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Measurement technologies for pipeline transport of carbon dioxide-rich mixtures for CCS

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ABSTRACT

Carbon capture and storage (CCS) is necessary to achieve the long-term temperature goals of the Paris Agreement. The mass of CO_2 that will be transported for permanent storage by 2050, to meet the International Energy Agency (IEA)'s Sustainable Development Scenario, is of a similar scale to the current global market of natural gas. Such trading levels require significant and expedited technological efforts. The urgency of the climate goals requires technological innovations to build from existing technologies operating in similar environments. The present work aims to be a stepping stone towards the realisation of the CCS business, which relies on accurate metrology and tight control systems. Here, various established technologies are screened, and for each principle, their possible niches of operation within CCS are identified. Eight technologies were shortlisted and assessed against selected benchmarking criteria. The most promising solutions for the various operative scenarios encompassing bulk flow measurement, structural flow identification, composition, and leak detection are described. All surveyed technologies require further experimental verification for one or more of the operating schemes throughout the CCS value chain. A roadmap to further explore the applicability of various measurement principles in CCS is also provided.

1. Introduction

The Paris Agreement treaty acknowledges the need to address climate change, a concern for humankind. Reducing the global CO_2 emissions in 50–85 % by 2050 to meet the Paris Agreement targets requires widespread Carbon Capture and Storage (CCS) [1]. Successful business models are the stepping stones towards the realisation of a full-scale CCS value chain. Reducing risks and costs throughout the value chain is key for widespread CCS. Transport and control of the CO_2-rich streams are key to the reduced financial risks of CCS trading parties.

Enabling fair CO_2 accounting and optimized process control is fundamental for the extensive implementation of CCS. Technologies for monitoring the transport of CCS streams are still in an early stage of development. The performance of the most promising flow measurement technologies has yet to be thoroughly assessed for all CCS conditions [2]. The theoretical applicability of various CO_2 flow metering techniques at different conditions has been previously investigated [2–10]. Benchmark studies have shed light on the most promising technologies for flow measurement. However, the focus of most of such studies [6–8] has been on accurate flow measurement, i.e., fiscal metering, for CCS. Initial assessments point out that existing commercially available measurement equipment can only address part of the measurement needs in ongoing and future CCS projects. Broader measurement and monitoring needs are thinly documented [11]. Limited experimental data exists on inline second-phase identification technologies or composition measurements for transporting CO_2-rich mixtures.

This work focuses on readily available technologies that can expedite the deployment of CCS transport through pipelines. Most existing multiphase flow metering technologies integrate several sensing principles with the combined potential of detecting and measuring phase distributions and flow rates. Such technologies often combine two or more of the following: differential pressure technology (e.g., Venturi meter), gamma densitometer, and electrical or microwave measurement [12]. Gravimetric and or volumetric flow and phase recognition have also been used for years in various other industries. An earlier work [13] shows that the applicability of these commercially available sensors for CO_2 pipeline transport has not been assessed thus far. Further research must be conducted to enable such solutions to meet the CCS requirements. The present work aims to provide a better understanding of the potential of eight of such technologies for CCS, and highlights some of the existing knowledge gaps. This paper combines a literature review

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of metering principles, including experimental and theoretical assessments, and insight knowledge from technology developers. Thus, the work provides, for the first time, an overview of the most promising technologies to meet the diverse metering and monitoring needs of CCS pipeline transport. It differs from published work on the breadth of technologies assessed, the number of transport needs covered and the inclusion of techno-economic aspects. Further, the proposed roadmap addresses both wide-ranging and specific development needs for some of the assessed technologies.

An outline of the operational framework for the CCS value chain is presented in Section 2. A survey of existing technologies is provided in Section 3. Section 4 shows a benchmarking study highlighting the possible niches of operation of each principle. A plan to further explore the applicability of various measurement principles in CCS is depicted in Section 5.

2. Method

The methodology adopted to identify promising metering solutions for CCS pipeline transport is based on recognizing challenges and requirements, surveying existing technologies, and categorising their potential applications.

2.1. CCS transport requirements

Expectedly, normal pipeline operations for CCS will transport single-phase CO_2-rich mixtures in gas, liquid, or dense phases. The composition of the CCS stream varies in time and space depending on the upstream capture processes and CO_2 sources [11]. The most common impurities in the CCS streams are O_2, N_2, Ar, H_2O, SO_2, H_2, and CH_4.

The current stage of development of the CCS industry means that there is limited publicly available information on the process conditions and specifications of upcoming projects. After a thorough review of the more advanced developing projects [14–18], the specifications for measurement and control of CCS networks were narrowed down to those defined in Table 1. Overall, gas CO_2-mixtures are expected at the outlet of capture plants and in onshore networks, and liquid/dense phase in export pipelines, loading and off-loading terminals, export pipelines, and injection wells.

The CCS value chain and stream phases are illustrated in Fig. 1. The colour of the pipelines shows the predominant phase state throughout the CCS value chain. A thorough description of the flow metering nodes along the CCS value chain is given in Ref. [23]. A simplified view of the metering points and post-capture metering nodes described in Ref. [23] is also illustrated in Fig. 1.

2.2. CCS networks measurement challenges

The overarching use of measurement technologies in the developing CCS value chain comprises (i) process monitoring, as redundancy measurements, or to complement other measurement methods in multimodal configurations, as well as composition and flow-phase checks to ensure the accuracy of flow metering devices; and (ii) flow assurance, including dry ice formation, pipeline integrity, and leak detection [13, 23].

Measurement equipment shall help operators control the process and overcome the following predominant challenges:

Dynamicity of the network. Unlike traditional fossil fuel-based power plants, industrial CO_2 sources will not continuously operate at baseload conditions 24/7. The asynchronous inlet of CO_2 streams in the transport networks grants temporal and spatial variations in the compositions of the streams, mass flow rate, pressure, and temperature. Such operational

Table 1
CCS projects with total CO_2, a summary of conditions and processes.

Parameters	Capture clusters	Onshore pipeline/network	Offshore/ Export pipelines	Subsea wellhead	Remarks
Phase state	Gas	Gas[a]	Liquid/dense		[a] Most onshore pipelines will handle CO_2 gas, except for the Sapling project that plans to transport CO_2 onshore in a dense phase [19]
Flow rate [t/h]	31–160	450–1150	450–1700 [b]		[b] Flowrates and offloading terminals are estimated based on the number of ducts, the target storage capacities of the consulted CCS projects, and a discussion with relevant stakeholders.
Process temperature [°C]	ambient - 40	ambient	-2–8		
Ambient temperature [°C]	−20–30	−20–30	3–20	3–15	Northern Europe/North Sea location
Pressure [barg]	2–50	15–70[b]	50–120		[b] Most onshore networks plan for a maximum pressure of 70barg, except for the Sapling project, which aims at a maximum pressure of 120 barg [19].
Impurities	[%mol]	[ppm v/v]			
O_2	0.04–5	5–50,000			Composition in clusters is the maximum range of impurities from capture given by IPCC, in agreement with range of compositions at the outlet of various capture technologies [20].
N_2	0.02–10				
Ar	0.005–3.5				
NOx	<0.002–0.3	10–2000			Impurities in pipeline transport account for limits imposed in existing demonstration projects [21].
SO_2	<0.001–1.5				
H_2O	-	30–100			The early stage of the CCS projects results in very cautious specifications. Thus, strict and often only implicit limitations for non-condensables other than O_2, i.e., N_2, Ar, CH_4, etc., are given.
H_2S	0.005–6.5	9–100			
CO	<0.001–0.2	100–900			
H_2S/COS	0.01–1.5				
H_2	0.06–4				
Amines	0.7–4				
NH_3	<0.001–0.01				
SOx		10–25,000			
Pipe diameter [inch]	N/A	24–36	12–30	6	
Pipe thickness [mm]	N/A	8.525–19.05	6.35–28.575		Considers the nominal wall thickness for seamless and welded steel pipes according to ANSI B36.10. The maximum operating pressure of the CCS pipes was set slightly above the maximum allowable pressure as per Barlow's formula for A53 Grade B Steel Pipe with a Yield Strength of 35 ksi and design factor of 0.7 [22].

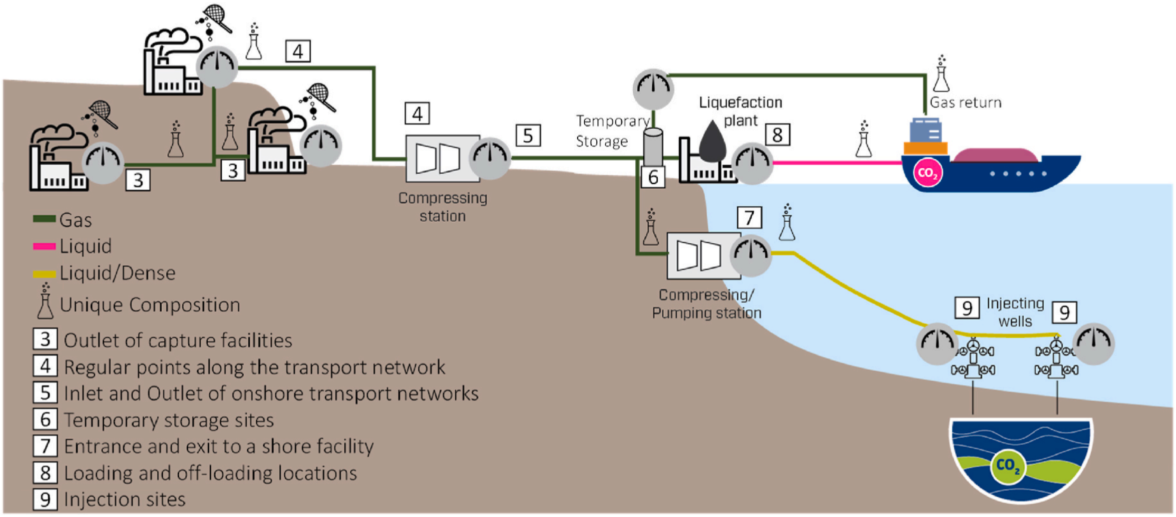


Fig. 1. CCS value chain showing post-capture measurement nodes and varying stream composition.

changes yield distinct flow assurance challenges.

Varying composition. Different capture processes produce a distinct assortment of impurities in CO_2-rich streams. Even in small concentrations, impurities could drastically affect the phase behaviour and cause a two-phase flow where the composition of each phase will differ. A second phase will typically be enriched with possibly flammable, corrosive, and or toxic impurities.

Formation of an impurity-enriched second phase. Two-phase transport is expected in various scenarios depending on the operation conditions, terrain topology, and operational philosophy. Some causes for two-phase flow include unintended shutdown sequences, terrain topography favouring liquid deposition in low points, evaporation of components from the CO_2 liquid stream, or operational conditions close to the saturation line, as is the case of CO_2 ship offloading. Two-phase flow can considerably deteriorate the accuracy of the measurement technologies.

2.3. *Definition of technologies with potential for CCS networks*

A thorough literature review was performed to identify metering solutions that could, in principle, be used to overcome the above challenges. Screening state-of-the-art metering solutions allows identifying promising technological options for further consideration. Emphasis was put on the technology readiness level (TRL) in similar operating conditions to increase their applicability for CCS.

The Technology Survey section provides an overview of the metering principles analysed. Vendors' self-assessments were vital to ensure the relevance of the selected technologies and subsequent analysis; for more details of the surveyed technologies, refer to the Appendix.

2.4. *Assessment criteria*

Four criteria were used to assess the suitability of the various technologies in addressing the unique challenges that CCS transport presents, namely.

2.4.1. *Bulk measurement*

Multiple components in the flow can yield multiphase flow, in which, depending on the ratio of inertia to gravity forces, the phases can distribute within the pipe in a segregated or distributed form [24]. In this work, the term bulk refers to the average properties of the fluid over the pipe cross-section, as if the phases were homogeneously distributed. It does not mean that such is the case. In this sense, bulk flow measurement is the overall flow rate of all combined components in a given period. Other properties like permittivity and density can also be referred to in bulk or average terms.

2.4.2. *Phase identification*

Even in small concentrations, impurities in the streams could drastically affect the phase behaviour and can considerably deteriorate the accuracy of the measurement technologies, especially if a second phase arises. It is relevant to identify the presence of a second phase, particularly for composition tracking and to ensure the health of meters that are flow-pattern or phase-sensitive, like fiscal meters.

2.4.3. *Composition*

The measurement of- or the measurement-based estimation of the species and concentrations in the pipeline is relevant for inline-quality checks and process control.

2.4.4. *Leak detection*

The use of the technologies for leak detection here encompasses both measurement-based leak identification and technologies that enable flow-based leak detection and mass balance tracking.

3. Technology survey

Eight technologies were shortlisted, and their applicability for CCS applications is discussed below. A full review of their capabilities is provided in Table 5 to Table 13.

3.1. *Dielectric measurements*

Dielectric measurement principles rely on the sensitivity of the sensors to changes in the dielectric properties of the fluids. The difference between the dielectric properties of different components gives rise to variations in the inter-sensor measurement. Dielectric measurements allow monitoring the temporal evolution of the phase fractions of multiphase flows via different techniques, i.e., capacitive-, conductive-, impedance-, microwave-, or induction-based measurements. The different dielectric techniques have different properties and may find different application areas within the CO_2 monitoring space, or combinations could be advantageous. Capacitance-based measurement is one of the best-established dielectric measurement principles [25–31]. The technology is commercially available and has a proven uncertainty of down to 2 % for the measurement of volumetric fractions of contrasting permittivity of oil-gas mixtures [32,33], which could be leveraged for CCS applications.

There have been limited applications of dielectric-based methods for CCS. The results of an electrical capacitance meter tested in CO_2 show that the cross-sectional distribution of two-phase CO_2 can be successfully monitored with 6 % accuracy for gas holdups of 0–77 % [34]. Capacitance methods combined with ultrasonic measurements have also been used at a lab scale to monitor CO_2 capture processes [35,36]. Further, pilot tests for geological monitoring of CO_2 were successful in the Northeast German Basin [37]. The work in Ref. [13] discussed that the contrasting electromagnetic properties of the components of the CO_2-rich streams can be leveraged by dielectric measurement techniques. The contrast between the CO_2 and common impurities, for gas and liquid CO_2 pipeline transport, can potentially be detected, provided water fractions are low enough to avoid parasitic coupling [38].

Dielectric sensors have potential for estimation of phase fractions as redundancy measurements or to complement other measurement principles. Phase change identification would offer opportunities for real-time measurement corrections in CCS, especially for measurement from phase- or flow regime-sensitive technologies, like fiscal meters.

3.2. *Gamma*

Gamma radiation is a form of electromagnetic radiation deriving from the radioactive decay of atomic nuclei. Gamma rays have been successfully used for density measurements, where the attenuation of the radiation through a media is related to the density of the matter. Gamma-ray apparatus typically use radiation in the range from 10 keV to 1 MeV. The choice of energy depends on measurement geometry and materials, including piping and fluid components.

There is limited bibliography on gamma-ray technology for applications fitting for CCS. As a proof-of-principle, the publications from Kelly et al. [39,40] provide a relevant indication of the potential of gamma-ray-based technology to identify dry ice. Using gamma rays, Kelly et al. obtained an approximation of the thickness of a CO_2 frost layer (dry ice) within g/cm^2 resolution. As per the work in Ref. [13], the density contrast between dry ice and CO_2 mixtures in post-carbon capture processes is in the order of 1 g/cm^3 and above. However, the photon energy should be chosen so that the count rate at normal conditions is sufficiently high for CO_2 transport. Such count rate, which depends on the density of the stream, is estimated to range from 5 keV for low-pressure gas phase up to 50–90 keV for liquid CO_2 for a 25 cm path length [13]. One limiting factor is the contrast between different components. Although there is some contrast for Ar, H_2, and CH_4, detecting small impurities dissolved in gas or liquid could prove unfeasible with gamma-ray. Expectedly, gamma density measurements would find its most relevant niche of application as input for differential pressure flow rate measurements.

3.3. *Ultrasonic measurements*

Ultrasonic flow meters measure the velocity of a fluid to calculate volume flow. Time-of-flight ultrasonic meters employ transducers to alternately send and receive ultrasonic pulses, recording the transit time of the signal between the transducers. Factors like fluid viscosity, temperature, pressure, and acoustic signal attenuation affect the measurements. The latter depends on the sound frequency and properties of the specific fluid of interest.

In recent years, ultrasonic technologies have evolved such that many measurement challenges of CCS can be overcome using more sophisticated and powerful signal processing features and diagnostics. Ultrasonic technologies have been the subject of evaluations for various CCS-relevant applications, including CO_2-blends with natural gas [41,42], CO_2-pure or close-to-pure CO_2 in the gas phase [10] and pure CO_2 in the liquid phase [43].

The attenuation of ultrasound waves through CO_2 is a challenge. Although attenuation is not unique for CO_2, the predominant deterrent is that the acoustic attenuation peak for gaseous CO_2 is in the frequency range typically used in ultrasonic flowmeters [44]. This effect is, however, less prominent for liquid CO_2, as the relaxation frequency is approximately proportional to density up to 900 kg/m^3 [45–47]. For most process conditions relevant to CCS pipeline transport in the liquid phase, where density is lower, signal degradation yielded reduced accuracy, with a deviation from the theoretical speed of sound of over 4 % [43]. In the gas phase, ultrasonic measurements in Ref. [10] replicated speed of sound estimations within 1.5 % range.

3.4. *Coriolis*

Coriolis flow metering consists of one or two measuring tubes that vibrate at their natural frequency. The fluid through the vibrating tubes is forced to accelerate or decelerate as it moves toward or away from the point of peak-amplitude vibration, respectively. The forces exerted by the tubes on the flowing fluid cause a delay or time shift between the inlet and outlets of the tubes. These forces are proportional to the inertia and, therefore, to the mass flow of the fluid. Given that the measuring tubes are constrained, the stiffness is affected by changes in the process fluid temperature. To correct for such changes, Coriolis meters employ compensation algorithms.

Small-scale studies [4–6] have shown that Coriolis mass flow meters perform adequately under CCS-similar conditions. In the absence of a large-scale liquid CO_2 test rig, stakeholders claim that Coriolis calibrations for fiscal metering are currently based on existing standards and tests with water and oil [48,49].

3.5. *Differential pressure*

There are various types of Differential Pressure (DP) flow measurement devices. Orifice plates rely on the principle that a pressure differential is proportional to the flow rate across an orifice placed in a pipe. The key influence on the overall meter accuracy is the accuracy of the differential pressure measurements, especially at lower flow rates, and the knowledge of the fluid properties, particularly the density, which must be either measured or inferred. Measuring the density leads to an added uncertainty. Calculating the density from the equations of state becomes more challenging with increasing number of impurities in the CO_2 stream. Orifice plates DP meters are a well-established, relatively low-cost technology that can be easily scaled to large pipelines. They have long been used in CO_2 injection for Enhanced Oil and Recovery (EOR), where accuracy requirements (5 % [50,51]) are more relaxed than for CCS (1–2.5 % [52,53]). A recent study [54] proposed new equations for mass calculation from Orifice plates for CO_2 service. The new equations can reduce the system's overall flow rate prediction uncertainty while increasing the metering system's flow turn-down. However, the approach was tested only with up to 40 % CO_2 content in a natural gas blend.

Similarly, Venturi DP meters restrict the flow in a pipe section, throat. The increased flow velocity and corresponding pressure drop enable the deduction of the flowrate via Bernoulli's equation across the throat. For a compressible fluid, there will be a change in density when it passes through the contraction.

A review of the main available options for CO_2 measurement for CCS is provided in Ref. [3]. The Venturi meter has been demonstrated subsea and has the added advantage over other benchmark technologies, like ultrasonic, in that it has a lower sensitivity to density changes. Accordingly, Venturi meters are expected to perform well for all fluid phases and large pipelines, but shortcomings are envisioned when a second phase is formed, and impurities are present.

3.6. *Absorption spectroscopy*

Absorption spectroscopy measures the concentration of impurities in the CO_2 gas stream and, in some cases, the determination of the phase of the material. In an absorption spectroscopy system, a light emitted from a source is passed through a sample of interest. Then, the light is detected by an intensity detector or a spectrometer. Gas spectroscopy in the infrared region (IR) is common. IR light can induce molecular vibrations, causing unique absorption at wavelengths for each gas, provided there is no crossover with other gases. To ensure that the measured absorption only results from the gas being measured, it is important that only the intensity at the specific wavelength is detected. For practical reasons, a tuneable diode laser is used as the monochromatic source, i.e., tuneable diode laser absorption spectroscopy (TDLAS). To measure several gas impurities, a TDLAS system would require several lasers, tuneable in the region of a spectral line of each impurity to measure, yielding increased costs. Instead, using a spectrometer as the sensor, several spectral lines can be detected simultaneously with the same system. Dry ice could be detected with TDLAS since the transmission spectra of solid and gas phases differ, as shown in Ref. [55].

Fourier-transformed infrared (FTIR) spectroscopy is a common method for inspecting large spectral ranges. The linewidth of a spectral line depends on several factors, including pressure and temperature [56]. High-pressure and or high-temperature concentration measurements are often infeasible, as the broadening decreases the sensitivity and might lead to crossover. The maximum pressure depends on the gas constituent mix; it is, however, rarely feasible above 2 bar.

Absorption spectroscopy is well established in several industrial processes, with systems like the ones required in a CCS setting. However, there are no public records of spectroscopy systems aimed explicitly at high-concentration and high-pressure CO_2 streams. To illustrate the potential of spectroscopy systems in a CCS pipeline setting, we must appraise systems aimed at other gas streams. Two state-of-the-art systems are considered here, i.e., the TDLAS system “LaserGas II SP” from NeoMonitors [57] and the FTIR system MGS300-KIT from MKS [58]. Table 2 below summarises the impurities that can be detected with an IR absorption spectroscopy system. Due to the high pressure intended, all impurities, other than oxygen, are only detectable using bleeder systems.

Table 2
Impurity concentration and indication of measurability with IR absorption spectroscopy.

Impurity	Typical impurities in CCS streams [%mol]	Detection range [ppm v/v]	Measurable in low-pressure bleeder system
O_2	0.04–5	5–50,000	Yes
N_2	0.02–10		No
Ar	0.005–3.5		No
NOx	<0.002–0.3	10–2000	Yes
SO_2	<0.001–1.5		Yes
H_2O	–	30–100	Yes
H_2S	0.005–6.5	9–100	Yes
CO	<0.001–0.2	100–900	Yes
H_2S/COS	0.01–1.5		N/A
H_2	0.06–4		N/A
Amines	0.7–4		N/A
NH_3	<0.001–0.01		N/A
SOx		10–25,000	Yes

3.7. Optical particle counter

The principle of an optical particle is based on a light source aimed at the gas/liquid stream, which is then detected using a photosensor. If a particle is in the optical path, the light will scatter, reducing the detected signal. The reduction in intensity will depend on the size of the particle. Therefore, most optical particle counters can count particles into different-size bins. As with the spectroscopy system, either a window or a bleeder system is needed for accessibility.

Optical particle counters are currently used in several industries, including clean room facilities, pharmaceuticals, hydraulics and oil and gas monitoring, yet not in CCS applications. However, optical particle counters suited for high-purity CO_2 streams are commercially available, like in Ref. [59], for in-line particle counting of high-purity process gasses.

3.8. Distributed fibre optic sensing

Distributed fibre optic sensors can measure strain and temperature over long distances with relatively high spatial resolution. By detecting abnormal temperature changes along a pipeline, gas leakage locations can also be estimated.

A fibre optic distributed temperature and strain (DiTeSt) monitoring system is often based on a nonlinear optical effect called stimulated Brillouin scattering [60]. Brillouin scattering results from light scattering by sound waves in the material [61]. The scattered light is frequency-shifted due to the Doppler effect. The magnitude of this shift is denoted the Brillouin shift and is linearly dependent on the temperature and strain of the material.

Distributed temperature and strain sensors have already been used for pipeline monitoring, providing structural monitoring and leakage detection. However, these systems are typically custom-made, meaning that performance will vary. Similar systems should, in theory, apply to CO_2 pipelines.

The technical characteristics of the surveyed technologies are summarised below. Table 3 depicts the characteristic capacity of the sensing principles, costs, TRL for CCS, typical dimensions, and knowledge gaps. The data is based on the review of the references therein and vendor’s self-assessments. More details are in the Appendix.

3.8.1. Analysis

Table 4 summarises the potential applicability of the technologies studied for the process conditions described in the criteria above. A qualitative scale of poor, intermediate, and good scale was used. The applicability of the technologies for all process conditions throughout the value chain was considered, i.e., gas, liquid, and multiphase flows for pipeline and shipping offloading operations. The operational window of the technologies and installation requirements/limitations were also studied and detailed as annotated comments. The shaded cells highlight the technologies with higher potential per criterion.

In general, for bulk flow of single-phase CO_2-rich flow measurements, DP, Ultrasonic, and Coriolis meters have, as expected, the largest applicability. Dielectric and gamma-ray are also promising for bulk flow measurements and provide advantages when a second phase is formed. The capabilities of these technologies to monitor changes in the mixture’s relative permittivity and density can also shed light on variations of the stream composition. Although for inline composition analysis, absorption spectroscopy is the best solution of the ones studied. Yet for field operations, either transparent windows or a bleeder system that lowers the pressure are needed.

Identification of a second phase, e.g., gasified species or dry gas in a liquid stream, can be potentially done in line with gamma- and dielectric-based meters and to some extent with optical techniques. Regarding the former two, the capabilities depend on the volumetric rate of the minor phase being larger than the spatial resolution of the equipment. Further identifying the spatial distribution of such phases within the pipe cross-section, and correspondingly the properties, requires special setups with various sensors around the pipe perimeter. Optical particle counters can potentially be used to detect dry ice particles in liquid or gaseous CO_2 stream, making it useful in a setting where dry ice formation is a possibility.

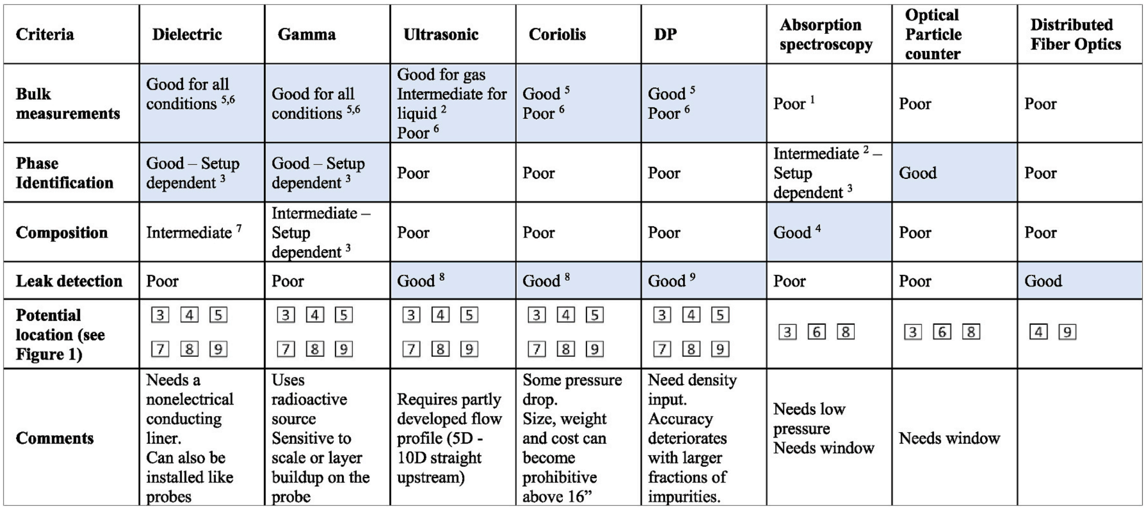
Distributed fibre optics is the best option for expediting the detection of small leaks. Due to large installations of fibre optics in long pipeline systems, combining bulk flow measurement technologies with pressure and temperature monitoring may be beneficial. Other technologies identified either rely on mass balances, with intrinsic delays in detection capabilities or require large leak volumes.

Table 3
Summary of technology characteristics.

Technology	Principle/Sensitivity	Capacity	Cost[a]	TRL	Dimension range	Pressing knowledge gaps
Dielectric	Permittivity (changes in composition)	Permittivity contrasts of 0,2 and above are feasible [13]	€	3	All (Likely to be implemented as a probe)	Sensitivity to the various impurities expected in CCS streams. Accuracy for small fractions.
Gamma-ray	Density (changes in composition)	Density difference of 1–2 kg/m3 and above are feasible [13]	€	3–4	All (No limit of pipe diameter)	Sensitivity and accuracy to phase changes CCS streams. Relevant fraction and flow structure that hinder the use.
Ultrasonic	Speed of sound (flow rates)	Up to 47,000 m^3/h (gas) and 22000m3/h (liquid)	€€	3–6	4" - 30″	Attenuation of CO_2 and impurities in liquid phase. Transducer design to meet accuracy requirements
Coriolis	Mass/density	Up to 550 t/h	€€	9	Typically 16″ and smaller	Validity of water calibration for high accuracy applications. Accuracy for service with supercritical fluids.
DP	Pressure difference across a constriction	Depends on size, beta ratio and required accuracy. E.g., 20–300 m^3/h for a 5″	€	9 for single phase, pure CO_2	Up to 24″	Effects of impurities at varying concentrations in performance of DP meters.
Absorption spectroscopy [57,58]	Infrared absorption (composition)	<10 ppm	€-€€	3	All (bleeder system required)	Effects of high CO_2 concentration not validated.
Optical particle counter [59]	Photosensitivity (bubble/droplets/solids detection)	100 % efficiency for large particle sizes	€€	9	All (bleeder system required)	Relevant size of dry ice particles that can be detectable.
Fiber Optics [62]	Strain and Temperature (leak detection)	1–3 m of spatial resolution	€/km	6	Up to 150 km range	Masking of environmental CO_2/pH variations

[a] € → <50 k EUR, €€ → 50 k-200 k EUR, €€€ → >200 k EUR.

Table 4
Potential applicability of in-line measurement system.



Criteria	**Dielectric**	**Gamma**	**Ultrasonic**	**Coriolis**	**DP**	**Absorption spectroscopy**	**Optical Particle counter**	**Distributed Fiber Optics**
Bulk measurements	Good for all conditions [5,6]	Good for all conditions [5,6]	Good for gas Intermediate for liquid [2] Poor [6]	Good [5] Poor [6]	Good [5] Poor [6]	Poor [1]	Poor	Poor
Phase Identification	Good – Setup dependent [3]	Good – Setup dependent [3]	Poor	Poor	Poor	Intermediate [2] – Setup dependent [3]	Good	Poor
Composition	Intermediate [7]	Intermediate – Setup dependent [3]	Poor	Poor	Poor	Good [4]	Poor	Poor
Leak detection	Poor	Poor	Good [8]	Good [8]	Good [9]	Poor	Poor	Good
Potential location (see Figure 1)	$\boxed{3}$ $\boxed{4}$ $\boxed{5}$ $\boxed{7}$ $\boxed{8}$ $\boxed{9}$	$\boxed{3}$ $\boxed{4}$ $\boxed{5}$ $\boxed{7}$ $\boxed{8}$ $\boxed{9}$	$\boxed{3}$ $\boxed{4}$ $\boxed{5}$ $\boxed{7}$ $\boxed{8}$ $\boxed{9}$	$\boxed{3}$ $\boxed{4}$ $\boxed{5}$ $\boxed{7}$ $\boxed{8}$ $\boxed{9}$	$\boxed{3}$ $\boxed{4}$ $\boxed{5}$ $\boxed{7}$ $\boxed{8}$ $\boxed{9}$	$\boxed{3}$ $\boxed{6}$ $\boxed{8}$	$\boxed{3}$ $\boxed{6}$ $\boxed{8}$	$\boxed{4}$ $\boxed{9}$
Comments	Needs a nonelectrical conducting liner. Can also be installed like probes	Uses radioactive source Sensitive to scale or layer buildup on the probe	Requires partly developed flow profile (5D - 10D straight upstream)	Some pressure drop. Size, weight and cost can become prohibitive above 16"	Need density input. Accuracy deteriorates with larger fractions of impurities.	Needs low pressure Needs window	Needs window	

1 Some applicability for bulk measurements might be feasible depending on the species.
2 Requires experimental validation.
3 Performance is dependent on the arrangement/setup.
4 For high accuracies (ppm) sampling is required. For higher concentration thresholds (%) useful information might be obtained at higher operating pressure.
5 Pipeline service (gas and liquid phase), shipping offloading (supercooled liquid).
6 Operating conditions where multiphase flow can arise.
7 Small changes in impurities (within the same phase), likely difficult to identify.
8 For flow-based leak, tracking mass balance.

Beyond the above potential of the technologies to independently address the identified challenges for CCS pipeline transport, combining of two or more solutions can prove beneficial. The operation of a technology that identifies and quantifies a second phase in series with a flow meter can yield corrected flow metering accuracies. Similarly, real-time identifications of varying compositions in the stream can assist operators in better-informed decision-making for process control.

3.8.2. *Roadmap*

The following is a guide to advancing TRL of monitoring & control technologies for CCS. The roadmap comprises four stages and builds on the roadmap proposed in Ref. [63]. The guidelines focus on demonstrating capabilities of sensors for CCS service (stage development 1 in Ref. [63]).

The present roadmap focuses on some of the abovementioned technologies to expedite their deployment. Having established the need for a metering solution, the immediate steps to advance beyond the current state of the art comprise: (i) identifying metering principles with the potential to solve existing challenges. This requires a deep understanding of their principle of operation, capabilities, and sensitivities.

Following, a (ii) theoretical validation of such promising principles is needed. Such validation requires dedicated assessments of the technological product, its capabilities and potential to meet the specification in the operating environment of interest. This step benefits from simulations, in-depth theoretical analyses, and dialogue with technology developers. Here, a review of available experimental data in the literature and understanding the uncertainty of reference data and models is needed. A thorough insight into existing datasets and models for CO_2 is given in Ref. [64].

Next, (iii) a proof of principle of functionality in relevant CCS environments needs to be designed and executed. For such proof, a test campaign must cover the operational envelope of interest. Selection of CO_2-mixtures that are well documented and of isotherms, with good agreement with predictions in the operational range of interest, e.g., 274–303 K, is of paramount relevance. The campaign shall be defined so that after completion, it answers if the performance of the equipment is as predicted

Using specific cases, 'type tests' are discussed following. Such type tests serve as examples of how to test some functionalities in the hope of closing part of the knowledge gaps identified in Table 3. Care is advised, as the design of the experiments shall be tailored to establish the limits of the technology, and thereby its applicability under different conditions. Such design shall also consider the sensitivity of the metering principle under tests. Moreover, different conditions or impurities can yield contrasting behaviours and metering needs. For demonstration purposes, a CO_2–N_2 mixture is used following. However, the selection of target concentrations shall consider the sensitivity of metering equipment and, to the largest possible extent, typical concentrations of the given impurity in CCS streams.

Fig. 2 shows the pressure-CO_2 concentration diagram of a CO_2–N_2 mixture at 288 K. The figure illustrates three state points in grey markers. At 100 bar, 'A', we find pure CO_2 in the liquid state. In 'B', the mixture contains 90%mol CO_2 and 10%mol N_2. State 'C' is in the two-phase region where the liquid phase containing close to 95%mol CO_2 and 5%mol N_2 coexists with a gaseous phase containing 68%mol CO_2 and 32%mol N_2.

3.8.2.1. Proof of functionality of technologies for phase identification. A density-based technology (like gamma) would require a sensitivity greater than 0.2 g/cm^3 to identify a second phase at conditions 'C'. For a dielectric-based technology, the relative-permittivity-sensitivity necessary to differentiate between the two phases is in the order of 1×10^{-1} Fm/Fm. Since calibrations with pure CO_2 and pure N_2 are advised for both methods, a logical testing sequence would be A-B-C. Tight mass balances are needed as well as continuous sampling.

3.8.2.2. Proof of functionality of technologies for composition changes. Assessing absorption spectroscopy for a multicomponent mixture requires tuning the laser so that the specific wavelength or the targeted component is detected. Considering typical impurities and the indication of measurability with IR absorption spectroscopy in Table 2, the rate of transmission (0–1) of CO_2 and (0.9–1) impurities is plotted in Fig. 3. For the assessment, it was assumed that a bleeder system is used at atmospheric conditions. The transmission coefficients were estimated using HITRAN database [28]. From Fig. 3, it is evident that wavelengths for CO_2 and other components, like N_2 and O_2, at the concentrations and conditions given are different; thus, measurement is feasible. Dry ice could also be detected, as solid and gaseous CO_2 transmission spectra differ (see Fig. 4, which is a simplified view of the transmission spectra in Ref. [25]).

Since absorption spectroscopy requires low pressure, a special setup must be used, ensuring the homogeneity of the bleeding line compared to that of the main flow. Thus, testing the accuracy of an absorption spectrometer for conditions between A-B, or a similar single-phase path in the liquid phase region, would require gasification of the sample. For tests, the meter shall be installed in series with a gas chromatograph.

3.8.2.3. Bulk flow measurements for CCS streams. Increasing the TRL of ultrasonic technologies and DP meters requires decreasing the measurement uncertainty. Both technologies provide volumetric flowrates, hence, relying heavily on knowledge of the stream density, and, thus, of the composition.

To advance the TRL of ultrasonic meters for CCS, it is critical to characterise the acoustic properties of the CO_2-mixtures correctly. There is limited reference data on the speed of sound of CO_2 at conditions relevant to CCS. Experiments from Lin and Trusler [47] show a 1.5 % deviation in the speed of sound from the Span−Wagner equation of state at pressures between 80 and 250 bar. The lack of traceable liquid CO_2 calibration facilities, in addition to the reported deviation in the speed of sound measurements to the reference model, precludes validation of such meters at the required measurement accuracy (1 % [52]). Data and consecutive model improvement are key for the further development of the technology, and for the optimum selection of the operating frequency and processing method of weak signals.

Finally, (iv) communication of results from the proof of concept is paramount. Any deviations identified shall be fed back to the manufacturer and the general audience such that necessary changes are

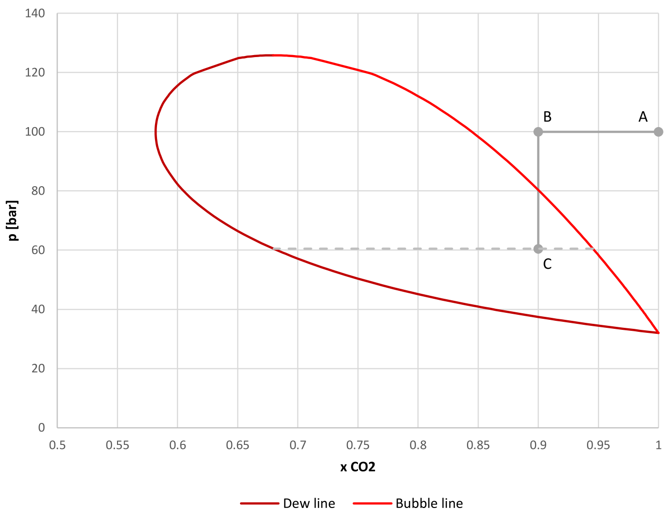


Fig. 2. Pressure-Composition diagram of CO_2–N_2 at 288 K

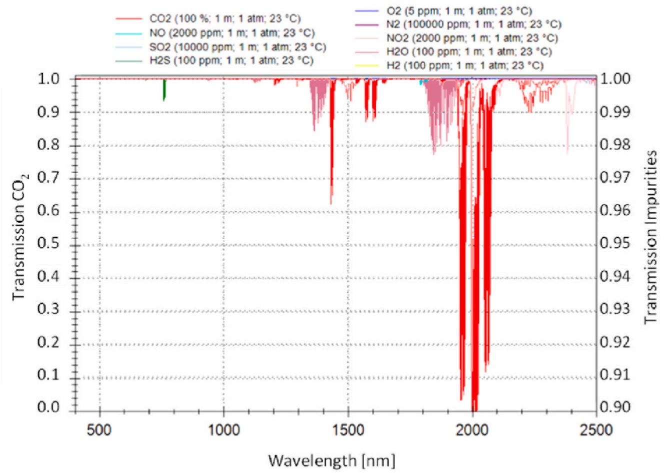


Fig. 3. Rate of transmission spectra for 1 m path length for CO_2 and impurities at wavelengths between 400 and 2500 nm. Conditions are atmospheric (1 bar, 23 °C).

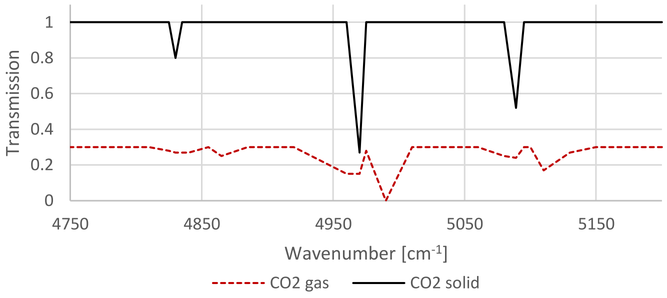


Fig. 4. Transmission spectra of CO_2 in solid and gas phase from 1.9 to 2.1 μm wavelength (figure modified from Ref. [25]).

incorporated for further product development.

4. Conclusions

Successful implementation of metering solutions within the CCS value chain offers improved process control and flow assurance monitoring. This work assessed eight high TRL technologies and their potential to address the challenges of CCS networks, i.e., dynamic operation schemes, varying stream composition, formation of an impurity-enriched second phase with possible impacts on the integrity of the pipelines and equipment, as well as on the accuracy of fiscal metering devices.

The complexity of challenges and operating conditions in pipeline networks precludes the existence of a one-size-fits-all solution. This work discussed what technological modalities could address the identified measurement challenge and how their sensitivity can be better exploited. Most of the technologies analysed can be instrumental in the control of CCS networks, particularly as redundancy or in complementary setups.

Five measurement technologies have been identified as feasible for CO_2 measurement and monitoring of average properties of the fluid along the pipe cross-section, e.g., flow, composition, and density. The most pressing challenge for deploying flow measurement technologies (ultrasonic, Coriolis, and DP) is related to the lack of demonstrated accuracy (between 1 and 2.5 % as per current regulations) at all operating conditions of CCS systems.

Optical-, density- and dielectric-based technologies have the potential to identify phase separation and quantify volumetric fractions. However, the sensitivity of such metering principles to detect density variations in the order of a fraction of a g/cm^3 and in the same range for permittivity contrasts is challenging and requires proof-of-concept tests. Examples of such tests have been outlined in the roadmap section.

Inline composition monitoring of streams is readily available and broadly applicable via hyperspectral, dielectric, and gamma solutions. Nonetheless, measurement access to the process can be challenging, especially at high pressures. For absorption spectroscopy, a thorough design of bleeder systems is required, and during initial tests, a gas chromatograph in series is needed. Large limitations for field use and accuracy are expected; thus, possible applications need to be studied on a case-by-case basis.

This work focused on technologies with a solid record of applications in environments like CCS and considered the challenges of CCS networks. However, applying the various benchmarked solutions requires further work, as only a few technologies have been tested for selected scenarios relevant CCS applications, as is the case of, e.g., flow meters for CO_2 in gas form. For all solutions, it is necessary to understand how small mass fractions in the CO_2 stream affect their capabilities and accuracies. A road map was developed to address some of the most pressing challenges to advance the TRL of the technologies for CCS applications. The roadmap exemplifies how, via type tests, the sensitivity of some technologies can be tested as proof-of-concepts.

CRediT authorship contribution statement

Y. Arellano: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing - original draft, Writing - review & editing. **S.-A. Tjugum:** Formal analysis, Investigation, Validation, Writing - original draft. **O.B. Pedersen:** Formal analysis, Investigation, Methodology, Writing - original draft. **M. Breivik:** Formal analysis, Investigation, Writing - original draft. **E. Jukes:** Formal analysis, Investigation, Validation, Writing - original draft. **M. Marstein:** Formal analysis, Writing - original draft.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Yessica Arellano reports financial support was provided by Research Council of Norway.

Data availability

No data was used for the research described in the article.

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APPENDIX A

Characteristics of measurement principles

Table 5
Summary characteristics of the Dielectric measurement technology (Ref: Consultation with technology developer ans specs of Roxar™ 2600 MPFM [65], and APL-C-900 [66])

Parameters	Value/range	Comments
Measurement range	Full range	No relevant as it is not used for fraction measurement and not flow rate measurement
Process pressure limit	700 bar is possible	Will most likely be a probe for large pipe sizes (8″ and above)
Process Temperature range	−20 °C–130 °C	
Ambient temperature	−20 °C–50 °C	
Composition ranges/limitations	0–10 % impurities in CO_2	The upper limit is likely higher. Accuracy declines for small fractions.
Pressure drop	0	
Multi-phase sensitive	Free gas will influence the measurement uncertainty. The effect of free gas will depend on the dielectric properties of the impurities and will be less for water compared to other impurities.	

(*continued on next page*)

Table 5 (*continued*)

Parameters	Value/range	Comments
Density relation	N/A	
Weight and footprint	Requires 2 inch entry flange. In the range of 10–20 kg.	Likely to implemented as a probe
Recalibration interval/method	Not assumed to require recalibration	Recalibration would most likely require the probe to be retrieved from the line.
Long-term measurement stability	Not assumed to drift	The electronics can self-calibrate against internal reference
Dimension range	All	Likely to implemented as a probe
TRL	TRL 3 or 4	The technology must be proven for CCS
Knowledge gaps	Sensitivity to the various impurities	
Zero stability	TBD	Assumed very high stability based on use in Oil and Gas applications.
Other limitations/advantages	Will be sensitive to scale or layer buildup on the probe.	

Table 6
Summary characteristics of Gamma technology (Ref: Consultation with technology developers from ROXAR, specs of Roxar™ 2600 MPFM [65] and work in Ref. [13])

Parameters	Value/range	Comments
Measurement range	Full range	The density gauge must be designed to fit the required measurement range. This implies choosing the gamma-ray energy (by choice of isotope) and the beam path length through the flow.
Process pressure limit	No limit	The source and detector are not exposed to the process pressure. These components will be installed on the outside of the pipe or outside a pressure barrier.
Process Temperature range	No limit	The system should be designed so that the detector is not exposed to the process temperature, in particular for high process temperatures.
Ambient temperature	−40 °C–60 °C	Some industrial gamma-ray detectors can be used up to 60°C or short periods of 70°C.
Composition ranges/ limitations	No limitation	
Multi-phase sensitive	The density gauge typically measures the centre beam density of the flow.	For inhomogeneous flow the centre beam density is often different from the cross-sectional density.
Density relation	The electron density of the material is measured, this is close to proportional to the mass density.	The relationship between mass density and electron density depends on the molecular composition of the material.
Weight and footprint	This depends on the isotope used and the detector technology. A typical weight range is 10 kg–60 kg and the components are most often small enough to fit on a 20 cm pipe spool.	The gamma ray density gauge can vary in size and weight. High energy gamma-rays require a larger shield.
Recalibration interval/method	Calibration on empty pipe or know flow density, typically on a yearly basis	The calibration interval depends on the required accuracy and the detector stability.
Long-term measurement stability	Typically, 2–5 kg/m^3 drift of measured density between calibration intervals.	Higher accuracy could be obtained by the choice of detector technology, gamma-ray energy and measurement geometry.
Typical list price	In the range of 100 kNOK for a full system	
Dimension range	No limit concerning pipe diameter	For small pipes it is preferrable to tilt the beam or to use a low energy gamma-ray source. Large pipes diameters require a higher gamma-ray energy.
TRL	TRL 3-4	The use of a standard industrial gamma-ray density meter on CCS does not require significant technology development. There may be the need for some effort for obtaining the required measurement accuracy and integrating the density system in a CCS flow meter. A custom gamma-ray system for CCS would require more development.
Knowledge gaps	This is a new type of application and there are knowledge gaps concerning the required accuracy of a density measurement and in general on how to use the gamma-ray measurements to meet the required accuracy of CCS flow metering.	
Zero stability	A gamma ray system normally requires re-calibration at regular intervals, depending on the detector technology and accuracy requirement.	
Other limitations/ advantages	For fraction measurement the accuracy is limited when there is a small difference in density between the different components.	

Table 7
Summary characteristics of ultrasonic technology (Ref: Consultation with Technology developers from Panametrics, KROHNE and TECHNIP FMC, and work in Ref. [67])

Parameters	Value/range	Comments
Measurement range	Gas USM: 9–47,000 m^3/h Liquid USM: 9–21,800 m^3/h	Standard nominal size 4" to 30". Typical axial velocity range 0.3–14 m/s for liquid. Typical axial velocity range 0.3–30 m/s for gas. Standard nominal size 4" to 30".
Process pressure limit	Gas USM: 250 barg Liquid USM: 150 barg	Typical values. Pressure rating is limited by maximum rating for the ultrasonic transducers.
Process Temperature range	−50 °C to +120 °C	Typical values. Temperature rating is limited by body material type and transducer temperature rating. Lower and higher temperature rating for different models and manufacturers.
Ambient temperature	−40 °C to +60 °C	Typical values.

(*continued on next page*)

Table 7 (*continued*)

Parameters	Value/range	Comments
Composition ranges/ limitations	Gas USM: Up to 30 % CO_2 in natural gas. Liquid USM: Up to 100 % CO_2.	Several manufacturers have tested and/or approved their gas ultrasonic flow meters for up to 30 % CO2 in natural gas. Development is ongoing for use of gas USM up to 100 % CO_2.
Pressure drop	Negligible. Non-intrusive design.	
Multi-phase sensitive	Yes.	Small amounts of gas in liquid or liquid in gas will increase signal attenuation and flow meter uncertainty.
Density relation (attenuation)	Higher density reduces signal attenuation and improves flow meter performance.	
Weight and footprint	Flange-to-flange length: 600–1700 mm Weight: 100–3000 kg	For standard flange size 4" to 30".
Recalibration interval/method	Typical recalibration interval: 1 year or longer. Preferred calibration method: Flow calibration at accredited flow laboratory on similar fluid and process conditions as expected during operation.	Alternative calibration methods: 1) Flow calibration at similar Reynolds number range 2) Static calibration/verification of measured velocity of sound with known fluid at known pressure and temperature.
Long-term measurement stability	Typically, less than 0.1 % for liquid USM on petroleum liquids. Typically, less than 0.2 % for gas USMs on natural gas.	Large meters have long-term stability since time-of-flight measurement is less affected by changes in transducer response/shifts.
Typical list price	EUR 20000 and higher depending on size, body material and number of transducers.	
Flange dimension	4" - 30" typical size.	2" - 60" available from some manufacturers or upon request.
TRL	Gas USM: TRL 3-4 Liquid USM: TRL 5-6	
Knowledge gaps	Promising results has been achieved for liquid USMs on liquid CO_2 at static conditions. Full scale flow calibration and operation at test installation to be conducted when such facilities are available. Gas transducers optimized for CO_2 operation to be developed and tested.	DNV Groeningen has flow tested 2-inch and 3-inch flow meters, including USM, on 95 % and 99 % CO2 in gaseous phase. Preliminary tests shows that transducers developed for natural gas do not provide required accuracy for CO2 gas flow measurement.
Zero stability	Typically, 0.01–0.02 m/s axial flow velocity	
Other limitations/ advantages	Advantages: - Non-intrusive design, low pressure drop - High turn-down (max-min flow range) - Bi-directional flow measurement - Condition monitoring features (path velocity, path VOS, signal attenuation, turbulence, flow profile) Disadvantages: - Requires partly developed flow profile, minimum 5D - 10D straight upstream pipe - High signal attenuation in gaseous CO_2 Full size flow calibration laboratories for liquid CO_2 are not yet available.	

Table 8
Summary characteristics of Coriolis technology (Ref: Consultation with Technology developers from KROHNE and work in Ref. [67])

Parameters	Value/range	Comments
Measurement range	550 t/h	8" meter at 1 bar pressure drop
Process pressure limit	SS316, 100 barg, Duplex SS/Hastelloy C22 200 barg	
Process Temperature range	−200 °C to +230 °C	
Ambient temperature	−40 °C to +65 °C	
Composition ranges/limitations	No limit to composition.	
Pressure drop	1 bar at nominal flow	
Multi-phase sensitive	Sensitive – level of sensitivity depends on flow regime (bubble size, viscosity etc.)	
Density relation (attenuation)	No effect	
Weight and footprint	~450 kg, 0.6 m^2	Typical 8" bent tube meter
Recalibration interval/method	Interval not specified; method depends on required uncertainty	
Long-term measurement stability	Not defined	
Typical list price	~€60,000	8" meter, with standard flanges – high pressure adds cost
Flange dimension	Depends on meter size	
TRL	9	Coriolis meters are already in service for CO_2 measurement
Knowledge gaps	Validity of water calibration for fiscal/high accuracy applications. Measurement accuracy for supercritical fluids.	
Zero stability	Typical 8" < 27.50 kg/h	
Other limitations/advantages	Advantages: - Direct measurement of mass flow. - Measurement principle not affected by composition for single phase flows Disadvantages: - Not full line size – there is some pressure drop. The size, weight and cost can become prohibitive above 16" line size	

Table 9
Summary characteristics the Differential Pressure technology (Ref: Consultation with Technology developers from KROHNE and work in Ref. [67])

Parameters	Value/range	Comments
General	Applicable for all but mainly considered for Venturi.	
Measurement range	Example: 20–200 m^3/h for a 5" meter	Depend on size, beta ratio and required accuracy. Typical 1:4 range but may be extended.
Process pressure limit	700 bar is possible	
Process Temperature range	−20 °C–130 °C	
Ambient temperature	−20 °C–50 °C	
Composition ranges/ limitations	0–10 % impurities in CO_2	Need density input. Accuracy will deteriorate with larger fractions of impurity.
Pressure drop	Typically less than 1 bar	Most of the dp will be recovered. Maybe higher for orifice (less recovery). Also lower recovery for large fractions of impurities.
Multi-phase sensitive	yes	
Density relation	Require density input.	
Weight and footprint	Venturi: Length typical 3 times inner diameter. Orifice will be shorter. Weight will depend on pipe size and pressure.	
Recalibration interval/ method	Several years/dp calibrated against reference dp.	
Long-term measurement stability	TBA	
Typical list price	TBA	
Dimension range	All applicable	
TRL	TRL 9 for single phase flow, lower for CCS with impurities.	
Knowledge gaps	Application on CCS with impurities.	
Other limitations/ advantages	Dp measurements is by nature intrusive technology. Advantages; well-known technology, no moving parts.	
Economics	Assumed cost effective, orifice favourable for large pipe sizes.	

Table 10
Summary characteristics for absorption spectroscopy TDLAS system (Ref: Consultation with Technology developers from NeO and specs of LaserGas II SP [57])

Parameters	Value/range	Comments
Detection limit	<10 ppm	Maximum detection limit of relevant gases. Limit is gas dependent. Inline detection, lower limits possible with bleeder system
Process pressure limit	~1.5 bar	No lower limit. Depends on composition, 2 bar acceptable for most gases
Process Temperature range	Max 200 °C	Depends on gas composition, max 200C valid for all measurable gasses
Ambient temperature	−20 °C to +55 °C	
Pressure drop	None	
Multi-phase sensitive	No	
Density relation	Not applicable	
Weight and footprint	11,7 kg	Per TDLS unit, one needed per impurity that is detected
Recalibration interval/method	Every 12 months	
Long-term measurement stability	1 % repeatability	
TRL	9 for other applications (3 for CCS)	
Knowledge gaps	Effects of high CO_2 concentration	
Other limitations/advantages	Only one impurity detectable per unit	
Economics	Expensive, one unit required per impurity	

Table 11
Summary characteristics for absorption spectroscopy FITIR system (Ref: MGS300-KIT [58])

Parameters	Value/range	Comments
Detection limit (ppm)	0.6 ppm	Maximum detection limit of relevant gases, using bleeder system
Process pressure limit (bar)	5–8 bar	Pressure in pipeline, bleeder system extracts sample and lower pressure for measurements
Process Temperature range	Max 250 °C	
Ambient temperature	5 °C–40 °C	
Pressure drop	Unknown	
Multi-phase sensitive	Potentially	Could potentially be used to detect different phases of CO_2
Density relation	Not applicable	
Weight and footprint	11 kg	Only sampling probe (pump, sampling line and analyser needed as well)
Recalibration interval/method	N/A	
Long-term measurement stability	N/A	
Dimension range	160 × 350 × 290 mm	Only sampling probe (pump, sampling line and analyser needed as well)
TRL	9 for other applications (3 for CCS)	
Knowledge gaps	Effects of high CO_2 concentration	

Table 12
Summary characteristics of an Optical Particle Counter (Ref: HPGP 101-C from Particle Measuring Systems [59])

Parameters	Value/range	Comments
Counting efficiency	>50 % @ 0.14mu	Counting frequency gives the probability that a particle will be counted at a given size (approaches 100 % for larger particles)
Process pressure limit	10.3 bar	
Process Temperature range	N/A	
Ambient temperature	0 °C–45 °C	
Pressure drop	Unknown	Flow rate of 2.8 l/min at operating pressure into the system
Multi-phase sensitive	Yes	Could potentially be used to detect different phases of CO_2
Density relation	Not applicable	
Weight and footprint	20.4 kg (660 × 200 × 220 mm)	Only sampling probe (pump, sampling line and analyser needed as well), an off-site analyser is also required
Recalibration interval/method	N/A	
Long-term measurement stability	N/A	
Typical list price	N/A	
Dimension range	N/A	
TRL	9	Given that the system can be used at an appropriate pressure and temperature
Knowledge gaps	Relevant size of dry ice particles	
Other limitations/advantages	Connected to the gas pipe as a bleeder system	

Table 13
Summary characteristics of a Distributed fibre opstic system (Ref: DiTeSt system [60])

Parameters	Value/range	Comments
Measurement range	Up to 150 km	Per system analyser, several can be used to extend range
Spatial resolution	1–3 m	Depending on distance
Temperature resolution	0.1 °C	
Temperature range	−270 °C - +500 °C	Depends on the type of sensing cable
Strain resolution	0.002 mm/m	
Strain range	−1.25 to +1.25 %	
Acquisition time	2 min	

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