21GRD06 MetCCUS

D4 - Report on the options for the measurement and reporting of emissions to air from different stages of the CCUS process and the performance and capabilities of techniques to monitor emissions into the environment through carbon capture processes, infrastructure (leaks), or geological storage

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TABLE OF CONTENTS

1 Summary

This report addresses the options for the measurement and reporting of CO_2 emissions to air from different stages of the CCUS process and the performance and capabilities of techniques to monitor emissions into the environment through carbon capture processes, infrastructure (leaks), or geological storage.

2 Introduction

Europe plans to reduce CO_2 emissions to meet stringent reduction targets related to climate change. Carbon capture utilisation and storage (CCUS) can be used to remove the CO_2 produced by industrial processes for storage either underground or locked in an alternative material. To accomplish this goal, it is necessary to develop the metrological support to enable the measurement and reporting of emissions to air from different stages of the CCUS process. The CCUS stages are (i) Capture (ii) Transport and (iii) Utilization or Storage.

This report addresses the options for the measurement and reporting of emissions to air from these different stages of the CCUS process and the performance and capabilities of techniques to monitor emissions into the environment. The report addresses specifically the assessment of fugitive CO_2 emissions produced by leaks at CCUS stages i.e. by individual components up to large scale facilities.

Nothing is absolutely tight; therefore, tightness should be defined by the smallest detectable leak based on the chosen leak detection technique. While bubble testing is hardly quantitative, it can detect leaks down to 10^{-3} cm^3/s (Standard conditions, 101.325 kPa, 273.15 K). Other techniques employing portable leak detectors may offer greater effectiveness. Consequently, the result of a leak test should not be 'leak-tight' or 'no leakage,' but rather as 'leakage < 10^{-3} Std cm^3/s", for a bubble test.

The atmospheric amount fraction of CO_2 is approximately 400 µmol/mol (= ppm), a number that has been increasing steadily since the mid-1800's (where it was estimated to be about 280 ppm), and especially within the last 50 years, with no signs of stopping. This value should serve as the minimum concentration of interest for leak detection in the CCUS infrastructure. Any amount fraction exceeding this value is indicative of possible leakage. While small CO_2 leaks may be negligible in certain applications, the ability to quantify such leaks is crucial in deciding whether to 'neglect,' 'repair,' or simply 'monitor.' Therefore, the quantification of leak rates should be performed at the various stages of CCUS infrastructure.

The primary motivation for monitoring CO_2 leakage is based on environmental and health and safety considerations. Given that the entire CCUS process is expected to prevent the release of CO_2 into the atmosphere to combat climate change, it is crucial for the entire infrastructure to maintain gas tightness. Furthermore, elevated concentrations of CO_2 pose a health risk, with levels exceeding 5000 ppm representing both the Permissible Exposure Limit (PEL) and the Threshold Limit Value (TLV) for an 8-hour exposure given by US agencies (OSHA and ACGIH).

Beyond environmental and health concerns, there are economic implications associated with leakage that cannot be disregarded. Leaks often serve as indicators of a defective or faulty component, necessitating attention and potential repair. Therefore, addressing and minimising leakage not only align with environmental and safety objectives but also contribute to the overall efficiency and reliability of the CCUS infrastructure.

The term 'leakage' refers to an unintentional loss of process fluid, through defects in components, welding, valves, seals, etc. It is often measured using two distinct quantities: concentration and flow rate. An alternative way to determine leakage is by monitoring the amount of stored fluid that's lost per unit of time, should one want to look at an entire facility as a whole. While most portable leak detectors focus on concentration, it is the flow rate that enables the accurate calculation of CO_2 emissions and, consequently, the assessment of its potential environmental impact. When leak detectors are equipped with a suitable pump, concentration can be converted to leak rate by directing the entire leakage into the detector.

Depending solely on concentration measurements may not provide a reliable indicator of the leak size and certainly not of the emission rate. Therefore, if it isn't possible to perform measurements of leak rate, it is crucial to use methods that convert concentration measurements into leak rates or correlate measured concentration with an estimate of leak rate. This conversion can be accomplished through the application of reference leaks or flows, or by the use of correlation factors as detailed in EN15446 (for VOC emissions, correlation factors for CO_2 would need to be established).

3 Options for the measurement of emissions to air from different stages of the CCUS process

There are different measurement techniques and method for measuring CO2 emissions. EN1779 outlines criteria for selecting the most suitable method and technique for assessing leak tightness through the measurement of gas leakage. The standard encompasses three primary methods: tracer gas, bubble test, and pressure change. Each of these methods is further divided into several techniques based on factors such as the target tightness and the side under pressure.

For CCUS infrastructure, the use of portable detectors aligns with Technique B3 'Accumulation' and B4 'Sniffing test.' The former is recommended for leak measurement, while the latter is suitable for leak location. The specified minimum detectable leak is 10^{-6} Std cm3/s, but this is inherently limited by detector sensitivity and background signal considerations, as discussed earlier.

Technique B3, also referred to as 'bagging,' involves using a hood around the test area. If a large hood is employed, it provides the integral leak rate for all potential leaks underneath, even intermittent leaks. If the test result is positive, then leak sources can be pinpointed by scanning the area with the detector probe. Measurement traceability is achievable by using a calibrated reference leak connected to the same hood for a defined period.

While basic, bubble testing by spraying a surfactant (Technique C2) offers sufficient sensitivity for many scenarios. Though not quantitative, the proposed minimum detectable leakage is 10 Std cm3/s, albeit operator-dependent. Constraints, such as the need for access to all areas, a free line of sight, and permission for wetting the areas under testing, often limit the use of this technique to specific situations.

In cases where a section of the infrastructure can be isolated by closing valves, the pressure decay test (Technique D1) serves as an integral leak test for the whole section and intermittent leakage can also be identified. In the event of leakage, portable leak detectors can be employed for locating the leak. For larger volumes, the minimum detectable leakage is influenced by how well the temperature can be maintained constant during testing, limiting the application of this technique. A decrease in 1 K is equivalent to an apparent loss of 0.3% of the volume (≈1/300) in the gas under pressure inside the section. In the case of a large volume, such apparent leakage is equivalent to a huge leakage rate.

At large scale facilities, leak monitoring techniques currently used in natural gas sites may not all be applicable to carbon dioxide monitoring. For example, Optical Gas Imaging (OGI) is commonly used in natural gas monitoring because methane is very visible in IR, while CO_2 detection remains possible. Aerial/satellite remote sensing is challengng and an option in the natural gas industry, but still not as advanced in CCUS considering that the CO_2 signal is weaker in open air (atmospheric column of CO_2 is already quite significant, thus it would need a very large source to produce an enhancement above that column). Factors to consider when choosing different techniques include the detection sensitivity, background levels of CO_2, regulatory requirements and integration of multiple methods. For contnous monitoring, some systems are commercially available. They include, non-dispersive infrared (NDIR) analysers, Tunable Diode Laser Absorption Spectroscopy (TDLAS), among others. They represent a promising real-time monitoring solution considering their robustness for stack and area monitoring, as well as high sensitivity. Costs are still high for stationary emission monitoring and technical challenges to track non-stationary emissions remain (Ding. et. al, 2025).

3.1 Techniques for fugitive CO_2 emission measurements at the component spatial scale

The following are techniques typically use for CO_2 leak detection as well as their capabilities and performances.

3.1.1 Non-Dispersive Infrared (NDIR)

NDIR sensors operate based on the absorption of infrared light by CO_2 molecules. As the IR light passes through the sample tube of air, the CO_2 gas molecules absorb the specific band of IR light while letting other wavelengths of light pass through. At the detector end, the remaining light hits an optical filter that absorbs every wavelength of light except the wavelength absorbed by CO_2 molecules in the sample tube.

NDIR-based CO_2 sensors offer several advantages:

- High selectivity to CO_2, with minimal cross-sensitivity to other gases;
- Long-term stability and robustness, as they are non-consumable sensors;
- Low maintenance requirements compared to chemical or electrochemical alternatives.

However, performance differences between devices may arise from:

- The optical path length and internal geometry of the sensor;
- The quality of filters and detectors used;
- The presence or absence of active air sampling (e.g., pump-assisted vs. passive diffusion);
- Environmental compensation, particularly for temperature and humidity effects.

In the context of leak detection or ambient CO_2 monitoring in CCUS environments, these factors can strongly influence detection thresholds, response times, and the ability to operate reliably under variable conditions. Recent developments in sensor design have improved the robustness and miniaturisation of NDIR instruments, enabling their deployment in both laboratory and field environments. Low-cost commercial sensors have become increasingly popular for large-scale monitoring networks, although they require appropriate calibration and environmental compensation (e.g. for temperature, pressure, and humidity) to achieve high accuracy. Research has also addressed long-term drift, particulate matter interference, and integration with portable or UAV-based systems, demonstrating the adaptability of the technique to diverse measurement contexts. Overall, NDIR sensors offer a balance of sensitivity, reliability, and operational simplicity, making them particularly suitable for detecting and quantifying CO_2 emissions from industrial processes, leak monitoring, and environmental surveys.
As an example in the MetCCUS project to ensure traceability, NDIR detectors were tested against reference leaks developed by NOVA and validated at NPL using a primary piston volumetric flow standard. Stainless-steel capillaries provided reproducible CO_2 flows in the range of 20–100 sccm for input pressures between 1 and 5 bar, with agreement between NOVA and NPL results within ±5% of the calibration certificate. GC-column-based capillaries allowed lower flow rates (≈3–20 sccm) but showed instability and blockages under higher pressures, confirming stainless steel as the preferred material for robust reference leaks.
Using these calibrated leaks and additional test setups at NOVA and NPL, the following results were obtained:

Minimum detectable leak rates: NDIR detectors reliably detected leaks as low as ~5 sccm ($\approx 10^{-3}$–10^{-4} Std cm^3/s) when the probe was held within a few millimetres of the source.

Static tests: At leak rates between 5 and 20 sccm, clear signal increases were recorded, with response times of a few seconds. Signal variability of ~± 8% was observed, attributed mainly to passive diffusion sampling.

Dynamic tests (probe in motion): Successful leak localisation was possible, but performance strongly depended on probe speed and alignment. Slower scanning (≤ 6 mm/s) yielded clearer peaks correlated with plume passage.

Field simulations at NPL: The detectors identified leaks from 5 to 30 000 sccm in flange and tube fitting assemblies. At short distances (≤3 cm), even the smallest leaks (5 sccm) produced detectable signals. For larger leaks (≥ 5 000 sccm), sensors reached saturation (>30 000 ppm), confirming sensitivity but also highlighting dynamic range limitations.

Environmental effects: Natural ventilation significantly reduced signal stability and amplitude, underlining the importance of controlled sampling conditions or repeated scanning in real-world applications.

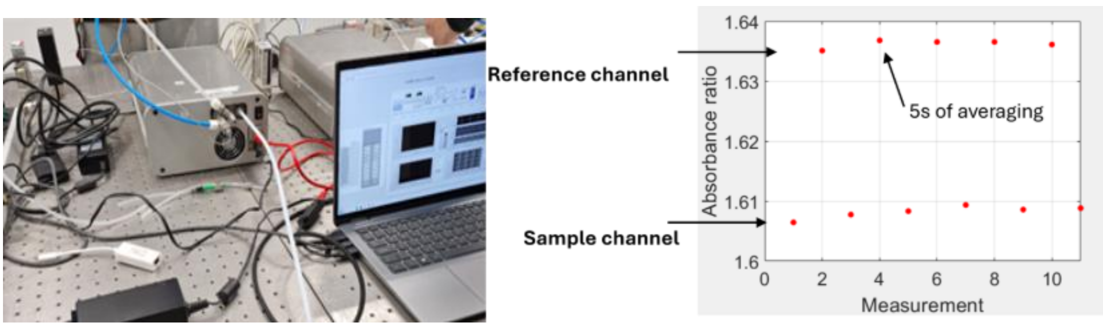
The joint NOVA–NPL work demonstrated that NDIR leak detectors, when benchmarked against traceable reference leaks, provide a reliable means to detect and localise CO_2 emissions in CCUS-relevant conditions. While quantitative correlation between leak rate and measured concentration is limited by plume dispersion and passive sampling, the technique is highly effective for identifying leaks above ~10 – 30 sccm and for monitoring CO_2 accumulation indoors. Stainless-steel capillaries were shown to be robust and accurate tools for establishing reference leak flows on order of 100 sccm, enabling consistent laboratory-to-field comparisons and supporting the development of harmonised benchmarking protocols. (References: J. Hodgkinson, Sensors 2013, 13, 13984–14018; S. Kim, S, Sensors 2022, 22, 11874: Y. Zhang, Sensors 2023, 23, 5123; Z. Liu, Sensors 2021, 21, 10455).

3.1.2 Tunable Diode Laser Absorption Spectroscopy (TDLAS)

TDLAS sensors use a tunable diode laser to measure the absorption of specific wavelengths of light by CO_2. The focus here is on a single absorption line in the absorption spectrum of CO_2 (or other species of interest). The wavelength of a diode laser is tuned over a particular absorption line and the intensity of the transmitted radiation is measured. Some advantages of TDLAS are high sensitivity and selectivity. However, they are expensive compared to NDIR instruments.

In the scope of this MetCCUS project, VTT tested the feasibility of detecting CO_2 leaks from geological storage sites using an optical isotope ratio spectrometer (OIRS), based on TDLAS, developed at VTT. The instrument was tested both in the laboratory and at a field site hosted by PTB. PTB performed parallel measurements with ambient CO_2, while VTT carried out measurements using pure CO_2 and controlled gas mixtures designed to simulate leak conditions.

The measurement campaign was conducted at PTB in March 2025 and included four main experiments, ranging from laboratory calibration against reference gases to field mixing tests and PTB's CRDS instrument (see section 3.1.3). The experiments were conducted using the VTT optical isotope ratio analyzer, which has two input ports (sample and reference). The analyzer alternates between the two channels and determines isotope ratios of CO_2 by measuring the absorbances of $^{13}C-CO_2$ and $^{12}C-CO_2$. Each data point corresponds to a 5-second average, and each measurement cycle (3 minutes) consists of six sample and five reference measurements as shown in Fig. 1. Optimal thermal stability was reached approximately 40 minutes after power-up, and Allan deviation predicted 0.1‰ measurement precision for $\delta^{13}C/\delta^{12}C$ and $\delta^{18}O/\delta^{16}O$ ratios as shown in Fig. 2.



(a) (b)

Fig. 1: The isotope analyzer setup in the laboratory is shown in (a), while the plot in (b) illustrates example absorbance ratio measurements. Each red dot represents a 5-second average of the sample and reference channel signals.

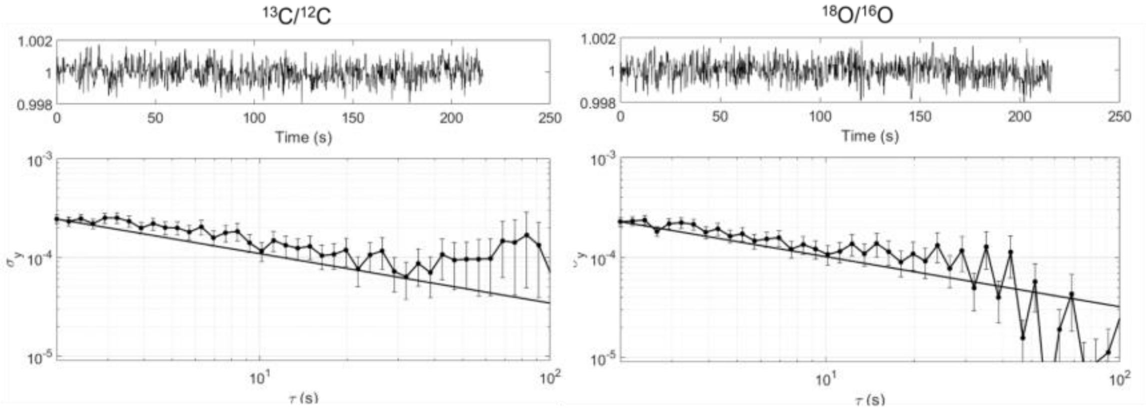
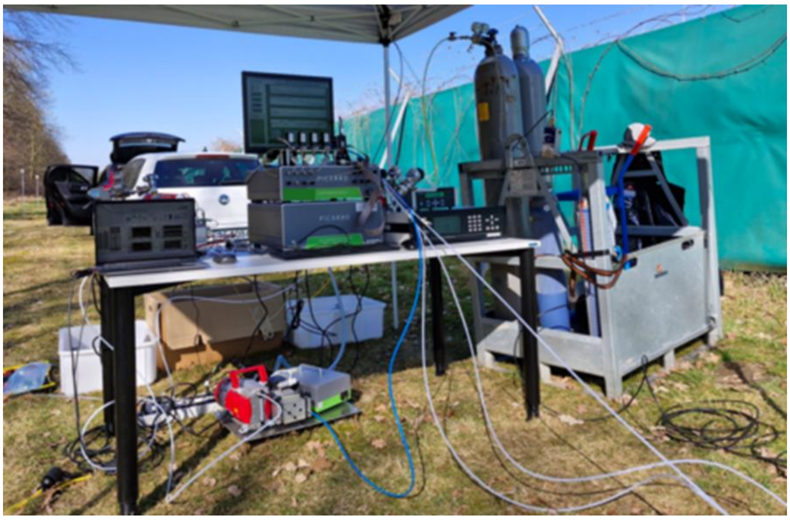


Fig. 2: The figure presents an Allan deviation analysis, where the upper panels show time series data for the $^{13}C/^{12}C$ and $^{18}O/^{16}O$ measurements, and the lower panels display the corresponding Allan deviation plots. The Allan plot demonstrates the instrument's stability as a function of averaging time.

The analyzer was validated in laboratory measurements by testing sample gases containing pure CO_2 as well as low-concentration CO_2 (2000 ppm). Subsequently, field measurements were performed to detect isotopic shifts in gas mixtures by dynamically mixing two gases using mass flow controllers. The experimental field setup and the corresponding results for the mixing ratios are shown in Fig. 3.



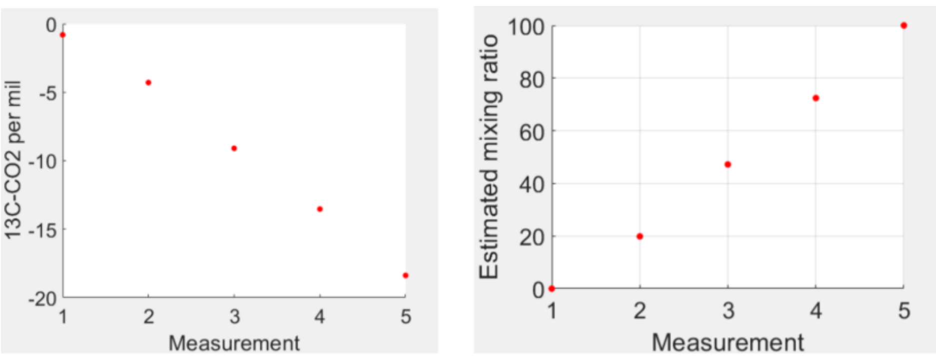


Fig. 3: Experimental setup at the PTB field site for CO_2 isotope ratio measurements, including the VTT optical spectrometer, reference gas cylinders, and auxiliary equipment is shown in the upper panel. Isotopic measurements of CO_2 mixing ratios are shown in the bottom panel. The left panel shows $\delta^{13}C$-CO_2 values for individual measurements, while the right panel presents the corresponding estimated mixing ratios, demonstrating the analyzer's ability to resolve changes in sample composition.

The analyzer tracked the isotopic shifts as expected across the mixing ratios. The $\delta^{13}C$ results showed close agreement with theoretical mixing values, with deviations within a few per mil. $\delta^{18}O$ results also followed the mixing pattern, though with greater scatter. These findings confirmed that the instrument could capture isotopic gradients in real-time mixing scenarios, an essential feature for field-based carbon cycle studies.

3.1.3 Cavity Ring-Down Spectroscopy (CRDS)

In CRDS the ringdown time with and without absorption by CO_2 is measured. By means of these ringdown times, the absorption coefficients is calculated, which is used in the evaluation of the CO_2 amount fraction (=concentration). CRDS is a very sensitive spectroscopic technique due to multiple reflection of laser light in a high finesse cavity reaching effective pathlength of many kilometres. Using CRDS, the concentration of CO_2 as well as the isotope ratio ($\delta^{13}C$-CO_2) can be measured for leak detection.

At PTB controlled release experiments (see Figure 4) were carried out to determine if CO_2 isotope ratio (isotopic shift) can be used for leak detection from CO_2 underground storage facilities.

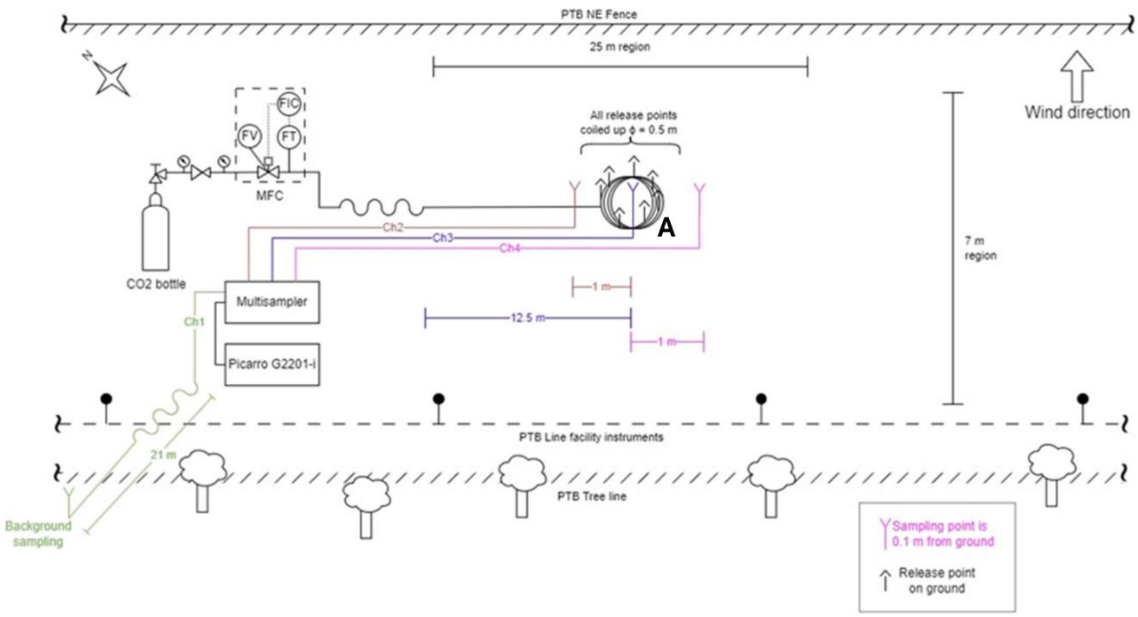


Fig. 4: Schematic of CO_2 release experiment setup at PTB. MFC: Mass flow controller. Ch: Chanel

As shown in Fig. 4, a CRDS instrument (Picarro) with a multi-sampler was used to perform the measurements. Figure 5 depicts measurements (CO_2 amount fraction and $\delta^{13}C$-CO_2) performed while switching from channel 1 to 4. Note that ppm = µmol/mol. As shown in Fig. 4, Ch 1 (sampling pipe) measures ambient CO_2 isotope ratio far away from Ch 2, 3 and 4 which are each 1 m away from the release point. For a CO_2 source (from the CO_2 bottle in Fig. 4) with $\delta^{13}C$-CO_2 of -20 ‰ release at point A, isotope ratios up to about -18.75 % (see Fig. 5) were measurement while switching from one channel to the other, corresponding to isotopic shifts up to about -10.75 ‰ away from ambient level of about -8 ‰, demonstrating that CO_2 isotopic shifts can be used for CO_2 leak detection.

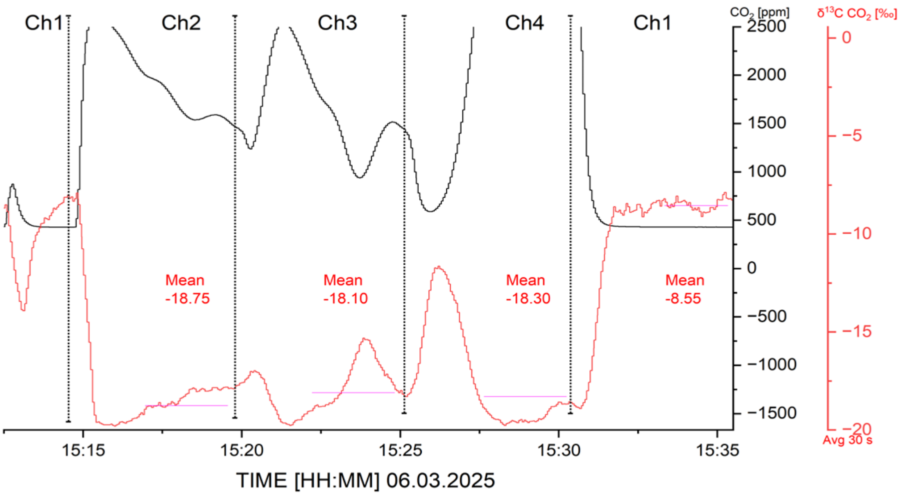


Fig. 5: Carbon dioxide amount fraction (= concentration) and isotope ratio ($\delta^{13}C$-CO_2) results

3.1.4 Photoacoustic sensors

These sensors measure the sound waves produced by the absorption of modulated light by CO2 molecules. As the pulsed IR radiation is absorbed, the gas heats up and expands, being detected by e.g. a microphone as a sound wave. The advantages of Photoacoustic sensors is high sensitivity and selectivity. However, they would be more expensive compared to NDIR sensors.

3.1.5 Electrochemical sensors

When CO_2 enters the sensor, it chemically reacts within the sensor. As this reaction occurs, the sensor experiences an electrical change. Depending on the specific type of sensor, the reaction can make the sensor pick up an electrical current, change an existing current, or change how well the sensor would carry a current. The sensor will then use the type and amount of electrical change to determine how much CO_2 is present. An advantage of electrochemical sensors is that they are portable and cost effective. However, they have limited lifespans and are sensitive to environmental changes.

3.1.6 Metal Oxide Semiconductor (MOS) sensors

Similarly, to Electrochemical sensors, MOS sensors detect changes in electrical conductivity based on the interaction of CO_2 with a metal oxide. A MOS sensor has a metal strip or film that is exposed to the air you want to test. This strip has a constant electric current running through it. As the target gas comes into contact with the piece, it will interact with the metal and change the chemical composition either through a reduction or oxidation reaction. When this happens, the resistivity, or conductivity, of the metal will be altered. Some advantages of MOS are that they suitable for some portable applications and are cost effective. However, the have moderate accuracy and are sensitive to environmental changes.

3.1.7 Capacitive sensors

These sensors measure changes in capacitance caused by the interaction of CO_2 with a dielectric material. When a CO_2 molecule interacts with the dielectric layer, it causes a change in the capacitance of the device. This change in capacitance can be measured and used to determine the concentration of the target gas. One of the key features of capacitive gas sensors is their use of specialised polymer-based dielectric materials. These materials can be engineered to selectively interact with specific gas molecules, allowing selective gas detection. An advantage of capacitive sensors is that they have low power consumption. However, May have limited accuracy compared to some other sensors above

3.1.8 Thermal conductivity sensors

Thermal conductor CO_2 sensors measure CO_2 concentration based on the relationship between CO_2 gas's thermal conductivity and its concentration. The sensor includes a thermocouple or a thermal resistor, with one part heated and maintained at a constant temperature, and another part serving as a reference temperature. When CO_2 gas flows through the sensor, it carries away heat from the heated part, resulting in a temperature difference. The sensor measures this temperature difference and converts it into a CO_2 concentration reading. Some advantages of Thermal conductivity sensors are that they have a simple design, are costs effective, **s**uitable for detecting various gases including CO_2. However, the have lower sensitivity compared to some of the sensors above and are prone to interference of other gases and from changes in humidity and pressure.

It could be noted that, some of the above sensors face limitations such as a restricted detection range, making them well-suited for monitoring overall CO_2 concentration but less effective in pinpointing small leaks in polluted ambient. Additionally, selectivity challenges may arise, causing some sensors to produce 'false' signals for CO_2 in the presence of other gases and vapours. Another critical factor is the response stability over time, particularly affecting solid-state sensors that may age rapidly when exposed to elevated gas concentrations. This ageing can result in a permanent change in sensitivity, necessitating sensor replacement, a need that can be confirmed only through the use of reference leaks or calibrated mixtures. Optical-based sensors stand out with superior performance, as they detect the intensity of IR radiation. Photon to electric current conversion is not affected by the composition of the sampled gas. Therefore, these sensors are very stable in the long term.

3.1.9 Other emerging solutions for CO_2 emissions measurements

The following summarizes other emerging and promising CO_2 leak detection technologies as well as specific advanced CO_2 leak monitoring solutions

Emerging and promising CO_2 leak detection and quantification methods

- Fiber Optic Sensing (Distributed Sensing). Advantages include high spatial resolution, real-time data, scalability.
- Geochemical and Tracer-Based Monitoring. MetCCUS report A2.3.4 explores zero background tracer suitability for geologically stored CO_2.
- Acoustic Emission and Beamforming Techniques. Detects the sound signature of gas leaks using arrays of microphones or piezoelectric sensors.
- IoT and AI-Enhanced Sensor Networks. Internet of Things (IoT) online monitoring technology that connect various types of sensors forming Wireless Sensor Networks (WSN), that transmit data over the internet for remote access, allowing simultaneous monitoring of different parameters. Combining IoT technology with Artificial Intelligence (AI) and Machine Learning (ML) could lead to the development of advanced automated monitoring systems.
- In MetCCUS report A2.2.6, a proof of concept high flow sampling instrument for CO_2 leak quantification was developed, with an asociated method of use. It was demonstrated that emission rates from point source fugitive emissions with emission rates between 20 and 5000 mL/min could be measured.

Specific advanced CO_2 leak monitoring solutions

- Soil Gas Flux and Surface Monitoring. Soil accumulation chambers and flux meters detect CO_2 emissions at the ground surface, useful for CCS sites and facility perimeters (Pokryszka et al, 2010). This method is field-proven in CCS and industrial sites. However, background CO_2 flux can complicate interpretation; spatial coverage is limited.

- Geophysical monitoring (sonic, acoustic, fiber optic). Time-lapse seismic (4D seismic), distributed acoustic sensing (DAS), and vertical seismic profiling are used to monitor subsurface CO_2 movement and potential leak pathways (Li. C., Zhang, X., 2024)

3.2 Capabilities and performance requirements for CO_2 leak detectors (VTT)

Generally, the following capabilities and performance requirements are proposed for CO_2 instruments (or sensors) based on the techniques in section 3.1:

1. Instrument shall be equipped with a suction probe so that a continuous sample is provided to the detector.
2. The instrument shall preferably have a scale in leak rate and / or concentration units.
3. The limit of quantification (LOQ) for CO_2 shall be 10^{-3} Std cm^3/s or 100 ppm, so that the background level can be securely measured.
4. The limit of detection (LOD) shall be 10^{-4} Std cm^3/s or 10 ppm.
5. Instruments shall have a minimum measurement range up to 10 L/min or 50 000 ppm (5%).
6. Instruments shall have a response to other common process gases lower than 10% of the CO_2 signal for the same concentration or leak rate.
7. Instrument response time shall be equal to or less than 5 s, measured when 90% of the stable reading is attained after a ‘zero gas’ is switched to a calibrated mixture.
8. Repeatability over the whole range shall be lower or equal than 10 %.
9. Instruments shall be calibrated annually against traceable standards with a measurement uncertainty equal or lower than 10%.
10. The maximum drift over one year shall be lower or equal to 5×10^{-4} Std cm^3/s or 50 ppm.

4 Reporting of CO_2 emissions

With the introduction of the European Green Deal and the Corporate Sustainability Reporting Directive (CSRD) (EU regulation 2022/2464), reporting of CO_2 emissions will become mandatory or is already mandatory for most industries and companies. In addition to the reporting responsibilities, large businesses and companies in the energy, marine, transport and aviation sector have to participate in the EU Emissions Trading System (ETS or ETS2). This system introduced a capped CO_2-equivalent allowance per industry which will be gradually reduced each year to reduce the CO_2 emissions. The allowances can be allocated by the member states or bought by the companies on an allowance market. An exception in the ETS states that no allowances must be surrendered in case CCS technologies ensure that the generated CO_2 is verifiably stored permanently (EU directive 2003/87/EG). In case of leaks out of the CCS facility the operator of the facility must account for the leak and surrender the equivalate number of CO_2 allowances. In accordance with EU directive 2009/31/EC also known as CCS Directive, the amount of CO_2 stored as well as any leaks must be reported to the national authorities. Operators of CCS facilities are also required to develop a monitoring plan which must be approved by the national authority. In addition to these European regulations, the Greenhouse Gas Protocol (GGP) gives further guidance on how to calculate and categorize CO_2 emissions. Parts of the GGP have been converted into the international standard ISO 14064. Future reporting structure requirements for fugitive emissions from CCUS infrastructure could be based around those recently developed for methane by the Oil and Gas Methane Partnership (OGMP 2.0), or those for diffuse VOC emissions detailed in EN17628 and EU Regulation 2024/1787.

5 Conclusions

The options for the measurement and reporting of emissions to air from different stages of the CCUS process and the performance and capabilities of techniques to monitor emissions into the environment through carbon capture processes have been identified and summarized in this report. Some of the sensors (or instruments) as well as methods for CO_2 leak detection were tested as part of the MetCCUS project. In a joint NOVA–NPL work, it was demonstrated that NDIR leak detectors, when benchmarked against traceable reference leaks, provide a reliable means to detect and localise CO_2 emissions in CCUS-relevant conditions. Findings with a TDLAS instrument confirmed that the instrument could capture isotopic gradients in real-time mixing scenarios, an essential feature for field-based carbon cycle studies. In controlled release experiments with a CRDS instrument, it was demonstrated that CO_2 isotopic shifts can be used for CO_2 leak detection.