Flow Measurement Challenges for Carbon Capture, Utilisation and Storage

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ABSTRACT

Carbon Capture, Utilisation and Storage (CCUS) is a key element in the United Kingdom Government strategy for reducing carbon dioxide (CO_2) emissions. The UK aims to capture and store 10 million tonnes of CO_2 each year by 2030.

At each stage in the CCUS infrastructure, accurate measurement of the CO_2 flow rate is required, over a range of temperatures, pressures, flow rates and fluid phases, where the flow measurement must be validated through a credible traceability chain. The traceability chain provides the underpinning confidence required to verify meter performance, financial and fiscal transactions, and environmental compliance. The UK equivalent of the EU Emissions Trading System (EU ETS) specifies a maximum uncertainty value for CO_2 flow measurement. Accordingly, the provision of accurate and traceable flow measurement of CO_2 is a prerequisite for an operational CCUS scheme.

However, there are currently no CO_2 flow measurement facilities, nationally or internationally, providing traceable flow calibrations of gas phase, liquid/dense phase and supercritical phase CO_2 that replicate real-world CCUS conditions. This lack of traceable CO_2 gas and liquid flow measurement facilities and associated flow measurement standards is a significant barrier to the successful implementation of CCUS projects worldwide.

This paper presents an overview of the traceability chain required for CO_2 flow measurement in the UK and globally. Current challenges are described along with potential solutions and opportunities for the flow measurement community.

1. INTRODUCTION

In 2021, fossil fuels provided over 75% of global energy [1]. According to the International Energy Agency (IEA), in the same year, energy-related CO_2 emissions were approximately 36.3 gigatons (Gt) [2]. This emission rate, the highest on record, was partly driven by an increase in coal usage. The economic recovery from Covid-19 has not, so far, prioritized environmental sustainability.

Carbon Capture, Utilisation and Storage (CCUS) is considered an essential means of reducing anthropogenic carbon dioxide emissions in the transition towards sustainable and clean green energy sources [3] [4]. After decades of little progress, there now appears to be growing interest and investment in CCUS schemes globally.

In the UK, CCUS is a key policy within the UK Government's 'Energy White Paper: Powering our net zero future' [5]. As part of the UK's industrial decarbonisation strategy, the UK government has committed to deploy two CCUS clusters by mid-2020s (with a further two by 2030 [6]): the East Coast Cluster (Teesside & Humberside linked to the Northern Endurance Partnership offshore storage site), and HyNet (Merseyside region and North Wales linked to storage sites in the Irish Sea).

It has been estimated that the UK sector of the North Sea has sufficient capacity to store around 78 Gt of CO_2 in saline aquifers [7]. Based on the UK's 2021 CO_2 emissions, this corresponds to over 200 years of capacity. Reaching net-zero emissions without employing CCUS is not considered feasible [8]. CCUS will be essential to reduce anthropogenic CO_2 emissions and will help Paris agreement signatories to meet their legally binding greenhouse gas reduction targets [9].

Eradicating all anthropogenic CO_2 emissions at source is not an option. Most scenarios (88 out of 90) envisaged by the IPCC rely on carbon removal technologies to compensate for residual emissions which cannot be avoided or abated, and to reduce the amount of CO_2 in the atmosphere to acceptable levels [10]. CCUS is currently the only solution that can deliver negative emissions at large scale. Put simply, many key industrial processes will not be able to achieve net zero emissions without implementing CCUS. For example, the production of cement emits significant levels of CO_2 as a by-product during the process of heating limestone and breaking it down into calcium oxide [11].

CCUS will also be essential to support negative emissions directly through Direct-Air-Capture (DAC) and indirectly through Bioenergy with Carbon Capture & Storage (BECCS) [12]. These negative emissions technologies (NETs) offer considerable capacity for reducing CO_2 emissions further and faster than relying solely on decarbonising the energy sector and hard-to-abate sectors (e.g., steel, chemical and manufacturing).

Many nations are now aiming to support "*a thriving low carbon hydrogen sector*" [13]. CCUS will be central in enabling the rapid upscaling of low-carbon hydrogen production via steam methane reforming [14]. Methane reforming with CCUS provides a clear pathway for the low-cost generation of hydrogen and is expected to be widely adopted.

One less considered aspect of CCUS is the need for suitable flow measurement technology for CO_2 streams [15]. Understanding, monitoring, and controlling the flow rate of CO_2 will be essential for the viable operation of CCUS. This will require a clear understanding of temperature, pressure, and phase behaviour, including the influence of various levels of impurity. Appropriate flow measurement technology must be selected with verification of its proper operation and metrological performance. Unfortunately, there are currently no accredited flow calibration facilities anywhere in the world which use CO_2 as the fluid medium and which can fully replicate CCUS conditions. This paper presents an overview of the flow measurement challenges of CO_2, the flow measurement methods, potential technologies for use in CCUS, and the regulation landscape, aimed at a readership of flow measurement researchers and practitioners. It is partly based on a report by one of the current authors which focusses on policy issues [15].

2. FLUID PROPERTIES OF CO_2

The unique fluid properties of carbon dioxide present several measurement challenges. At ambient temperature and pressure (e.g., 1 bar and 20 °C), CO_2 is in a gaseous state and its flow measurement is relatively straightforward. However, CO_2 readily liquifies at around 57 bar and 20 °C. Furthermore, above the critical point of 31.1 °C and 73.9 bar, CO_2 becomes supercritical, i.e., it exhibits properties which are hybrid between gas and liquid. As 31.1 °C is close to ambient in many regions of the world, CCUS operations may readily approach the critical point. Operating near the critical point can present significant technical challenges for process control and measurement as small changes in temperature and pressure may result in large changes in fluid properties. The phase diagram for CO_2 and the anticipated operating range for the CCUS chain are shown in Figure 1.

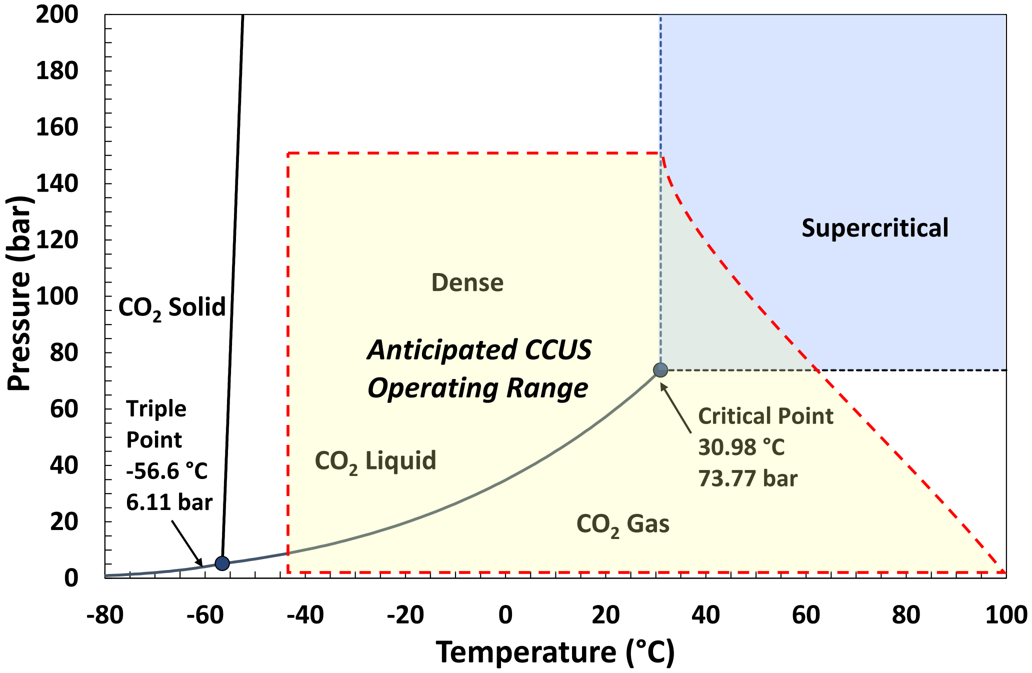

Figure 1: Pure CO_2 phase diagram (CCUS operating range highlighted in yellow) [15]

Within the operating region of the CCUS chain, CO_2 can be single-phase liquid, single phase gas, two-phase liquid and gas, or supercritical fluid. Each of these four phases may present different measurement challenges [16] [17] [18]. Furthermore, as the phase boundaries lie close together, maintaining the desired fluid phase may be problematic [19] [20] [21]. This is particularly the case for CO_2 transportation across large pipe networks [22] [23]. Regulating the temperature and pressure over pipelines that span hundreds of miles may prove difficult, when varying climate and elevation, as well as the diurnal cycle, are likely to result in changing ambient conditions.

The possibility of phase change is further exacerbated by the likelihood of impurities being present in the CO_2 stream. Depending on their type and concentration, impurities may cause significant shifts in phase boundaries, the critical point, and specifically the two-phase region. Impurities may create two-phase flow at process conditions that would be single-phase gas or single-phase liquid for pure CO_2 [24]. For example, Figure 2 shows the shift in the gas-liquid transition region and critical point location, for a mixture of CO_2 and hydrogen (H_2) with varying hydrogen concentration.

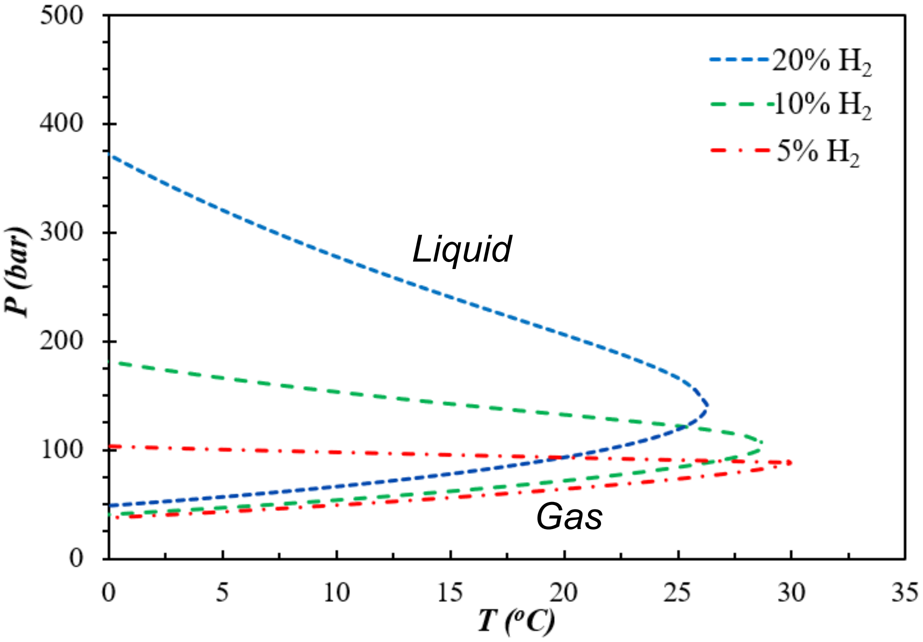

Figure 2: Phase diagram of CO_2/H_2 mixture with varying H_2 concentration [25]

Traces of impurities such as NO_x, SO_x, N_2, H_2S, H_2O, and CH_4 may have a large influence on the density and compressibility of the process stream [26]. Changes in physical properties are functions of the component mixture and quantity. Thus, CO_2 streams across the CCUS chain will require careful modelling to determine their theoretical phase envelope, alongside regular sampling to determine the actual fluid composition, to ensure the desired operating conditions and/or fluid phase are maintained [27]. Accordingly, the well-established pure CO_2 phase diagram and equations of state (EOS) cannot be relied upon for industrial CCUS streams. Physical property software modelling packages can be used to generate fluid property data for the anticipated range of CO_2 mixtures. However, these models will require experimental validation.

The potential for large scale changes in the fluid phase within a single pipe network, varying with time and/or location, presents clear flow measurement challenges [17]. It is possible for example that gas meters might be required at certain points in the network while liquid meters are used elsewhere.

Another measurement challenge presented by CO_2 is that it exhibits acoustic attenuation, which may impact ultrasonic flow meter technologies in particular [28] [29]. While this phenomenon is more significant in gaseous CO_2, it has also proved problematic in liquid CO_2 [30]. CO_2 exhibits acoustic attenuation due to a molecular relaxation process [31], arising from an exchange of energy between molecular vibrations and translations. This attenuation may cause an ultrasonic meter to lose the signal passing between its transmitters and receivers. The effect is more significant at low pressure. A reduction in the ultrasound signal strength will impact the measurement resolution and may have a detrimental effect on accuracy. This attenuation occurs at a specific frequency, which depends on the stream composition, density, phase, temperature, and pressure. Further research into thermal relaxation and the effect on CO_2 and flow metering technologies is required.

Any free water within the process stream may potentially result in the formation of highly corrosive carbonic acid and of hydrates that could impede the flow and risk pipeline integrity [21]. Hydrates may plug flow lines and in severe cases may even result in pipeline ruptures. The interaction of CO_2 with water may raise additional measurement challenges, such as the requirement for water content to be monitored throughout the CCUS chain.

3. MEASUREMENT STAGES FOR CCUS

The measurement locations for CCUS schemes depend upon the specified measurement uncertainty limit, the fluid phase, the transportation method, and the regulatory requirements.

At the time of writing, CCUS schemes in the UK are covered by The Energy Act 2008 [32]. This Act provides a licensing regime that governs the offshore storage of carbon dioxide. The Carbon Dioxide Regulations 2010 (SI 2010/2221), which transposes many other requirements of the CCS Directive, became legislation in 2010 [33]. The UK Government (UKG) is currently formulating a framework for CCUS in the UK with further details to be published in 2022 [34]. Also in 2022, following BREXIT, the UKG has defined the UK ETS scheme [35] which is similar to the EU ETS [35], and includes comparable measurement uncertainty requirements. However, these uncertainty figures could reduce as the importance of CCUS, and the value of carbon credits, increases with time [36]. There is further discussion of the regulatory requirements and carbon credits in Section 6.

For CCUS scheme reporting purposes, the EU Monitoring and Reporting Regulation (MMR) defines a set of accuracy levels (tiers) [37].

Table 1
EU ETS Tiers for activity data and maximum permissible uncertainty[1] ([38], [37])

Tier Number	**1**	**2**	**3**	**4**
maximum permissible uncertainty	± 10 %	± 7.5 %	± 5 %	± 2.5 %

For the purposes of illustration, Figure 3 shows a typical CCUS transportation network with its corresponding measurement nodes. These measurement nodes are denoted in the diagram as red circles with a white “M”. Table 2 describes the activity taking place at each node in Figure 3.

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[1] The expanded measurement uncertainties quoted in this paper have a coverage factor of 95% (k=1.96)

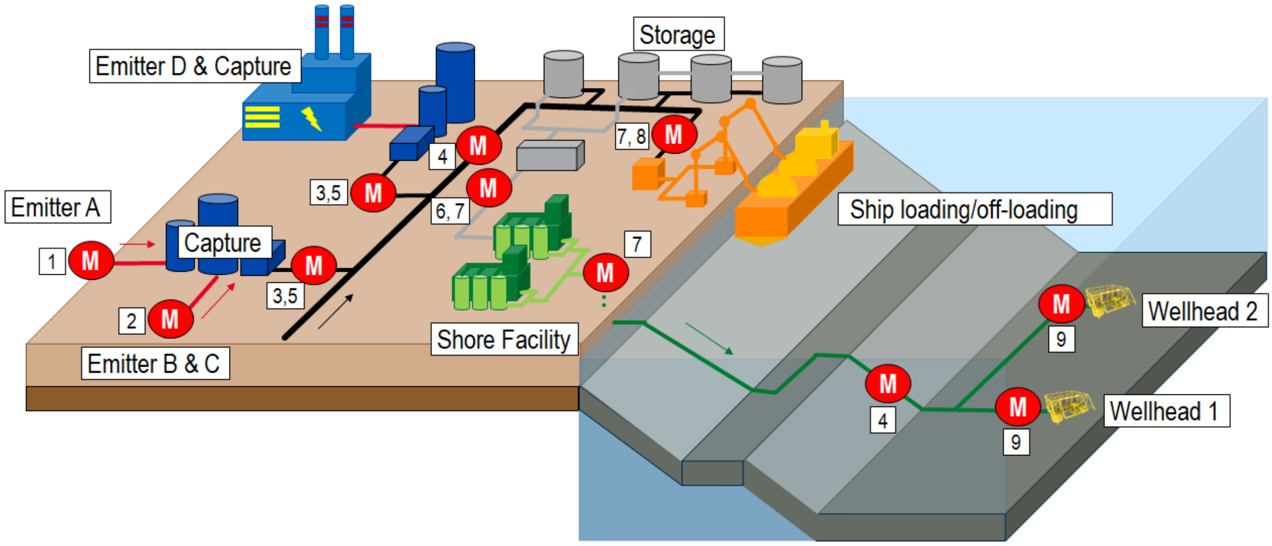

Figure 3: CCUS transportation measurement nodes. Adapted from [15]. For measurement node types, refer to Table 2.

Table 2

Typical CCUS Network Measurement Locations (as illustrated in Figure 3)

Measurement Node	Location
1	Outlet of an emission source (e.g., flue gas from a coal fired plant)
2	Inlet to a CO_2 capture facility
3	Outlet of a CO_2 capture facility
4	Regular points along the transport network (e.g., at pumping/compression stations)
5	Entrance and exit to an onshore transport network
6	Temporary storage sites along the transport network
7	Entrance and exit to a shore facility
8	Loading and off-loading locations (e.g., ships)
9	Injection sites (e.g., North Sea wellhead)

The highest tier shown in Table 1 (Tier 4) is applicable to the measurement of the CO_2 transferred out of the installation to:

- a capture plant for the purpose of transport and geological storage (e.g., measurement node 1 or 2 in Figure 3)
- a transport network with the purpose of geological storage and storage network (measurement node 3)

Tier 4 is applicable to transferred CO_2 for all emitter installations irrespective of annual emissions. However, depending on technical feasibility and financial costs, the operator may apply for Tier 3 status. The monitoring plan for the installation must be submitted and approved by the relevant national Competent Authority. Importantly, the limits given are for the overall measurement uncertainty, i.e., for the combination of flow meter and composition analyser. Accordingly, to achieve Tier 4 uncertainty of 2.5 % overall, the flow metering component will need to provide a lower measurement uncertainty, typically around 1 %.

While the primary function of the transportation network chain is to facilitate CO_2 capture, it retains the potential to become itself a source of CO_2 emissions, principally via losses and leaks through the system. To monitor and assess the overall fugitive losses within a CCUS process, a mass balance approach may be used across the network up to and including the injection wellhead. This may further require the tracking of CO_2 composition at multiple locations within the CCUS transportation network. A "by difference" method requires flow (and composition) measurements with low uncertainty if the loss detection threshold is to be acceptably small. The characteristics of CO_2 metering technologies, including typical uncertainties, are discussed in the next section.

4. FLOW METERS FOR CCUS APPLICATIONS

CCUS has been the focus of continuous policy discussion and pilot schemes over several decades. Unfortunately, there has been only limited investment in the core CCUS infrastructure and facilities that are needed to underpin the measurement traceability chain for CCUS. While there are over 100 flow calibration facilities globally for water and hydrocarbons, there are only two calibration facilities offering carbon dioxide as a test medium [16] [30], and both of these are limited to gas phase [39].

Without sufficient research to verify the measurement performance of flow meters with CO_2, there remains the concern that they might not in practice deliver the required uncertainty over the full range of CCUS conditions. This would result in a substantial gap in the traceability chain for the flow measurement of carbon dioxide, which falls short of metering best practice and regulatory guidelines [40]. To provide confidence in the flow measurement of CO_2, there needs to be readily available and traceable flow facilities that offer CO_2 in all industrially-relevant phases as a test medium [41].

Historically, a range of flow metering technologies have been employed for CCUS applications, including differential pressure devices (particularly orifice plate meters), turbine meters, ultrasonic meters, and Coriolis meters. As CO_2 emissions are traded by mass under the carbon credit scheme, volumetric devices require accurate fluid properties of the CO_2 rich stream composition to provide a corresponding mass measurement.

Orifice meters have been used for measuring CO_2 injection in a variety of Enhanced Oil Recovery (EOR) projects [42] [43] [44]. EOR is a process for maintaining oil extraction from a depleted reservoir whereby a bulk material (often water) is injected into the reservoir, typically by reconfiguring old wells to be used for injection. Where CO_2 is injected, this has the benefit of simultaneously extracting fuel and sequestrating CO_2 in the reservoir. Orifice meters are widely used for single phase gas flow and liquid flow applications. If the fluid properties are accurately known, then orifice meters may provide low flow measurement uncertainty. For steady-state, single phase CO_2 flow streams, orifice meters have reported measurement uncertainties within 1 % [45]. This performance is claimed for both single-phase liquid and single-phase gas CO_2. However, this has not been verified at a traceable flow laboratory using CO_2 as the calibration medium. Orifice plates have also been shown to perform well in two phase wet gas flow [46]. At the time of writing, no published claims have been made for orifice plate flow measurement performance with supercritical CO_2. However, if the composition, density, and viscosity are known, it is possible that orifice meters might be suitable across the CCUS chain, the only issue being the lack of traceable flow data.

One potential concern is pressure drop induced phase change. As an orifice meter is intrusive into the flow and may create high pressure losses, consideration must be given to its location in the CCUS pipeline to avoid any pressure drop induced phase change. This is of special concern at operating points where the CO_2 density may change significantly with small variations in temperature and pressure. However, the risk of phase change at an orifice meter due to pressure drop is unlikely to be significant in a well-designed and managed system.

Turbine flow meters are still one of the most commonly used flow meters for low uncertainty measurement of high value liquids and gases [47]. They have been used extensively for measuring both liquid and supercritical CO_2 flow in pipelines [18]. They have also been used for CCUS EOR applications with stated measurement uncertainties of less than 1 % [17]. Again, these claimed uncertainties require verification in traceable test facilities.

Historically, ultrasonic flow meters have not been used for CO_2 gas applications due to ultrasound signal attenuation [30], as discussed above. As the density can vary significantly in supercritical CO_2, the ultrasonic transducer frequency required to maximise the signal might extend beyond the frequency offered by the USM. Transducers and frequencies are chosen to match the normal range required for regular fluids, but the absorption characteristics of supercritical CO_2 mixtures are in general unknown. This is particularly true for large diameter pipes. Furthermore, as USMs are ultimately velocity measurement devices, the flow profile is important and requires adequate corrections which are dependent on the density and viscosity of the fluid.

Despite these difficulties, recent developments in transit-time ultrasonic flow meters have shown potential for providing a low measurement uncertainty system for CCUS, but further research is required. A number of recent USM trials in CO_2 rich applications have reported good results, where an orifice meter is used as a reference [45].

Coriolis mass flow meters provide measurements of both the mass flow and the density of the process fluid. They can be utilised for nearly all types of flow applications and show significant potential for CO_2 processes. Applied to CO_2 measurement, Coriolis meters have been used extensively at Yates Field in West Texas and at a CCUS plant in North America [48] [49]. Small scale gravimetric trials have been completed at Herriot-Watt University with pure CO_2 liquid, where measurement uncertainties of around 0.11 % for mass have been reported [50]. Coriolis meters have also been used successfully in dense phase / supercritical ethylene applications for custody transfer [51].

Unlike most other flow meter types, a Coriolis meter can operate in single phase liquid or single phase gas without modifications to the sensor. Changes in fluid phase from single phase liquid to single phase gas, and vice versa, should not be challenging and the devices should be able to operate across the full range of phase conditions that may occur in CCUS applications. Furthermore, there has been significant work by some Coriolis manufacturers to provide reliable measurements in two and three-phase flow [52]. While these techniques have not been adopted by all manufacturers, recent developments suggest that most Coriolis meters will in future be able to successfully operate and measure in two-phase conditions. However, the measurement uncertainty is likely to be an order of magnitude higher than for single-phase liquid or single-phase gas [53].

Factors involved in the selection of appropriate measurement technology for CCUS applications include availability, compatibility, cost, reliability, and measurement uncertainty. However, the selection of the most appropriate flow meter technology must be complimented by appropriate calibration and operation, which in turn requires appropriate test and calibration facilities, best practice guidance, and regulations.

5. CCUS MEASUREMENT RESEARCH

This section provides a brief overview of current research being conducted into CO_2 flow measurement technologies and CO_2 physical properties for CCUS applications.

5.1 Research Programmes at NEL

As the UK Designated Institute (DI) for flow, NEL receives Flow Programme funding from UKG to conduct research into flow related issues for the benefit of industry. At present, NEL has three CCUS projects focussing on flow measurement and equations of state. There is also a project relating to CCUS funded by the European Metrology Programme for Innovation and Research (EMPIR) projects, under EURAMET (the Regional Metrology Organisation (RMO) of Europe).

- The EMPIR project ‘Metrology for decarbonising the gas grid’, provides support for distributing alternative fuels such as H_2 and CO_2 over existing gas networks [54]. NEL’s primary role involves the testing of small scale flow meters in single phase gas and single phase liquid CO_2 at a third party laboratory at Herriot Watt University (HWU) in Edinburgh, Scotland. The HWU laboratory is small scale (6 mm), has no accreditation, is not traceable, but does have a gravimetric primary standard. The flowrates are 10 to 70 kg/h for both single phase gas and single phase liquid. The results from the HWU laboratory will be compared with single phase nitrogen and single phase water results from NEL’s dry gas and water flow loops respectively. The NEL gas flow uncertainty is 0.35 % and the water flow loop is 0.15 %.

- A recently completed UKG funded project [54] assessed a variety of Equations of State using accurate physical property experimental data for different CO_2 blends in the presence of common impurities across a wide range of pressures and temperatures. This recommended the construction of an experimental facility to determine speed of sound and density for alternative CO_2 blends, which is now underway as part of a further UKG funded project.

- The UKG funded project ‘Flow measurement research to support CCUS’ will assess the performance of different metering technologies with pure CO_2 and CO_2 with impurities. An NEL nitrogen gas test rig will be modified to provide traceable operation using CO_2 gas. Liquid CO_2 tests will be conducted at a third-party laboratory with a metering transfer package traceable to NEL. The project will also investigate whether various meter types calibrated with nitrogen (for gas phase), or water (for liquid phase) provide acceptable uncertainty performance when operating with CO_2. This programme directly addresses one of the significant challenges outlined above: how restrictive is the current shortage of CO_2 calibration facilities in the provision of traceable flow measurement for CCUS schemes?

5.2 Research Programmes at other Institutions

There are other laboratories in Europe that are actively research the flow measurement of CO_2.

- The Norwegian independent research organisation, SINTEF, is implementing the MACON CCS project which aims to develop flow models and to improve sensor technology for CCUS flow streams. The project has several industrial partners and is partly funded by the Research Council of Norway [55]. This includes the characterisation of an ultrasonic flow meter in liquid and liquid dense conditions [29] and a study into the application of tomography throughout the CCS value chain [56].

- SINTEF are also the lead partner in the Norwegian CCS Research Centre (NCCS) which aims to accelerate CCUS development, providing innovation and support for the rollout of CO_2 storage in the Norwegian sector of the North Sea. The Centre was started in 2016, currently has 32 partners, and has completed research into fiscal measurement and thermodynamics [57]. In 2021, SINTEF put forward a design and business case for the construction of a traceable CO_2 flow measurement facility [58].

- Norwegian organisation DNV have extensive flow measurement experience and are currently researching flow measurement of CO_2 [59]. They can currently operate their gas flow facility with gaseous CO_2 with traceability to the German National Metrology Institute (NMI) Physikalisch-Technische Bundesanstalt (PTB). DNV produced the seminal report on the design and operation of CO_2 pipelines [22], which includes some discussion of metering and fluid properties.

6. INTERNATIONAL CCUS REGULATIONS

Some of the main drivers for improved traceability, R&D investment, reduced measurement uncertainty and flow measurement innovation are regulations and international standards. While CCUS has been a focus of policy development for several decades, legal requirements remain limited and vary around the world.

At the time of writing, there are approximately thirty commercial CCUS schemes operating in nine countries. The majority of these are located in USA. However, plans are in place for the development of additional CCUS installations in over 25 countries. For some regions, these new facilities will require new regulations to be drafted and implemented. Other regions already have existing frameworks that will be implemented and then assessed. The 2022 IEA CCUS Handbook [60] is the global reference for the development and revision of the legal and regulatory frameworks. However, different regions retain differing approaches to CCUS legislation.

European regulations for CCUS are comprehensive. There are two main regulative frameworks: the CCS directive [61] and the previously described EU Emissions Trading System (ETS) [38]. The CCS directive concerns CO_2 geological storage and creates a legal framework for the safe and environmentally sound sequestration of CO_2 to enable the reduction in anthropogenic carbon dioxide emissions [61]. It specifies wide-ranging stipulations for identifying potential CO_2 storage locations. A storage site can only be designated after completing the required analysis where the results must demonstrate that, under the planned conditions, there are no significant risks of leakage or environmental damage. No geological storage of CO_2 can be undertaken within the EU without a storage permit [61].

The ETS is the main legislation in the European Union's strategy for eradicating climate change [38]. It is the first major carbon market in the world and remains the largest. The Emissions Trading System certifies that when a leakage occurs, the operator must surrender allowances equivalent to the resulting emissions. The Directive on Environmental Liability oversees the legal responsibility for damage to the environment. Individual liability for damage to health and property is left for regulation at the Member State level. In terms of reporting, the EU Monitoring and Reporting Regulation (MMR) defines the accuracy levels (tiers) [37]. The various tiers have different thresholds depending on the size of the installation (Table 1).

As previously introduced in Section 3, the EU ETS works on the 'cap and trade' principle with respect to 'carbon credits'. A 'cap' is set on the total amount of certain greenhouse gases that can be emitted by the installations covered by the system. This cap is then reduced over time so that total emissions fall within the agreed timescales. Within the cap, installations buy or receive emissions allowances (known as 'carbon credits'), which they can 'trade' with one another as required. The limit on the total number of carbon credits available ensures that they have a value linked to them. This is known as the 'carbon price'. As global CO_2 emission allowances decrease over time as we approach 2050, the demand for carbon credits will likely increase as the supply remains stable or even decreases. This well documented supply and demand relationship could result in the value of carbon credits increasing. As the value increases, it is logical to envision that the measurement uncertainty for CO_2 will decrease to reduce the financial exposure of key stakeholders. This potentially lower measurement uncertainty would present further challenges to the flow measurement community.

The regulation of CCUS schemes in the UK has been covered in Section 3. It operates a similar carbon credit scheme with trading occurring within a sector as required [62].

The International Energy Agency (IEA) has repeatedly stated the need for clear legal and regulatory frameworks to underpin the successful implementation of carbon capture, utilisation, and storage (CCUS). Thus: [as well as] "*ensuring the safety and security of CCUS activities, regulatory frameworks are also important to clarify the rights and responsibilities of CCUS stakeholders, including relevant authorities, operators, and the public, and to provide certainty for project investors*" [60]. The IEA have updated the key 2010 IEA Model Regulatory Framework [63] document with a new framework published in July 2022 [60]. This document will disseminate best practice for the development of CCUS legal and regulatory frameworks.

The USA is at the forefront of international CCUS efforts. In 2020, 60% of the world's CCUS schemes were located in the USA. Fortuitously, the vast majority of stationary sources of carbon emissions are situated nearby favourable geological storage sites [8]. It is estimated that there is over 160 years

(800 Gt) of potential storage available in the USA. Recent CCUS legislation enables US taxpayers to elect to receive a payment in lieu of the tax credits for carbon dioxide sequestration [64]. However, at present there are no stipulations on the measurement uncertainty required.

According to the IEA the required guidelines and regulations for the implementation of CCUS in the Southeast Asia region have still to be developed [65]. However, Japan launched the Asia CCUS Network in 2021 to provide "*a platform for policymakers, financial institutions, industry players, and academia to work together to ensure the successful development and deployment of CCUS in the Asia region"* [66]. It includes members from Japan, Australia, Cambodia, Indonesia, India, Lao, Malaysia, Myanmar, Philippines, Singapore, Thailand, USA, and Vietnam.

China has set targets to be carbon neutral by 2060 via the 30/60 plan (with carbon emissions peaking by 2030). However, the Global CCS Institute has commented that China's lack of a regulatory framework for CCUS, alongside its 'Five-year Plan' for CCUS policy is *"a key barrier for large-scale CCUS deployment"* [67], [68]. Notably, no measurement uncertainty stipulations have been published at present. At current emission rates, China has storage potential for over 40 years of emissions (425 Gt) [8].

Flow measurement will play a fundamental role in CCUS schemes around the world. However, the state of readiness to provide a CCUS measurement framework varies by region. Developing comprehensive regulations, standards, and a detailed traceability chain, will be pivotal in ensuring the successful deployment of CCUS systems worldwide. If one region can demonstrate sufficient accuracy, traceability, and regulations, it will provide a clear framework for others to follow.

While there is currently funding for CCUS schemes and significant drivers for support the development of CO_2 measurement technologies and facilities, without government support the requisite traceability chain and regulations are unlikely to materialise. Investment is required from governments, funding agencies and industry to ensure that the underpinning science for flow measurement of CO_2 is provided.

7. CONCLUSION AND CHALLENGES FOR FLOW MEASUREMENT DEVELOPMENT

At present there is limited traceability, technical knowledge, and underpinning research for CCUS flow measurement. The knowledge gap arises at least in part from the limited availability of traceable experimental data for measurement of CO_2 in a variety of fluid phases, flow rates, temperature, and pressures. This limitation can only be overcome through the development of appropriate experimental and standards facilities. Our findings are summarised as follows:

- Multiple facilities world-wide are required to provide traceability chains for gaseous, liquid/dense, and supercritical phase carbon dioxide flows. An operational CO_2 flow traceability chain will provide certified verification that a flow measurement device has a validated uncertainty performance referenced back to the national standard. This traceability chain will support the development of key documentary standards and CCUS regulations, as well as promoting new research and innovation. The opportunity now exists for the measurement community to develop traceable CO_2 flow facilities capable of recreating the challenging conditions that CCUS schemes will present, to support further research, development, and validation.

- CO_2 is a challenging medium for flow measurement, particularly given the likelihood of changes in property values, including density and even phase, during CCUS operation. Research is needed to investigate and improve flow meter performance over the likely range of CCUS conditions, including the development of diagnostics to detect non-ideal flow conditions for each flowmeter type.
- The well-established pure CO_2 phase diagram and equations of state cannot be relied upon for industrial CCUS streams with varying levels of impurities. The development and validation of the equations of states for CO_2 mixtures, via modelling and experimental verification, is a key technical challenge.
- At present there is a lack of documentary standards for the flow measurement of CO_2. Documentary standards provide end users with detailed specifications, stipulations and solutions for the selection, installation, and operation of measurement technologies. This lack of guidance presents potential risks for health, safety, and the environment. The development of documentary standards will support the optimum design and maintenance of CCUS schemes and presents a pressing challenge for the measurement community. Each standard normally requires several years of work from the relevant technical committee.
- While documentary standards remain under development, there is a pressing requirement for high quality information on the best practices for the flow measurement of CO_2 in the four potential fluid phases. The current lack of guidance presents clear risks to the successful rollout of CCUS worldwide. The measurement community are urged to provide technical leadership via National Measurement Institutes, universities, and other research bodies. These best practices and journal papers should provide novel solutions, information, and instruction for CCUS end users.

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