pH, CTD, other chemical	Stationary template, glider, AUV, survey vessel

### 3.1. Acoustic Sensors

Active acoustic sensors (sonars and echo sounders) rely on transmitting sound and using the reflected signal to detect the presence of bubbles in water or sediments, or to map the seabed [18]. Active acoustic sensors are particularly useful for detecting bubbles at a distance (tens to hundreds of meters for modest bubble seepage) because gas-filled bubbles in water are excellent acoustic targets. The detection range depends on the properties of the leak, such as the leak rate and bubble size distribution, as well as the type of acoustic sensor and its properties. Relevant acoustic sensor technologies are described below, and examples of documented system-specific seep detection ranges are provided. While it is common to mount active acoustic sensors on surface vessels or AUVs, they can also be mounted on a stationary platform for long-term monitoring of a region of interest, such as a well or above a geological risk structure [15,19–21].

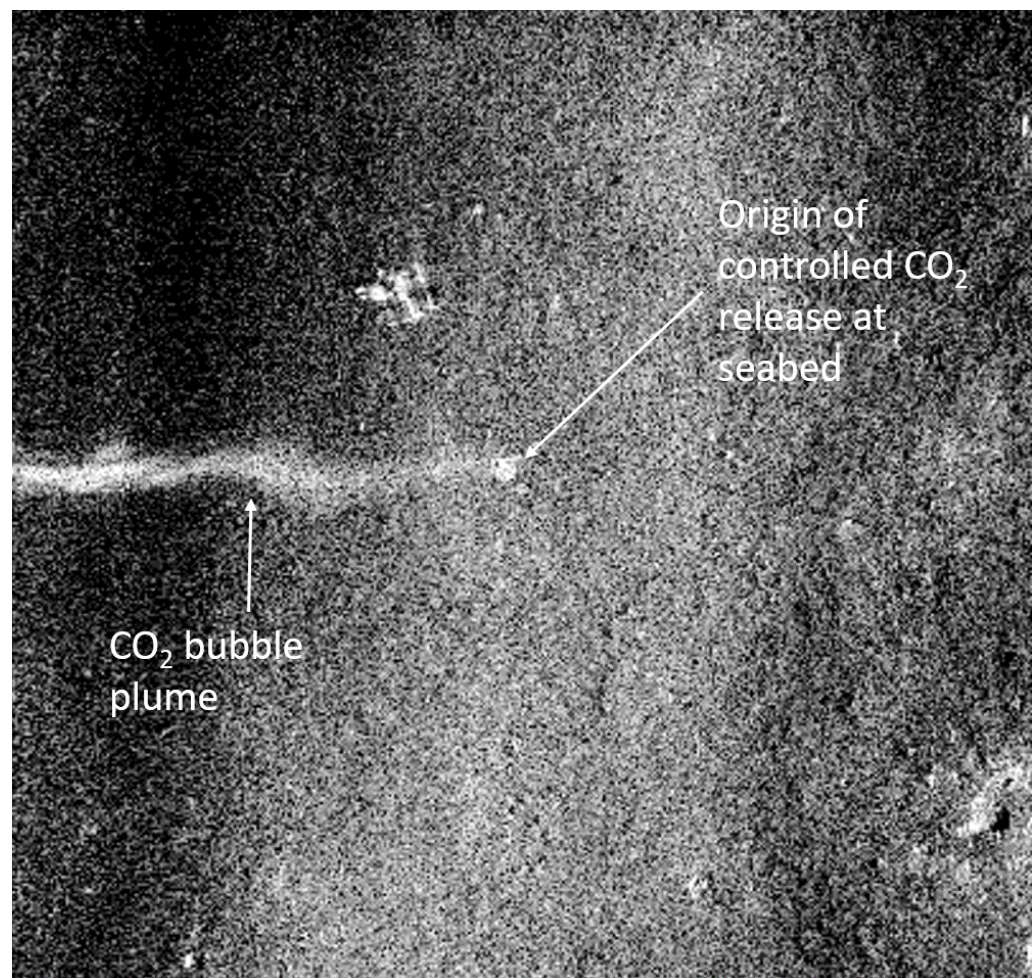
Marine acoustics is a well-explored and mature field, and there are many active acoustic sensors available on the market, ranging from low-frequency sensors with long

range and, in some cases, sediment penetration capabilities [22,23], to high-frequency, high-resolution systems suitable for detailed monitoring at close range [24]. Relevant active acoustic sensors for marine GCS monitoring include single- and split-beam echo sounders (SBES), multibeam echo sounders (MBES), imaging and fish-finding sonars, side scan sonars, and synthetic aperture sonar (SAS). Selecting the appropriate acoustic sensor depends on the monitoring task, in particular, the required range and area coverage rate, the required sensitivity (i.e., detecting single bubbles or larger emissions), and whether or not acoustic quantification is a requirement. For seabed mapping purposes, the required image quality and resolution need to be considered.

Side scan sonars are often mounted on AUVs and used to map the seabed. In the context of marine GCS monitoring, side scan sonars are highly useful tools because they can cover a large area efficiently and detect both bubble seepage in the water column and map the seabed, including features indicative of fluid flow and marine habitats [25–28]. The imaging and bubble-detection range of side scan sonars is system- and site-dependent, with typical ranges in the order of 50 to 200 m. Several publications demonstrate the use of an AUV-mounted side scan sonar to detect bubble seepage of CO<sub>2</sub> and CH<sub>4</sub> at the seabed [26,27]. While there are few studies that quantitatively investigate the detection range and sensitivity of side scan sonars in the context of bubble seepage, a few examples have been published. In [27], a modest amount of CH<sub>4</sub> escaping from an abandoned well is automatically detected at a distance of 110 m range using a side scan sonar operating at a center frequency of 100 kHz. In [26] the authors present an experiment using a dual frequency side scan sonar operating at 300 kHz and 600 kHz. Here, the observed detection limits are in the order of 10–20 m at a leak rate of 1 liter/minute of CO<sub>2</sub>.

SAS systems are based on hardware similar to a side scan sonar but were developed to achieve dramatically improved image resolution independent of range. In recent years, SAS has matured into a powerful tool, providing detailed seabed imagery and bathymetry as well as the ability to detect small-scale seabed features, including bacterial mats [29], in addition to bubble seepage. Example images (Figure 2) obtained during the ACT4storage controlled release experiment [30] show a 1.33 liter/min release of CO<sub>2</sub> bubbles imaged using the HISAS 1030 system mounted on the HUGIN AUV at a ground range (distance as measured along the seabed) of 60 m. Note that the aim of this experiment was not to demonstrate the detection range of the sonar and, thus, larger distances were not evaluated. Both for side scan sonars and SAS systems, the imaging geometry as well as the operating frequency of the system should be considered. Detection ranges and area coverage rates may be increased by utilizing low to medium frequency systems, and allowing the AUV to travel at a significant height above the seabed [15].

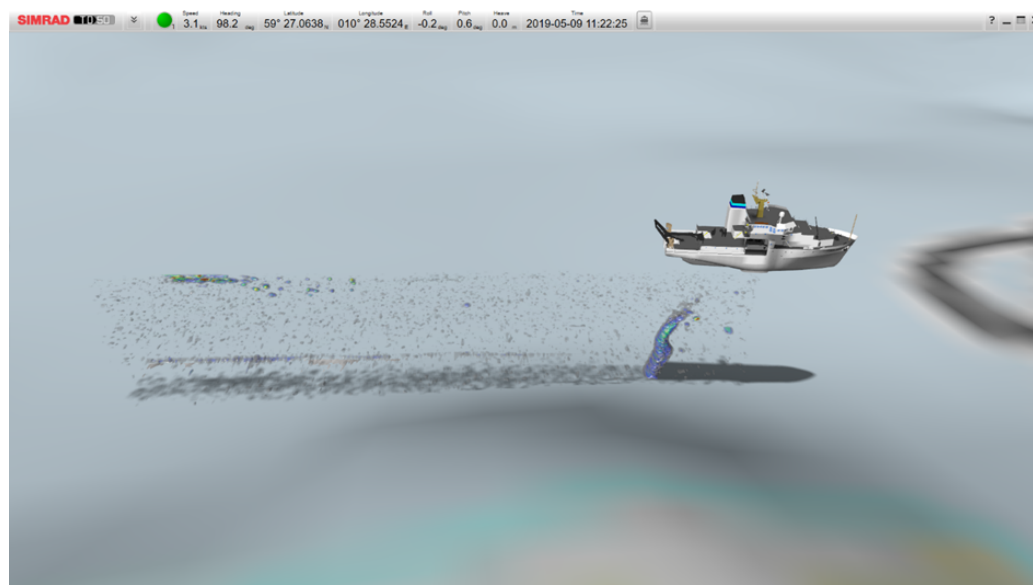
Echo sounders, both single- and multibeam, are traditionally mounted on the hull of a survey vessel and directed downward to map the water column and seabed. As the name suggests, an SBES emits a single acoustic beam and records the intensity of the echo reflected from the seabed and objects or particles in the water column. Single bubbles, bubble trains and bubble plumes are recognized based on their characteristic shape in the echogram [31,32]. Split-beam echo sounders make use of four separate quadrants on reception, which makes it possible to position a target more accurately. More importantly in this context, state-of-the-art split beam echo sounders may be absolutely calibrated, enabling acoustic quantification of bubble seepage [33–35]. MBES systems transmit multiple beams simultaneously, providing significant area coverage, with swath widths up to 140°. As such, vessel-mounted MBES provide a cost-efficient means of mapping a large region of the seabed, while simultaneously detecting the presence of gas seeps in the water column. In [30], small CO<sub>2</sub> bubble releases down to 0.1 liter/minute are consistently detected and visible in the echogram from an EK80 SBES and several MBES systems operating at different frequencies (EM2040, EM712, ME70 and SN90). Figure 3 shows an example image obtained using the Simrad ME70 MBES during the controlled release of 1.3 liters/minute of pure gaseous CO<sub>2</sub>.



**Figure 2.** Example image obtained using the HISAS sonar mounted on the HUGIN AUV during the ACT4storage controlled release experiment. The signature of a 1.3 liter/minute release of gaseous CO<sub>2</sub> can be seen as a high-intensity (white) plume originating at the release point.

A *sub bottom profiler* (SBP), sometimes also referred to as a shallow seismic sensor, is designed to penetrate the upper few meters of sediments (approximately 5–100 m, depending on sediment properties). These sensors either operate at low frequencies, or make use of non-linear propagation to generate a low-frequency pulse that is able to penetrate the seabed. In the context of GCS, SBPs are highly useful because they can reveal shallow risk structures, including shallow gas accumulations and potential migration pathways such as salt diapirs, pockmarks and faults [36,37]. These shallow features in the upper sediments are not easily captured using traditional seismics. Combining seismic imagery of the reservoir and deep geological layers with SBP data of the shallow sediments and acoustic mapping of the seabed and water column makes it possible to capture and interpret features ranging from the reservoir to the sea surface.

*Passive acoustic sensors*, or hydrophones, can be used to detect the presence of bubbles based on their acoustic emissions [18]. Several studies demonstrate the capability to quantify bubble seepage using passive acoustic sensors [38,39], although further studies are encouraged to investigate the accuracy of these estimates. The detection range depends on the background noise level, leak rate, and sensitivity of the sensor. Hydrophones have low power consumption, making them ideal for long-term deployment on stationary monitoring platforms in the vicinity of a risk structure, or on a moving vehicle, such as a glider with limited battery capacity.



**Figure 3.** Data acquisition using the Simrad Echo research vessel during the ACT4storage controlled release experiment. The seep visible in the image is the same as in Figure 2, here detected using the Simrad ME70 MBES. The release rate is 1.3 liters/minute of pure gaseous CO<sub>2</sub>.

### 3.2. Chemical and Oceanographic Sensors

While acoustic sensors are able to detect the presence of bubble seepage and related seabed features, chemical sensors are required to monitor the chemical composition of seawater, and to detect anomalies potentially related to CO<sub>2</sub> leakage. In the event of CO<sub>2</sub> escaping the reservoir and reaching the marine environment, changes in the carbonate chemistry of seawater may be detected as a spatially limited water mass with an anomalously high CO<sub>2</sub> concentration and, as a result, reduced pH. The chemical and spatial characteristics of such plumes may vary depending on the leak scenario and site-specific parameters. Depending on the properties of the upper sediments and overburden, a plume with additional characteristic properties, such as high salt content or the presence of characteristic heavy metals, may be an early indication of a pressure buildup prior to CO<sub>2</sub> leakage [13]. Robust chemical monitoring requires careful planning since the area to be covered is large, while the chemical footprint of a leak-related plume is expected to be small [40]. The trade-off in spatio-temporal resolution and area coverage needs to be carefully considered. While moving vehicles such as an AUV or a glider can provide an overview of an area at limited spatio-temporal resolution, fixed seabed installations can be used for continuous monitoring of a focus area at high temporal resolution. The ability to chemically detect a plume using a moving platform sets demands to the sensitivity of the sensor (i.e., the ability to detect a diluted plume over the background concentration), and is further limited by the dynamic response time of the sensor.

Relevant chemical sensors for marine GCS monitoring include CO<sub>2</sub>, O<sub>2</sub>, and pH sensors. Sensors for detecting metal contents may also be useful in order to detect pore fluids emanating from the seabed as a precursor to CO<sub>2</sub> emissions. Similarly, salinity, temperature, turbidity, fluorescence and optical sensors may reveal deviations from normal conditions caused by a pressure buildup in the reservoir or overburden, forcing shallow pore fluids and particles into the marine environment. CH<sub>4</sub> (methane) sensors are relevant in cases where one needs to differentiate between CO<sub>2</sub> and CH<sub>4</sub>, for instance, to ensure that detected bubble plumes are related to shallow CH<sub>4</sub> emissions and cannot be attributed to an ongoing CO<sub>2</sub> storage project. Because CO<sub>2</sub> is considerably more soluble than CH<sub>4</sub> in seawater, CO<sub>2</sub> bubbles dissolve faster and do not reach the same height in the water column as a CH<sub>4</sub> bubble plume with a comparable bubble size distribution. However, CO<sub>2</sub> bubbles have been observed to rise higher than previously expected, potentially due to the gas exchange allowing other, less-soluble gases to enter the bubble as the CO<sub>2</sub> dissolves



into the surrounding water [41]. Thus, chemical verification is recommended in addition to visual inspection of acoustic echograms to unambiguously differentiate between the two substances. In addition, project-specific knowledge, such as the use of a chemical tracer in the injected CO<sub>2</sub> or site-specific chemical composition of the overburden, may merit the use of other chemical sensors.

Chemical sensors are point sensors, and need to be inside the chemical plume in order to detect it. Therefore, the detection range of chemical sensors is affected by the properties of the plume and the effects of ocean currents. Since a CO<sub>2</sub> plume is quickly diluted in seawater, sensors need to be located within a few tens of meters of the leak origin to detect it. Experimental and modeling results indicate that the detection distance depends greatly on the emission rate as well as on ocean currents [10,42]. In [10], the authors have modeled a set of hypothetical leak scenarios and suggest similar detection ranges. For a 1 T CO<sub>2</sub>/year leak rate and ocean conditions representative of the North Sea, the authors estimate a chemical detection range of 60 m. At the same time, the impact radius (i.e., distance at which benthic habitats are temporarily affected by the leak) is estimated to be significantly smaller at 15 m. An understanding of the plume dynamics, including its spatial and temporal evolution, is important when planning either the location of stationary monitoring stations or the travel path of an AUV.

Currently available CO<sub>2</sub> and CH<sub>4</sub> sensors use a membrane through which the seawater diffuses before measurement. The diffusion process takes some time, which is reflected in the sensor response time. This becomes a challenge when the sensors are placed on moving platforms because the sensors may not have time to react properly to spatially limited plumes. When possible, faster responding sensors, such as pH, temperature and salinity, may be useful complementary sensors that can improve plume detectability. In particular, since pH is closely linked to CO<sub>2</sub> (an increase in the CO<sub>2</sub> content causes a reduction in pH), a pH sensor may be used as a proxy for a CO<sub>2</sub> sensor. This requires selection of a pH sensor with high sensitivity, in the order of 0.01, to detect the expected pH change induced by a CO<sub>2</sub> plume [10,42,43].

The water column, seabed and atmosphere are all part of an open system that is affected by a vast number of natural processes. Monitoring the water column therefore poses the considerable challenge of separating natural variability from anomalies related to unintended leakage from the reservoir. A strong understanding of the variability and heterogeneity of the ocean environment and, in particular, the carbonate chemistry is required to identify anomalies potentially related to a leak event without falsely attributing natural variability to the ongoing storage project. It is often necessary to evaluate several parameters together in order to identify key relationships that are expected both as part of the natural marine variability, and during a potential leakage event. For example, the coherence between CO<sub>2</sub> and O<sub>2</sub> is identified as a key chemical marker to differentiate between a leakage event and natural variability [42,44,45]. The authors in [46] use a stoichiometric method ( $C_{seep}$ ) to differentiate between potential CO<sub>2</sub> leakage and natural variability. Yet another approach to differentiating between natural variability and potential leakage is described in [14], where the authors use a coupled hydrodynamic–biogeochemical model to characterize the carbonate chemistry and recommend anomaly detection criteria.

### 3.3. Emerging Technologies

Significant technological progress has been made over the past years, and several promising technologies have been demonstrated but are not yet commercially available. The lab on a chip (LOC) technology was developed to enable standard wet laboratory procedures in situ, using a miniaturized chip [47,48], thereby significantly reducing the intensive post-analysis workload. While an ISFET pH sensor based on the LOC technology is commercially available, additional LOC sensors to measure the total alkalinity (TA) and nutrients were demonstrated during a controlled release experiment in the North Sea carried out as part of the STEMM-CCS project [7]. The eddy covariance method has been used for some time to detect and quantify CO<sub>2</sub> emissions to the atmosphere [49,50].

The method was recently demonstrated to monitor CO<sub>2</sub> escaping the seabed during a controlled CO<sub>2</sub> release experiment [51]. The eddy covariance method requires that the monitoring equipment is placed in the direct vicinity of the source, making it a promising technology for the long-term monitoring and quantification of a known leak. Fiber optic technology is rapidly advancing and seeing new areas of application. In the context of marine GCS monitoring, fiber optic sensing may provide a cost-effective means of monitoring subsidence and upheaval potentially related to the geological injection of CO<sub>2</sub>.

#### 3.4. Sensor Platforms

Monitoring sensors can be placed on different platforms, depending on the monitoring requirements, in particular, the size of the area to be covered, the level of detail required, and the time frame for monitoring. Relevant platforms include surface vessels, AUVs, gliders (also a type of AUV), and stationary monitoring solutions.

##### 3.4.1. Surface Vessels

A surface vessel, such as a survey ship or a seismic acquisition vessel, can efficiently survey a large area. A cost-efficient solution can be to combine the marine monitoring survey with other planned activities using these vessels, such as seismic acquisition or research expeditions. A vessel-mounted MBES provides efficient mapping of the water column (to document bubble seepage) and simultaneous seabed bathymetry mapping. If quantitative estimates of bubble flux from detected seeps are required, a calibrated echo sounder can be mounted on the same vessel. Measurements from the water column and seafloor can be complemented by SBP data revealing shallow structures in the upper sediments. Mapping the upper sedimentary layer can be helpful in data interpretation, potentially indicating whether a seabed feature is non-problematic for the storage project, or whether it can be related to a deeper risk structure. MBES and SBPs operate at distinctly different frequencies and can normally be operated simultaneously without acoustic interference affecting the data quality. These remote sensing techniques may be complemented by water and sediment samples collected at strategic locations. A surface vessel may also carry supplementary equipment, such as a towfish, with suitable acoustic and/or chemical/oceanographic sensors aimed at mapping deeper sections of the water column or seabed. The optimal vessel speed and line spacing is affected by the water depth and the area coverage of the sensors used. A conservative estimate of the area coverage rate in 100 m water depth and when using a MBES and an SBF is in the order of 4–6 km<sup>2</sup>/h [15].

##### 3.4.2. Autonomous Underwater Vehicles

While ship-based surveys are highly efficient for mapping large areas, AUVs have the additional advantage of traveling near the seabed and can therefore provide detailed information about the deep ocean layers and document the seabed on a finer scale. Their potentially significant sensor payload (subject to vehicle-specific limitations) enables AUVs to sample many parameters simultaneously for a complete chemical, oceanographic and acoustic survey. The AUV sensor payload can be adjusted according to monitoring needs, for example, detailed mapping of the seabed using side scan or synthetic aperture sonar (SAS) to document pockmarks, bacterial mats and bubble seeps, while simultaneously measuring the level of dissolved CO<sub>2</sub>, pH, O<sub>2</sub>, salinity, temperature and turbidity. Depending on the capacity of the vehicle, the AUV may also carry a MBES and a sub-bottom profiler. A high-definition subsea camera can be used to document special areas of interest. State-of-the-art AUVs today follow a pre-programmed data acquisition path. A common data acquisition path is a lawn-mower pattern at a single depth, but this can be tailored to the monitoring needs. A wide range of AUVs are currently available on the market, ranging from small, low-power vehicles with a limited sensor payload but extended operation times, to larger and more power-demanding AUVs capable of carrying a significant sensor payload, including state-of-the-art imaging sonars for detailed seabed mapping. Typical operational times are in the order of days. Area coverage rates are vehicle-, payload-, and

location-specific. For the HUGIN AUV (Figure 4) equipped with chemical sensors and a SAS system, area coverage rates are estimated to be in the order of  $2 \text{ km}^2/\text{h}$ . AUV-related research efforts are currently directed toward improved vehicle autonomy, including the ability for the vehicle to actively adapt to its environment [52,53] and endurance [54,55], as well as on solutions with resident AUVs able to re-charge their batteries using subsea docking stations [56] or wireless charging systems [57].



**Figure 4.** The HUGIN AUV equipped with a sensor payload including the HISAS system with capabilities for mapping the seabed and detecting gas seeps in the water column. This image was taken in Horten during the ACT4storage nearshore experiment.

### 3.4.3. Gliders

Gliders are a specialized type of AUV, described separately here for clarity. Traditional gliders do not use a propeller but a combination of hydrofoils and buoyancy control to maneuver in a zig-zag pattern between two depths in the water column. This low-power solution allows for long-term deployment of up to several months depending on sensor payload and battery capacity. In the context of marine monitoring for GCS, these vehicles are particularly well suited for gathering oceanographic data from vast ocean areas. Information about long-term temporal and spatial variability in ocean geochemistry enables more robust differentiation between natural variability and potential anomalies, and is also valuable input to oceanographic models. Gliders are generally optimized for long endurance, and therefore carry a limited sensor payload compared to AUVs. Typical sensor payloads include CTDs, salinity, and turbidity sensors. Chemical sensors have also been demonstrated, including pH,  $\text{CO}_2$ , and  $\text{CH}_4$ . As mentioned above, the relatively long response times of currently available  $\text{CO}_2$  and  $\text{CH}_4$  sensors make them less suited for deployment on a moving platform. This is particularly problematic for a glider that moves up and down in the water column because of the significant naturally occurring vertical variability in these parameters. In recent years, new glider platforms have become available on the market, including surface gliders and hybrid gliders. The latter use a propeller to mimic AUV-maneuverability for short periods of time. Glider sensor payloads are also in rapid development, with recent advancements including a scientific echo sounder [58].

#### 3.4.4. Stationary Monitoring Solutions

Stationary monitoring solutions can take many forms, including seabed templates deployed for long periods of time (months or years), temporarily deployed landers, or remotely operated vehicles (ROVs) maintaining a fixed position for some period of time. Stationary monitoring solutions are particularly relevant near identified risk structures, but may also be used to collect baseline data at strategic locations or prior to CO<sub>2</sub> injection. Which sensors to install will depend on the available infrastructure for power supply and data management, and on the monitoring requirements. Typical low-power sensors include chemical and oceanographic sensors as well as hydrophones, while active acoustic sensors (sonars and echo sounders) are more power demanding. Stand-alone solutions, including echo sounders deployed for several months, are commercially available.

For chemical and oceanographic monitoring, remaining at a fixed position over time and acquiring data at a high sample rate increases the ability to detect small or diluted chemical plumes. Because most chemical and oceanographic parameters have larger variability in the vertical direction than in the horizontal direction, maintaining a fixed vertical position over time results in less noise in these measurements.

#### 3.5. The Role of Modeling

The lack of sufficient observational data both on a temporal and spatial scale implies that models have a significant role to play in the context of marine GCS monitoring [14,59]. While the marine environment has been studied for decades, it remains poorly described if we consider only the available observational data. However, a range of marine system models have been developed to describe both physical flow (ocean currents and tidal effects) and biogeochemical systems, including carbonate chemistry. Specialist models may be used to describe leak-related features, such as bubble plume dynamics [41,60]. For CCS, marine models contribute to the baseline by providing complementary information about natural variability where observational data are lacking or incomplete. Further, the ecological impact of hypothetical leakage may be estimated based on numerical leakage simulations. Finally, the predicted footprint, or spatial and temporal extent of the leakage signal, has direct implications for the choice of monitoring strategy as well as sensor and platform configuration. Sensors must have sufficient sensitivity and be placed at an appropriate distance to detect an anomaly related to relevant leakage scenarios as identified during the risk assessment. Modeled predictions of leakage footprint may also be used to optimize the placement of stationary monitoring platforms as well as the travel path of an AUV [59,61].

### 4. Knowledge Gaps and Future Research Directions

Marine GCS monitoring has received significant attention over the past years, and there are now mature technologies and methodologies available on the market to allow adequate monitoring. High-resolution models and simulations of hypothetical leakage scenarios provide important knowledge where observational data are scarce. Strategies for cost-efficient monitoring have been developed and are generally agreed upon within the scientific community and supported by commercial operators. The remaining technological challenges can be categorized into sensor development, data management, and enhanced autonomy reducing the need for costly human involvement.

Sensor development related to emerging technologies as indicated in Section 3.3 is expected, as is further optimization of available technologies to improve their functionality related to marine GCS monitoring. Efforts are currently being directed toward reducing the response time of available CO<sub>2</sub> sensors, making them more relevant for deployment on AUVs and gliders.

AUVs have the potential to play a key role in marine GCS monitoring because of their ability to cover large areas and to carry a range of chemical, oceanographic and acoustic sensors. Currently, these vehicles have limited decision autonomy and therefore follow a pre-defined travel path. "Truly autonomous" AUVs capable of acting intelligently based on

their surroundings as measured by sensor measurements in real time are technologically within reach, and would significantly improve the cost-efficiency of these vehicles. This requires development related to data analysis, in particular, translating raw sensor data into high-level information based on which the vehicle can make an intelligent decision in real time. It also requires development related to AUV travel path optimization and real-time adaptation.

Finally, frameworks for managing the large amounts of data produced by different sensors acquiring high-resolution data over time need to be developed or tailored to the needs of the monitoring program. Streamlined solutions for data communication and information sharing between the different components of a monitoring program would further increase the efficiency of marine GCS monitoring. Big data analysis and machine learning techniques are expected to play a role in extracting key information efficiently from these significant data sets.

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