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CCS leakage detection technology - Industry needs, government regulations, and sensor performance

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Abstract

Reliable CCS monitoring is vital in order to confirm that injected CO_2 stays in the reservoir as intended, and that any occurring leakage is promptly detected allowing corrective actions to be initiated. Motivations for implementing monitoring strategies beyond the legal minimum required by government regulations, can be divided into economic, environmental and reputational factors, where the latter is significant; adequate monitoring is important for attaining public acceptance. CCS monitoring methods can be divided into deep focused (reservoir, overburden) and shallow focused (seabed, water column) methods. Shallow monitoring methods include acoustic and chemical sensors placed in the water column. For the CCS application, these sensor technologies are complementary; acoustic sensors are sensitive to CO2 in gas phase and chemical sensors can detect water-dissolved CO2 or formation fluids. We discuss the motivations for CCS monitoring, and offer a structured overview of acoustic and chemical technologies for CCS monitoring at the seabed and in the water column. Each technology is evaluated in terms of its applicability to CCS monitoring, highlighting its strengths and limitations for detection, quantification and characterization of CCS related leakage. We conclude that while state of the art sensor technology is sufficient to meet government requirements, there is potential for improved integrated monitoring through optimal use and combination of technologies. The concept of integrated monitoring where different sensor types measure different parameters is emerging as a promising monitoring strategy.

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1. Introduction

In recent years, carbon capture and storage (CCS) has emerged as a promising method for reducing CO_2 emissions and reaching international climate goals. Potential storage sites include geological formations located offshore the continental shelf. Guidelines exist for selecting CO_2 storage sites in order to minimize the likelihood of CO_2 leakage, e.g. [1], [2] and [3]. The need for reliable and cost-effective leakage monitoring methods for offshore CCS activities has been the motivation behind a range of government and industry-funded research projects. Recent projects include ECO2 [4] and QICS [5]. The ECO2 project established a framework for best environmental practices related to CO_2 injection and storage [6] [7]. The QICS controlled CO_2 release experiment focused on understanding and documenting potential environmental impacts in the event of CO_2 leakage through a large-scale experiment, and evaluated the detectability of such leakages [8] [9]. A recent study sponsored by the International Energy Agency gives a review of available monitoring methods and technologies, differentiating between 'deep focused methods' aimed at monitoring the reservoir and overlying geological layers, and 'shallow focused methods', aimed at monitoring the seafloor and water column [10].

The lack of systematic documentation or guidelines for leakage detection and monitoring may pose a challenge during the design phase of subsea leakage detection systems [11]. Operational experience and analysis of sensor data has shown the strengths of the combination of acoustic and chemical sensors for leakage monitoring in the water column [12]. It would be of great benefit to assess a range of leakage detection methods or types of sensors, and demonstrate the potential of different technologies in realistic leakage scenarios. Such a demonstration should take into account the impact of environmental conditions such as current, turbidity, marine growth etc. We believe the technology should be selected according to expected performance at a particular site, but also take into account the operational needs in the industry. A technical assessment of relevant sensor technologies is a step towards such a demonstration.

We present here relevant legislation from the European Commission and Norwegian laws as well as the economic, environmental and reputational motivations for CCS monitoring. We give a detailed presentation of acoustic and chemical CCS monitoring technologies, including state-of-the-art and emerging technologies. The latter are technologies that are assessed to have potential for gas leakage detection but so far have seen little use for this application. Finally, we identify some areas where the industry could benefit from further advances in research and technology, which come in addition to areas already mentioned in [10].

2. Motivations for CCS monitoring

We separate the drivers behind CCS monitoring into economic, environmental and reputational risk. The economic consequences are linked to complying with environmental legislation, the costs associated with actions to prevent and abate leakage as well as cost associated with pay back of carbon credits. Environmental consequences are effects on benthic and pelagic organisms from local acidification or other changes in the chemistry of the aquatic environment. Reputational factors include the public acceptance aspect for storage of CO_2.

2.1. Government and company regulations

The main regulation for CCS across Europe is the EU CCS Directive on the geological storage of carbon dioxide [1]. The directive focuses on selection of storage sites, permits for storage of CO_2, monitoring of the storage complex, closure and post-closure obligations, and transfer of responsibility. Directive article 13 sets the requirements for monitoring; section 1 states the purpose for monitoring, section 2 states that monitoring shall be based on a monitoring plan and gives some constraints to the content of such a plan.

The CCS Directive specifies the requirement of continuous or intermittent monitoring of fugitive emissions of CO_2 at the injection facility of CO_2 storage complexes. It does not state specific limits, such as minimum leakage rate for detection, aerial resolution for the monitoring, time-resolution for monitoring or minimum detection time. The Norwegian legislation regarding CCS is mainly given in the law “Lov om vitenskapelig utforskning og undersøkelse etter og utnyttelse av andre undersjøiske naturforekomster enn petroleumsforekomster/Act relating to scientific research and exploration for and exploitation of subsea natural resources other than petroleum resources” [13] and in the regulation “Forskrift om utnyttelse av undersjøiske reservoarer på kontinentalsokkelen til lagring av CO_2 og om transport av CO_2 på kontinentalsokkelen” [14]. These documents are based on the CCS Directive and state no additional requirements to monitoring.

2.2. Economic risk

According to the EU Emissions Trading System, if there is a capture installation, transport network and storage site permitted in accordance with the CCS Directive 2009/31/EC, CO_2 not emitted but transferred out of an installation can be subtracted from the total emissions. CCS installations are required to measure emissions in accordance with tier 4, with uncertainty less than 6.5% of the injected amount, unless the measurement is prohibitively costly or technically infeasible [15]. The economic consequence for an operator not able to quantify the injected volume would be linked to the EU ETS penalties; in 2013, this was €100 per tonne of CO_2. In the event of a leakage or false alarm, operators may be held economically and legally accountable for "worst case" leakage scenarios if they are unable to document the opposite.

The ETS rules for measurement do not directly apply to monitoring of stored CO_2, but of CO_2 captured, transported and injected. Hence, current legislation assumes that volume of CO_2 injected equals volume of CO_2 stored in the formation, and monitoring the injected volume is sufficient. It is reasonable to suggest that if there is suspicion of migration from a reservoir, legislation should to be updated to include monitoring of the stored volume.

2.3. Environmental risk

The environmental risk associated with offshore CO_2 storage is a combination of the likelihood that injected CO_2 may migrate to the seafloor or water column, and any environmental consequences of the resulting leakage. As part of the ECO2 project, DNV GL developed a Best Practice approach to Environmental Risk Assessment for offshore CO_2 storage sites [16]. The methodology was developed and applied for an actual storage site, in order to assess the environmental consequences of a potential leakage scenario [17].

For site selection, the ECO2 project recommended to choose storage sites that do not exhibit the following features relating to environmental risk:

- geological formations containing toxic compounds that can be displaced to the seabed,
- areas in which biota is already living at its tolerance limits because of existing exposure to additional environmental and/or other anthropogenic stressors,
- low-energy hydrographic settings with sluggish currents and strongly stratified water column,
- proximity of storage sites to valuable natural resources (e.g. Natura 2000 areas, natural conservation habitats, reserves for wild fauna and flora).

The motivation for monitoring is in this case documentation related to the first two bullet points above; that there is no increase of toxic substances in the water and that local biota is unaffected.

2.4. Reputational risk

Whenever public opinion is of importance, governments and commercial companies will seek to minimize negative publicity concerning their operations. Related to CCS monitoring, unwanted publicity could stem from e.g. observations of CO_2 bubbles emanating from the seafloor near a storage site, or an observed alteration of the local marine environment. In these cases, it is beneficial for the operator to minimize reputational damage by documenting that sufficient monitoring is being carried out, and to be able to locate, quantify and characterize any leakage an at early stage. According to an anonymous major operator, the main reasons reputational risk can be a motivation for water column monitoring are a) early detection of genuine leakage and b) assurance of storage integrity in case third parties claim a storage site is leaking.

In both cases, the water column monitoring system has to provide a detailed characterization of the marine environment in order to detect – or demonstrate the absence of – a chemical or biological signal originating from the storage site. Proving the source of the leakage is a critical part of the assurance process and operators need methods for determining that leakage of CO_2 or other substances are not a result of their activities.

3. Monitoring strategies

There exists a range of CCS monitoring technologies, aimed at monitoring either the reservoir, the overburden, the seafloor or the water column. The common goal is to detect, characterize and quantify any leakage of CO_2 from the intended storage site, but choosing the right technical solution for a given project is not trivial. While time-lapse seismic studies offer highly valuable information about the migration and development of the CO_2 plume and changes in the geophysical properties in and above the reservoir, these surveys are costly and performed relatively seldom (typically every 1-3 years). Electromagnetic and gravimetric surveys have also been used to monitor the stored CO_2 plume, offering potentially useful but less detailed information. Several studies [18] [7] [10], highlight the need for a multidisciplinary, site-specific approach to shallow CCS monitoring covering also the overburden, the seafloor and the water column.

In order to design successful and site-specific monitoring strategies, a clear understanding of the available technologies and their applicability to different CCS monitoring scenarios is necessary. Depending on the site in question, it will be up to the operator to tailor a suitable monitoring scheme, based on the available technologies and guidelines on how to use and combine these in a meaningful way. Current sites where CCS monitoring strategies are in place include Sleipner, Snøhvit, Peterhead, K12-B, ROAD, Tomakomai, Gorgon and Lula. The monitoring strategies for each site are discussed in [10], where one of the findings is that site-specific monitoring schemes are likely to include surveying of the entire area at regular time intervals using survey vessels and/or AUVs, combined with continuous or frequent monitoring of confined high-risk areas.

A range of relevant sensor technologies is available on the market. For shallow monitoring, [10] lists optical imaging, seabed displacement monitoring, sediment sampling and ecosystem response monitoring in addition to acoustic imaging and geochemical water column sampling. We will in the following investigate the latter technologies, and their applicability for CCS monitoring; active and passive acoustic sensors are able to detect bubbles in the water column, chemical sensors are able to detect dissolved CO_2 as well as aqueous concentrations of specific chemical components in the formation fluid or sediment pore water that can potentially be tracers for CO_2 leakage. Sensors for monitoring secondary parameters such as ocean currents, temperature and pressure may complement acoustic and chemical sensors. The major monitoring strategies discussed here are therefore:

- direct detection of CO_2 as gas phase with active and passive acoustic sensors,
- direct detection of dissolved CO_2 with pCO_2 sensors,
- indirect detection of CO_2 as pH change with pH sensors,
- indirect detection of leakage from the reservoir with sensors detecting chemical components in pore water or formation fluids.

Taking advantage of recent advances in digital communication and data processing, most of these sensors may be on-line allowing continuous or periodic monitoring at regular intervals. Benefiting from the high data rate, shallow monitoring systems are useful for detecting leakage as soon as it occurs, and for monitoring the behaviour of leakages that have reached the water column.

4. Acoustic sensors

Acoustic sensors are well suited for detection of CO_2 in gas phase because of the long-range capabilities of sound waves in water, combined with the characteristic acoustic properties of gas bubbles in water. Acoustic sensors can have operating ranges from a few meters up to hundreds of meters, depending on the system design, operating frequency and environmental conditions. Range limiting factors include topography, physical obstacles such as manufactured constructions on the seafloor, and background noise levels.

4.1. Active acoustic sensors

An active acoustic sensor detects the presence of bubbles in water due their high target strength caused by the significant contrast in acoustic impedance between water and gas. Active acoustic technologies applicable to CCS monitoring include multibeam echo sounders and sonars, scientific echo sounders and sonars, single beam scanning sonars, and high-resolution seafloor imaging sonars such as side-scan sonars and synthetic aperture sonar (SAS). When imaged using a hull-mounted echo sounder, a characteristic "flare" shape is often visible in the water column. High-resolution imaging sonars carried by AUVs may detect and visualize seep-related features on the seafloor such as pockmarks, bacterial mats, or local topography changes. With the exception of SAS systems which require a moving platform, all of these technologies have the flexibility to be mounted either on the hull of a surveying vessel, on an AUV, or on a stationary platform for long-term monitoring. Hull-mounted multibeam echo sounders as well as scientific single- and split beam echo sounders are currently state-of-the-art for marine gas seep detection.

In addition to being strong acoustic scatterers, gas-filled bubbles give rise to a characteristic frequency response with a strong peak at the bubble resonance frequency. This makes it possible to tune the operating frequency range to include the expected resonant frequencies of bubbles thereby maximizing their acoustic response, and to use the frequency dependent information for leakage characterization and quantification. Figure 1 illustrates the characteristic acoustic response (target strength, TS) of a single, spherical air-filled bubble in water at a water depth of 80 m. A very strong peak at the resonant frequency characterizes the response, which is largely dependent on the bubble radius. In addition, the acoustic response above resonance is high compared to a solid object of similar size, making bubbles in water detectable even in the presence of considerable background noise [19].

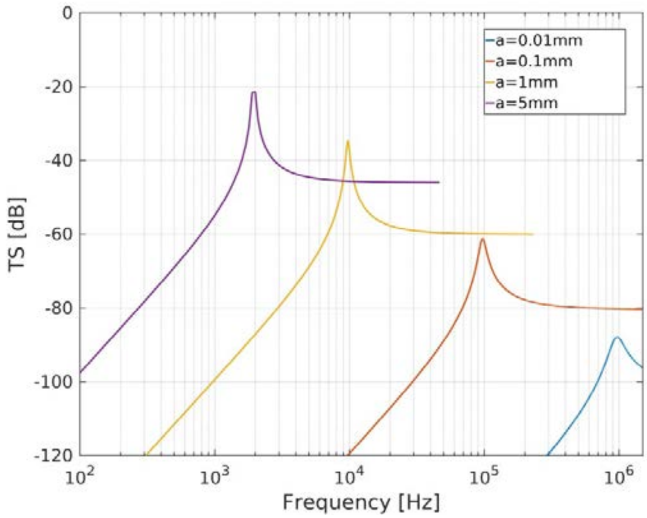

Figure 1- The acoustic target strength (TS) of a single, spherical air-filled bubble is characterized by a strong peak at the bubble resonance frequency. Each curve represents the TS of a single bubble with radii ranging from a = 0.01 mm to a = 5 mm at a water d depth of 80 meters, computed as described in [19].

4.1.1. *Multibeam echo sounders and sonars*

Hull-mounted multibeam echo sounders are commonly used for surveying purposes because of their excellent area coverage rate. The transmit beam is wide in the cross-track direction, with an imaging swath of up to 120 degrees, equivalent to several kilometers in deep waters. Recent multibeam systems also have the ability to store water column data, revealing the characteristic flare-like shape of gas leakages.

There exist a wide range of multibeam echo sounders and sonars, including imaging and profiling multibeams designed for subsea monitoring purposes. These systems consist of a sensor array with e.g. a 2D curved, cylindrical, or even spherical shape. The common characteristic of multibeam echo systems is that a wide transmit beam is emitted and high-resolution imagery or bathymetry obtained through receive beamforming [19]. The 2D array in a multibeam system makes it possible to steer the beam in the horizontal as well as the vertical direction for plume verification and characterization.

Multibeam echo sounders mounted on AUVs typically operate at higher frequencies than vessel-mounted ones, achieving higher seafloor image resolution at the cost of reduced operating range. The main advantages of a multibeam sonar over a single beam sonar for CCS leakage detection are area coverage rate, added flexibility in data processing and instantaneous, up to 360-degree image formation.

4.1.2. Scientific echo sounders and fish finding sonars

Single- and split beam scientific echo sounders have a much smaller area coverage rate than their multibeam counterpart, but display other properties that are useful for estimating fish populations, or equivalently, for seep characterization. These properties include multiple operating frequencies, broadband capabilities, and split-beam capabilities. The multi-frequency and broadband capabilities are particularly useful for seep detection and characterization, since the acoustic bubble response is highly frequency dependent. Fish finding sonars typically have the ability to operate at low frequencies (down to a few kHz), which results in long-range capabilities. Fish are often detected due to the strong response from the air-filled swim bladder, which is an acoustically very similar target to a (large) bubble. Finally, scientific fish finding echo sounders are often calibrated, which makes it possible to relate the target strength to bubble flux, given an estimate of the bubble size distribution [20] [21].

In contrast to multibeam systems, single beam systems typically consist of a single transceiver element. Traditionally, single beam echo sounders are mounted on the hull of a vessel to map the distance to the seafloor. Fish and bubbles in the water column are visible as regions of high intensity in the echogram. In recent years, split beam technology has improved bottom detection accuracy, and the ability to position a target within the acoustic beam. A split-beam echo sounder has multiple receiver elements (typically four), which can be useful in terms of leakage characterization [20].

4.1.3. Single beam scanning sonar

A single beam scanning sonar transmits a narrow acoustic beam and moves the transducer mechanically to form a complete 360-degree image of its surroundings. Most models operate at high frequencies, offering high image quality and resolution at the cost of limited range [11]. The main feature of a single beam scanning sonar is two-way side lobe suppression, resulting in less noise in the image. Both the transmit beam and the receive beams are focused, such that there is little interfering energy from off-axis directions.

While the simple design with a single transceiver element is an advantage in terms of cost, robustness and the amount of data storage required, single- and split-beam echo sounders and sonars lack the flexibility of multi-element systems. Array signal processing for improved image quality or automatic and robust leakage detection is limited or impossible. Finally, since the scanning process may take several seconds, the image does not represent an instantaneous snapshot of a 360-degree scene. This limits the ability to capture highly varying temporal fluctuations in a leakage.

4.1.4. Side-scan sonar

Side-scan sonars are frequently used for seafloor imaging purposes. They are typically carried by AUVs or towed vessels, operating near the seafloor and at high frequencies for optimal image quality. High-resolution side-scan sonars may have potential for CCS monitoring because of their ability to detect seep-related features on the seafloor. However, the imaging geometry of a side-scan sonar (operating near the seafloor and viewing a seep from the side) makes it difficult to detect the presence of a seep visually because it does not necessarily display the "typical" flare shape observable in hull-mounted systems.

4.1.5. Synthetic aperture sonar

In recent years, synthetic aperture sonar (SAS) has emerged as a mature seafloor imaging and mapping technology and a strong competitor to traditional side-scan sonar. SAS systems are typically AUV-mounted, and take advantage of the AUV movement to achieve seafloor imagery and bathymetry on a centimeter scale. SAS hardware is similar to that of a side-scan sonar, but improved image quality is achieved through dedicated SAS processing where data from multiple transmissions (pings) is coherently combined to form a long (up to hundreds of meters) receiver array. SAS technology is described in [22].

Most existing SAS systems are interferometric, i.e. consist of a single transmitter and two or more receiver arrays separated by a vertical baseline. This makes it possible to obtain centimetre-scale seafloor bathymetry co-registered with the high-resolution seafloor imagery. Interferometric SAS systems are highly valuable tools for CCS monitoring, with the ability to survey large areas (1-2 square kilometres per hour). The high-resolution seafloor imagery and bathymetry makes it possible to detect leakage-related features such as pockmarks and bacterial mats [7], [23]. The HISAS 1030 system [24] has a theoretical resolution of 3x3 cm, independent of range. Recent research using this system shows that a SAS sensor may also be used to detect the presence of bubbles in the water column [25].

4.2. Passive acoustic sensors

Gas bubbles emit several characteristic sounds in water; a distinct sound as the bubble enters the water column from the seabed, a characteristic sound caused by the oscillations of a gas-filled bubble in a fluid, and a high-frequent sound caused by a bubble as it bursts. Passive acoustic sensors (hydrophones) are able to measure these sounds, but the acoustic signal power is the power emitted from the bubbles alone, which is generally much lower than what is achievable using active acoustic systems. Consequently, passive acoustic sensors have limited sensitivity and operating range in areas with significant background noise.

Passive acoustic sensors have been used to detect leakage from pipelines [26]. In this case, the leakage may consist of either gas or fluid. The location of potential leakage is assumed (along a pipeline, typically at a flange or potential weak spot). In the case of a leakage from a pressurized pipeline, the flux is normally large and focused, giving rise to a strong acoustic signal. Hence, passive acoustic sensors detect leakage by significant changes in the acoustic field. For monitoring of a CO_2 storage site, the area coverage rate may need to be larger, and the expected location of potential leakage is not necessarily well defined. For this application, highly sensitive sensors and advanced processing may be required to identify a leakage and to differentiate between leakage and background noise caused by e.g. ships, operation activity, animals, breaking waves, currents, rainfall, etc. Relevant methods include use of directional sensors, and mounting of several sensors in an array configuration that allows more accurate positioning of a leakage as well as improved signal-to-noise ratio.

Passive acoustic sensors are low cost, robust and energy-effective, and of interest for long-term and large area monitoring. Several studies predict and demonstrate the potential for subsea leakage detection and quantification using passive acoustics [26] [27]. In [28], the authors propose a method for leakage quantification based on passive acoustic emissions. They also outline an approach to CCS monitoring where passive acoustic sensors, powered by e.g. solar power, can be used to detect leakage and offer a rough estimate of location and flux. Active acoustic sensors with higher demands to power and data bandwidth can then be automatically triggered for closer inspection and verification of leakage.

5. Chemical sensors

Several chemical sensors on the market are designed to measure the aqueous concentrations of specific chemical components that can be directly or indirectly associated with leakage of CO_2. Since seawater naturally contains many different chemical components, including CO_2, at variable concentrations, these sensors must give reproducible measurements that are solely an effect of the concentration of the analyte and not influenced by (or this can be corrected for) concentration changes of other components. The sensors are point sensors, as opposed to area sensors such as sonars, meaning that in order to measure a component in the water column, the component has to come in contact with the sensor. In the case of leakage, mixing into the water column does not happen instantly. Hence, the distribution of the chemical species in the water column is heterogeneous. Estimates of the concentration of a component at locations away from the sensor can be done with a model of the physical and chemical processes in the water column, including water currents and mixing factors.

5.1. pCO_2 sensors

The carbonate system in seawater is controlled by the following equilibrium equations:

$$CO_2 + H_2O \leftrightarrow H_2CO_3$$

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$$

These equilibriums imply that influx of CO_2 into seawater will increase the concentration of CO_2 and H^+ and reduce the concentration of CO_3^{2-} (carbonate anion). However, fluctuations in the carbonate system caused by release or uptake of CO_2 (e.g. degradation of organic matter or photosynthesis) or by carbonate (e.g. biogenic precipitation or dissolution of calcium carbonate) will also affect the concentration of CO_2 and H^+. In the North Sea total dissolved inorganic carbon (DIC) varies between 2135 and 2175 µmol per kg seawater near the bottom [29]. Modelling studies have concluded that the natural variability of pH and pCO_2 in the North Sea was from less than 0.2 pH units in areas with low biological activity to more than 1.0 pH units in areas with high biological activity [30]. In the same study, the effect of acidification due to input of atmospheric CO_2 was estimated to 0.1 pH units. In [31], 5 µmol CO_2 per kg salt water was defined as a threshold value for detection of increased CO_2 concentration from subsea leakages.

Several pCO_2-sensors are commercially available. In most cases, pCO_2 sensors are equipped with a membrane between the water column and an internal chamber where CO_2 in gas phase is quantified. It is assumed that the concentration in the gas phase is in equilibrium with the concentration in the water column. Physical obstacles such as marine growth may affect the diffusion through the membrane; this is a potential challenge for long-term installations. The transfer of CO_2 through the membrane means that there is a time lag between the concentration in the water phase and the concentration in the gas phase. The time lag has a consequence for survey strategies; if the sonar is mounted on a vessel, the vessel has to remain stationary until equilibrium is reached whenever the concentration is measured. Earlier evaluation of pCO_2 sensor performance has been done by the Alliance for Coastal Technology (ACT), which is an independent organization that provides evaluation studies of the performance of many different monitoring technologies [32]. Testing of sensor performance in the context of CCS has also been done in the QICS project [33].

ACT reports accuracies of these instruments as being below the expected increase in pCO2 (>1000 µatm) at 10–100 meters distance from a 'blowout' type of leak as described in [6]. However, the accuracies are higher or in the same range as an expected increase from the more moderate leakage scenarios described therein.

5.2. pH sensors

The concentration of H^+-ions (acidity) can be measured in the seawater by a pH electrode where the H^+-ions is adsorbed to a glass membrane creating a potential difference between the sides of the membrane. ACT has performed laboratory and field tests of different pH sensors. They report deviation between independently measured reference values and values measured with pH electrodes of more than 0.1 pH units for many of these sensors. This is a challenge since modelling estimates smaller changes in pH, typically less than 0.03 pH-units at a few hundred meters distance from moderate leakages [6]. This implies that it can be difficult to detect changes in pH caused by leakages and that it is important to assess the performance of such sensors over time in a realistic environment.

The accuracy of pCO_2 and pH sensors is close to the minimum needed for detecting CO2 leaks, implying that relative changes in the measured pH or pCO2 must be taken into account to identify a leak. It is therefore important to increase the understanding of variability in these parameters caused by natural processes in the sea, or caused by instrument conditions such as biofouling or wear.

5.3. Sensors for formation fluids

Leakage of CO_2 from a storage formation is likely to be accompanied or preceded by several other components. Brine, pore water, natural gases and residuals of oil may be pushed out of a reservoir preceding or accompanying a CO_2 leakage [34]. If any constituent of the leakage is dissolved in the water column in an amount that causes a significant and measurable concentration change, this parameter can be used as a tracer for early warning of CO_2 leakage. Sensors that are capable of detecting concentrations at a level expected for leakage of formation water or pore water exist only for a limited number of substances commonly found in brine.

The following group of parameters are potentially suitable for leakage monitoring:

- Salinity/conductivity
- Redox conditions
- Major elements dissolved from minerals
- Trace elements dissolved from minerals
- Nutrients
- Hydrocarbons

Table 1 shows examples of sensors for different parameters that are likely to be found in brine with significantly different concentrations from seawater. For many of the sensors there is little experience with long-term sub-sea monitoring. The natural variation of these parameters compared to the relative influence from a leakage situation and the long-term performance of the sensors themselves are not fully investigated.

Table 1 - Sensors for chemical components likely to be found in brine with significantly different concentrations from seawater.

Parameter group	Measurable parameter	Depth rating	Producer/sensor name/ reference
Salinity/conductivity	Conductivity	>1000 m	Several
Redox conditions	Redox potential (ORP)	200 m	TROLL® 9500 Sensor

	O_2-concentration	>1000 m	SAIV A/S, http://www.saivas.no/
Major elements dissolved from minerals	Cl^-	70 m	Mettler Lab-sensor and TROLL® 9500 Sensor
	F^-	Lab-sensor depth rating not reported	Mettler Lab-sensor
	I^-	Lab-sensor depth rating not reported	Mettler Lab-sensor
	K^+	Lab-sensor depth rating not reported	Mettler Lab-sensor
	Na^+	Lab-sensor depth rating not reported	Mettler Lab-sensor
	Ca^{2+}	Lab-sensor depth rating not reported	Mettler Lab-sensor
	Mn(II) and Fe(II)	150 m	Voltametric In-situ Profiling system (Idronaut) http://www.idronaut.it/products-groundwater-voltammetric-probes
Trace elements dissolved from minerals	Cu, Pb, Cd and Zn	150 m	Idronaut VIP
	Ag/S^{2-}	Lab-sensor depth rating not reported	Mettler Lab-sensor
	H_2S	100 m	Sea&Sun Submersible Sulphide/H2S Probe
	Radioactivity	100 m	Tsabaris and Thanos 2004 Mediterranean Marine Science Vol. 5/1, 2004, 125-131
Nutrients	Nitrate (NO_3^-)	14 m	TROLL® 9500 Sensor
	Ammonium (NH_4^+)	14 m	TROLL® 9500 Sensor
Hydrocarbons	Methane (CH_4)	>1000 m	Franatech, Contros and others
	PAH-fluorescence	>1000 m	Chelsea, Sun&Sea, Contros and others

6. Technology and research needs

Based on current regulations and knowledge about state-of-the art of CCS monitoring technology and practice, [10] suggests research needs for offshore CCS monitoring. For shallow focused monitoring, these include:

a) Robust quantification of seabed emissions, particularly by remote (acoustic) methods.
b) Data on variations in natural background flux and concentration measurements of CO_2 and other gases at the seabed and in the water column – the baseline issue.
c) Integrated point-wise and spatial sampling strategies for shallow monitoring systems (where, when, how much, and linked to the deep monitoring strategy).

d) Detection of emissions precursor fluids (e.g. subsurface brines).

Each of these needs represents a gap that requires advances in available technology, improved data processing algorithms, or further testing and verification. In addition, we propose the following research topics for shallow focused CCS monitoring:

e) Advanced data processing for automatic leakage detection
f) Integrated monitoring optimized for improved CO_2 detection and quantification
g) Emission characterization
h) Extensive hardware testing in a realistic environment

6.1. Integrated monitoring

Impact from the monitoring environment such as biological activity, currents, turbidity, temperature and water stratification causes the concentration of most substances in the water column to have natural fluctuations. These fluctuations will be the results of several overlapping fluctuations linked to diurnal, lunar or seasonal changes as well as changes on other time scales. This leads to a complex pattern of variation in each of the parameters that can be monitored, hence it will be difficult to distinguish between natural fluctuations and the initial changes in the concentration in the early stages of a leakage from CO_2 storage. In order to interpret measurements of CO_2, pH or formation fluids as natural or indicating leakage it is necessary to have a baseline with natural fluctuations established over time, including daily and seasonal fluctuations. Monitoring several parameters simultaneously can enable the identification of covariant patterns that characterize natural or leakage related changes and can be used to discriminate between these.

Assimilating and analyzing data from different sensor types gives new possibilities for data processing and enables creation of more comprehensive models. There exist methodical approaches to designing monitoring strategies based on multiple data sources [35]. Bluntly, the term 'integrated monitoring' is the concept of combining different sensor technologies in a monitoring system. For CCS monitoring, an integrated monitoring scheme should include deep-focused and shallow-focused methods. In the case of water column monitoring for subsea gas leakages, two main examples are;

- the combination of acoustic sensors to detect gas phase leakage and chemical sensors to detect water-dissolved molecules enables the monitoring system to detect a range of different leakages,
- the combination of current meters and chemical sensors enables the system to locate and quantify dissolved gas leakage.

A long-term study of subsea hydrocarbon concentration variations shows the close interconnection between the concentration of substances in the water column and secondary parameters affecting the measurement environment [12]. The baseline concentration is shown to vary with up to a factor of three within 24 hours, based on changes in the water currents. The fact that changes in the baseline can be explained by natural variations in the environment suggests the importance of integrated monitoring, where not only the parameter of concern is measured, but also the parameters that provide information about the larger picture of causes for the changes in the measurement environment. These parameters include current strength and direction, temperature, air pressure and wind speed at the surface.

In light of the knowledge of the complexity of variation in chemocean parameters, it is paramount to assess the potential for CO_2 leakage detection in an environment that includes these secondary parameters and their natural variability and therefore provides a realistic setting. For acoustic sensors, water currents and thermoclines will in some cases be a source of noise, but the information gained from monitoring the current vector and water temperatures may give an overall improved understanding and better leakage detection capabilities. For chemical sensors, the secondary parameters affect the measurements of dissolved gas or other substances even more directly, and they have to be monitored and analyzed to make sense of gas concentration measurements.

6.2. *Data processing for automatic leakage detection*

Limited efforts have so far been directed towards cost-effective, reliable and automatic leakage detection. In this section, we outline the areas where we believe there is significant potential for improvement.

6.2.1. Big data analysis/machine learning

In a long-term monitoring system designed for example to collect data from multiple sensors over an extended period of time, the amount of data collected becomes huge. In order to process these data in a meaningful way and extract meaningful information, it is possible to make use of the considerable recent advances in big data analysis and machine learning algorithms. Data from baseline studies could be used to make models that forecast the concentration of CO_2 or formation fluids in the water column based on parameters such as current strength and direction. The forecast can then be used to differentiate between natural variations of the baseline and increased influx of a substance to the water column, i.e. indication of leakage. For acoustic sensors, similar algorithms could be used to identify leakages that for a human operator would be drowned in the standard noise in sonar images.

6.2.2. Array signal processing

Many acoustic sensors consist of multiple receiver elements from which a single image is formed. Leakage detection based on active acoustic systems are generally based on interpretation of the final sonar image where a gas leakage appear as a region with high intensity compared to the background. It is possible to do additional image processing by analyzing the raw data received by each receiver element. This adds valuable information about for instance the movement of bubbles, or their spatial distribution. Targeted array processing algorithms for automatic leakage detection have recently been proposed [36] [37]. This type of processing may increase performance and cost-effectiveness of both stationary and vessel mounted monitoring systems.

6.3. Emission characterization

In order to determine the origin of a gas phase leakage, the monitoring system must be able to differentiate between CO_2 and other gases, e.g. CH_4. Acoustically, this is challenging since the acoustic impedance contrast between water and CO_2 is very similar to that of water and CH_4. Most chemical sensors are sensitive only to specific substances and may be used to differentiate between different gases. Relevant sensors should be tested in a realistic production environment setting to verify that they give reproducible measurements that are solely an effect of the concentration of the analyte and not influenced by concentration changes of other components.

6.4. Extensive hardware testing in a realistic environment

Testing of sensor technologies for CCS monitoring has been done in several research projects including QICS [33], LoVe [38] and MMV [39]. We suggest further testing of sensor technologies in realistic settings, to demonstrate whether currently available sensor technology can ensure leakage detection in accordance with regulations and the monitoring objectives of the CCS industry. Testing could also reveal if different technologies complement each other depending on application and environment. The motivation for this type of testing is three-fold;

- help operators choose the optimal technological strategy for their application,
- optimize the way current technology is being applied to CCS monitoring,
- demonstrate a potentially new application – CCS monitoring – for technologies originally developed for a different purpose.

6.4.1. Acoustic sensors

Many of the acoustic sensors applicable to shallow CCS monitoring were originally designed for other applications. Single- and split beam echo sounders are designed either for bottom detection purposes or for fish finding and characterization. Multibeam sonars are designed for efficient seafloor mapping. Passive acoustic systems were originally developed for military or seismic survey applications, and later re-designed for other applications ranging from noise and marine wildlife mapping to leakage detection on pressurized pipelines.

6.4.2. Chemical sensors

ACT [32] has tested several relevant chemical sensors, e.g. sensors for pH, pCO_2, salinity, nutrients, turbidity, hydrocarbons etc. These tests usually include both controlled laboratory testing and side-by-side testing for several weeks in field conditions. The tests were not done in a setting necessarily representative for CCS monitoring, with the influence of turbidity, marine growth, water currents or chemical components resulting from leakage or production activity. Testing a broader spectrum of sensors and sensor combinations for durability and stability over time and development of knowledge about parameter variability and co-variability and methodologies based on this to identify leakage situations, is identified as a gap.

According to [10], current off-the-shelf sensors for CO_2 and pH are only suitable for short-term deployment due to fouling and interference issues. Experience with long-term deployment for monitoring of methane leakage indicates that some sensor types based on membrane diffusion may already have potential for long-term deployment [12]. CO_2 or pH sensors based on the same principle should have the same level of resistance against fouling and marine growth.

7. Discussion and conclusions

In most cases, national and international regulations for CCS monitoring are clear on the monitoring objectives, for instance emission limits, plume expansion and reservoir conformity. They are less clear on *how* to achieve these objectives; monitoring strategies has to be developed on a site-by-site basis. When specifying CCS regulations for specific projects or storage sites, companies may have incentives to formulate internal requirements to leakage monitoring in addition to official regulations;

- regulations can be tailor-made to site and operation,
- performance and acceptance criteria can be quantified more precisely,
- ability to demonstrate that no leakage is present,
- public opinion and acceptance for new projects.

If existing environmental guidelines are followed, and the fines for CO_2 leakage stay on today's level, the most important motivation for implementation of water column CO_2 monitoring is arguably the reputational risk. The table below indicates that current state of the art technology has the potential to fulfil current regulatory and industry requirements. The capabilities and potential for each technology mentioned previously are assessed with regards to detection, localization, quantification and characterization ability. Note that this is a general assessment and comparison of the different technologies– there are large variations in the capabilities of different sensors depending on the system design. In addition, the limitations relate to how sensors are typically used today. While multibeam, single beam, side-scan, and SAS systems today are usually not calibrated, that could change in future developments, making leakage quantification possible.

Table 2 - Detection, localization, quantification and classification potential for different sensor technologies.

Sensor technology	Detection	Localization	Quantification	Characterization
Calibrated single/split beam echosounder	Good	Good	Potential	No
Multibeam sonar	Good	Good	No	No
Single beam scanning sonar	Good	Good	No	No
Sidescan sonar	Limited	Good	No	No
Synthetic Aperture Sonar	Limited *	Excellent	No	No
Passive acoustic	Good**	Limited	Potential	No
Chemical sensors	Good***	Limited	Limited	Yes

*: Gas leakage is poorly imaged using standard synthetic aperture sonar processing due to the non-stationarity of rising gas bubbles. However, targeted processing algorithms have been proposed which enable leakage detection [25] [37].
**: Recent research indicate that the use of passive sonar offers good detection capability and has potential for quantification [28].
***: Key to successful usage is that sensor placement takes local current pattern into account, as well as interpretation of natural variations in the baseline versus leakage indications.

Most sensor types in Table 2 have good capabilities for detection and localization of leakage. However, the detection and localization capability of acoustic sensors are good only for leakage in gas phase. Acoustic systems for detection of liquid phase leakage are being developed, but the technology is less mature. Chemical sensors are not able to detect gas phase leakage, but can detect CO_2 and formation fluids dissolved in the water column as a result of molecular mixing. We recommend that ambitious monitoring strategies should include both acoustic and chemical sensors for leakage detection in an integrated monitoring system.

Quantification of a leakage is necessary in order to assess both economic, environmental and reputational risks. Quantification techniques has previously been reviewed in [40]. Table 7 gives an overview of the quantification potential for different acoustic and chemical sensor technologies. Currently, a calibrated single- or split-beam sonar and passive acoustic sensors are the technologies with most potential for leakage quantification. These sensors can be used in stationary installations or in ship-mounted or AUV surveys. An alternative that is not yet on the market but technologically feasible is calibrated multibeam, synthetic aperture, or sidescan sonars. While calibration of these systems should be feasible, a remaining challenge is lack of knowledge about bubble size distributions for each leakage for reliable quantification. Such estimates can be obtained from detailed monitoring of representative leakages, such as demonstrated in e.g. [41], [26], [21]. Without calibration, only relative or rough estimates of flux are obtainable.

Being inherently sensitive to specific substances only, we classify chemical sensors as having good characterization capabilities. Currently, only monitoring systems including chemical sensors are able to characterize leakage as either CO2, CH4, or other substances. In order to detect leakage in chemical measurements, one needs site specific and long-term knowledge of the baseline concentration, as well as knowledge of the interplay between concentration and current, temperature and other secondary parameters. This emphasizes the importance of integrated monitoring strategies for CCS.

Most of the sensor types in Table 2 can be mounted on the seafloor, on a moving platform such as an AUV, or on the hull of a surveying vessel, which opens for different approaches to design of CCS monitoring strategies.

Several topics for further research were identified, including integrated monitoring strategies, and data processing for automatic leakage detection, as well as extensive hardware testing and demonstration of emerging technologies in a realistic environment.

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