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CO₂ Flow Metering Technologies

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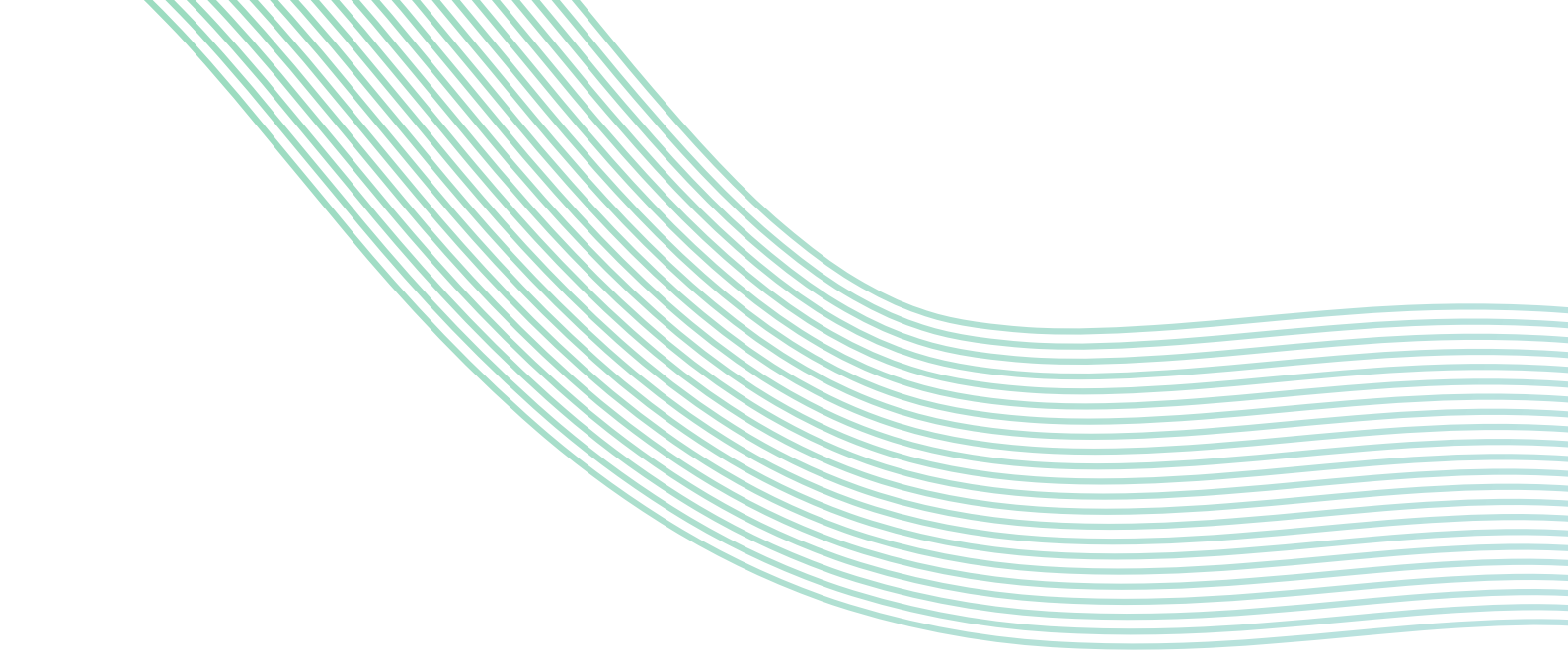
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Report Overview:

CO₂ Flow Metering Technologies

Introduction

The main objective of this study is to raise awareness of the relevance, state of the art, challenges and opportunities of flow metering for carbon capture, utilisation and storage (CCUS). Flow metering of CO₂ streams will be critical in supporting trade, protecting consumers, ensuring confidence, facilitating taxation, and meeting CO₂ reduction goals and treaty obligations. To date, standardized methods for accurately measuring CO₂—ensuring traceability and accountability—have not yet been developed. This presents challenges for process control, leak detection, and verification of emissions reporting.

Key Messages

- Flow metering of CO₂ allows verification of storage volumes and is critical for developing confidence in trading and ensuring regulatory compliance.
- The present work encompasses a review of the current development stage of metering technologies (i.e. Coriolis, Differential Pressure, Turbine, and Ultrasonic), and experimental facilities. This work documents how exploiting technologies with

high technology readiness level (TRL¹) fostered in certain existing applications, e.g. demonstrated at TRL 6-9 in CO₂ enhanced oil recovery (CO₂-EOR), or other industries has proven successful at the laboratory scale under various operating scenarios relevant to CCUS.

- Significant advancements in the chemical characterisation of streams and the development of thermophysical models for CO₂ mixtures are also reported. Yet, despite the important advancements, more research is still needed (e.g. ability to handle impurities for which the model was not developed).
- In this work, alternative pathways are provided to circumvent some of the current challenges (e.g. calibration with proxy fluids or non-flow verification for improving traceability, or virtual flow measurements for subsea applications) and ensure efficient implementations of state-of-the-art technologies.
- Future work should focus on, e.g.: inter-laboratory comparison campaigns, alternative calibration strategies, establishment of SI-traceable reference materials (i.e. ensuring trace-back to standards or references linked to the International System of Units), data sharing approaches, development of guidelines for CO₂ metering, and use of artificial intelligence (AI) to improve flow modelling.
- Establishing a legal framework and standards for CO₂ metering, aligned with technology readiness, will support the development of the CCUS value chain.

Scope

The scope of the study consists of the following tasks:

1. Investigate potential traceability chains that are suitable for measuring gaseous, liquid/dense and supercritical phase CO₂ flows.
2. Determine the correct equation of state (EOS) that should be used when calculating gas phase, liquid/dense phase, and supercritical CO₂ flows and compositions for CO₂ infrastructures.
3. Determine what CO₂ flow measurement test/facilities are needed to facilitate and calibrate fiscal CCUS meters.
4. Determine if there is a need for specific international laboratories to hold CO₂ samples that could replicate the conditions experienced within the CCS value chain
5. Identify the gaps in international standards that must be developed to facilitate the CCUS value chain.

¹ TRLs are a measurement scale from 1 to 9, where TRL 1 is the lowest level of maturity (i.e. basic principle reported) and TRL 9 is the highest (i.e. successful commercial operation).

6. Identify the TRLs for the various CO₂ flow metering and compositional analysis instrumentation currently in the market.
7. Screen which novel metering technologies are on the horizon and their ability to improve metering and close existing gaps.
8. Identify the expected accuracy levels, precision levels and expected reporting frequency for current CO₂ meters.
9. Assess how to cost-effectively deliver CO₂ flow metering in difficult and challenging environments, such as at subsea level, whilst meeting regulations. This should include an assessment of appropriate proxies.

IEAGHG commissioned SINTEF Energy Research to undertake this assessment.

Conclusions

Four technologies have been shown to have a high potential for use in CO₂ fiscal metering. Coriolis, Differential Pressure, Turbine, and Ultrasonic meters have been tested for CO₂ and CO₂-rich mixtures. The tests, conducted by different groups, took place in laboratory environments and resulted in a TRL of 4/5 for non-EOR CCUS applications. As per the existing body of knowledge, the best uncertainty in direct mass flow measurement that can currently be obtained is $\pm 0.25\%$, for gas phase and 0.35% for dense phase (i.e. under controlled conditions with CO₂ mixtures containing only non-condensables and CO₂ measured with a $\pm 0.027\%$ accuracy). The reported measurement uncertainties vary considerably and depend, among other things, on the measurement principle, the test conditions, the accuracy of the reference laboratory and the composition of the fluid. Comprehensive inter-laboratory comparison campaigns are required for CO₂ or CO₂-rich mixtures. Such comparative studies would help to clarify the accuracy of the metering technologies under the same controlled conditions.

One of the main inhibiting factors for TRL progress is the limited availability of infrastructure for researching and calibrating fiscal meters on a large scale. An alternative calibration strategy could be the use of traceable proxy fluids instead of CO₂ mixtures. The effectiveness of such a method for meters operating in CO₂ streams is sparsely documented. Laboratory tests indicate that this strategy is more promising for some technologies than others. Further research is needed.

Important challenges to CCUS arise from the presence of impurities in the CO₂ stream. Impurities may lead to changes in the physical state of the mixture. The precise characterisation of such impurities and the understanding of their effects is of utmost importance for transport and, not least, for fiscal metering. For the latter, the use of the EOS-CG-2021² is recommended, but it should be checked whether the impurities present

² Multi-parameter equation of state, necessary to model complex fluids, such as CO₂ mixtures.

are part of the systems to which the EOS applies. A characterisation of the CO₂ stream is essential for this.

Stream analysis is also the key to the flow metering for CO₂ mass accounting. The mass of CO₂ stored must be reported to regulators, but the field measurements relate to the flow rate of the CO₂-rich stream. Combined bulk mass flow rate and stream composition are required to calculate the net CO₂ mass flow. Knowledge of the in-situ density is also required when volumetric meters are used. Chemical characterisation of the stream usually requires several analytical methods. The highest accuracy can be achieved by analysing samples with equipment such as gas chromatography (GC), which can be expensive, time-consuming and requires skilled technicians. Characterisation of critical impurities that need to be measured faster could benefit from other methods such as mass spectroscopy, Fourier transform infrared spectroscopy (FTIR), and optical feedback cavity enhanced absorption spectroscopy (OFCEAS).

Stream analysers require calibration, which is carried out using traceable reference materials. In addition, representative samples must be collected, transported and stored for each analysis to characterise CO₂ streams. Chemical reactions in the storage cylinders or the transport containers for the samples must be avoided. Instabilities or degradations are undesirable for the storage of primary reference material in metrology institutes or for calibrations. Some research efforts have already been made to understand the stability of CO₂ samples. Nevertheless, further work on SI-traceable reference materials is needed to ensure global comparability. It is also recommended to carefully consider material compatibility and the choice of vessels for storage of reference materials for each mixture.

After determining the current state of the art, this study provided an outlook on the flow metering of CO₂. To this end, the study focussed on novel methods to close existing technological gaps, cost-effective solutions for subsea fiscal metering and methods to reduce measurement errors. Regarding the first point, the identified advances in Coriolis, Capacitance, Ultrasonic, and Gamma-ray technologies can help improve pressure drop in intrusive meters, detect second-phase formation, reduce measurement error due to gas-in-liquid phases, and reduce uncertainties in volume-to-mass conversion.

The use of technologies in difficult environments places higher demands on robustness, simplicity and costs. For offshore use, two alternative solutions for cost reduction were analysed. These solutions are based on (i) reducing the number of flow metering units serving multiple wells via manifolds, and (ii) estimating injection rates and virtual flow measurements that eliminate subsea flow metering altogether. However, the latter requires accurate flow models and proxy data (e.g. subsea temperature and pressure). Finally, to reduce the residual error after calibration of the metering, various filtering techniques were introduced to the raw data. These may help in reducing the overall variance of the measurements and thus improve accuracy.

From a technological point of view, there are significant prospects for the flow metering of CCUS. The challenges and solutions identified require further research to reach the required level of deployment. Data sharing, comparative studies and close collaboration among researchers, technology developers and operators will all have a role to play to deliver timely and accurate flow metering across the CCUS value chain.

The legal framework for CO₂ flow metering is still under development. The lack of traceable chains for CO₂ services may prevent providers and operators from calibrating to the highest tier defined in regulations (e.g. in the EU and UK Emissions Trading Systems (ETS)) and under realistic operating conditions in accordance with current regulations. Technological progress in CO₂ flow metering is expected to precede the enforcement of higher-tier compliance. This is an opportunity to shape the relevant legislation and standardised practices for the benefit of fair business. Repeatable, harmonized, agreed and documented methods and procedures for acceptable technologies for CO₂ metering are needed for the development of an international CCUS market.

Expert Review

Seven experts were invited to review the draft report, of which three provided comments within the deadline. Overall, the reviewers agreed that the report was well-written, reflected the current state-of-the-art and was an unbiased source of information on CO₂ metering technologies. Most comments were minor, requiring simple responses, clarifications and/or additions. The more substantive comments included:

- Add more information on operational challenges related to the verification of metering systems.
- Reevaluate the turbine technology, as there were now vendors supplying it.
- Provide more background on the use of reference materials with CO₂ compositions.
- Stronger emphasis on the lack of SI-traceable facilities and the development work underway in this area.
- Better reference and compare the UK and EU ETS requirements.

All the above have been addressed in the final version of the report. A suggestion for a comprehensive comparison of project-specific case studies has been deferred to future work.

Recommendations

- Inter-laboratory comparison campaigns are required for metering accuracy of CO₂ or CO₂-rich mixtures.
- Further research on alternative calibration strategies, such as the use of traceable proxy fluids instead of CO₂ mixtures.

- Further work on SI-traceable reference materials to ensure global comparability. It is also recommended to carefully consider material compatibility and the choice of vessels for storage of reference materials for each mixture.
- Data sharing, comparative studies and close collaboration among researchers, technology developers and operators are encouraged to ensure timely roll-out of CO₂ metering technologies.
- Comprehensive comparison exercise of project specific case studies.
- Evaluation of AI-based approaches for improvement of flow modelling.
- Detailed assessment of the economic and fiscal implications of different CO₂ metering technologies.
- Explore opportunities to advance the development of CO₂ metering standards.



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Report

CO₂ Fiscal Metering

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Abstract

To achieve the announced net-zero targets, global Carbon Capture, Utilisation, and Storage (CCUS) capacity must exponentially grow in the coming decades. Reaching the required widespread levels of CCUS entails overcoming the existing technological, economic, and regulatory challenges. Fiscal metering of CO₂ allows verification of storage volumes and is critical for developing confidence in trading and ensuring regulatory compliance. The present work encompasses a review of the current development stage of metering technologies, and experimental facilities. This work documents how exploiting high TRL technologies fostered in other industries has proven successful at the laboratory scale under various operating scenarios relevant to CCUS. Significant advancements in the chemical characterisation of streams and the development of thermophysical models for CO₂ mixtures are also reported. Yet, despite the important advancements, more research and larger-scale research infrastructure are needed. In this work, alternative pathways are provided to circumvent some of the current challenges and ensure efficient implementations of state-of-the-art technologies. For CCUS, technological advancements have driven regulatory and normative progress. Similarly, CO₂ fiscal metering can shape the future enforcement of the legislation. For this, standards in methodology for accurate CO₂ fiscal metering need to be established.

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Executive Summary

Motivation and Method

The main objective of this study is to raise awareness of the relevance, state of the art, challenges, and opportunities of fiscal metering for CCS. Fiscal metering of CO₂ streams will be critical in supporting trade, protecting consumers, ensuring confidence, facilitating taxation, and meeting treaty obligations.

The method for the study centred on reviewing and documenting the existing development stage of metering technologies, experimental facilities, and regulations via consultations of relevant public information. For key information that is not publicly available, direct contact was taken with stakeholders and project managers of ongoing research. The novel ideas brought forward during the discussions with relevant stakeholders were documented.

After establishing the state of the art, an outline of the future pathways of CO₂ fiscal metering was drawn. Novel technologies, methods for cost-reduction implementation and reduced uncertainties were further explored via dedicated assessments and documented in the body of the present work.

Fiscal metering technologies for CCS

Fiscal metering will be required to transfer CO₂ ownership from the capture plant to the storage site. When CO₂ streams contain impurities, the fluid properties change challenging metering methods. The presence of impurities in the CO₂ stream yields changes in the physical state of the mixture, e.g., non-condensable gases increase the pressure level of the bubble curve. Consequently, phase changes may happen at unexpected pressure or temperature levels if the mixture is not correctly characterised.

CO₂-rich mixtures will be transported under varying conditions, in some cases close to the vapour-liquid equilibrium curve of CO₂, the triple point or the critical point, where fluid properties change rapidly with temperature and pressure. Gas flow meters will be needed at the outlet of capture plants and onshore networks, liquid-service meters in export pipelines, loading and off-loading terminals, and injection wells.

Four flow metering technologies have shown potential for use in CO₂ streams, namely, Coriolis, Differential Pressure, Turbine, and Ultrasonic. The TRL of these technologies for CO₂-rich mixtures at conditions relevant to CCS, has been demonstrated at 4/5, mainly limited by the lack of large-scale test facilities and the early stage of development of CCUS projects.

Thermodynamic modelling

The thermodynamic properties for CO₂-rich streams relevant to metering are (i) phase boundaries and (ii) single-phase properties, including density and enthalpy. No single equation of state (EoS) is appropriate for all modelling purposes, as there is always a trade-off between accuracy, regions of validity, computational speed, and predictive ability. Generally, multiparameter equations of state are the most accurate and are applicable across all fluid phases. **The EOS-CG-2021 is the state-of-the-art multiparameter EoS for CCS systems and is recommended for all systems where it is applicable. It can be supplemented by other**



multiparameter equations of state, such as GERG-2008, if needed. If there are limitations to the use of multiparameter equation of state, an alternative is to use a simple engineering equation of state. One class of such equations is the cubic EoS. When fitted to the same data, these will generally be less accurate than multiparameter EoS. However, they are simpler, easier to fit, simpler to solve numerically, and computationally cheaper.

Traceability & calibration

Accurate fiscal metering operations that ensure fair trade and decreased financial exposure, **require accurate mass flow measurements traceable to the International System of Units (SI).** Two basic flow primary reference principles exist (i) gravimetric (realistic only for liquids), and (ii) volumetric. The latter encompasses **Small Volume Provers (SVP), a widely used primary reference method.** However, **the accuracy and repeatability of such equipment for CO₂ have not yet been thoroughly assessed,** as reference infrastructure is only being developed now. **An alternative path is the calibration of fiscal meters with proxy fluids. However, such methods work better for some technologies than others.** Initial experimental tests suggest that calibrations using alternative fluids are feasible, provided influential factors, such as temperature and pressure coefficients, density, and Reynolds numbers are correctly accounted for. However, further investigation is required before definite conclusions on this can be drawn.

Mass flow rate uncertainty

The uncertainty of the mass flow rate of carbon dioxide in a CO₂-rich stream at a given time combines the uncertainty of each of the measurements in the system. The uncertainties in mass depend on the type of meter, the mass fraction of the CO₂, the volume-to-mass conversion – if a volumetric meter is used – and the referential instrumentation for pressure and temperature. **As per the existing body of knowledge, the best uncertainty in direct mass flow measurement that can currently be obtained is $\pm 0.25\%$ ($k=2$), for gas phase and 0.35% ($k=2$) for dense phase.** These figures represent the lowest uncertainty reported for flow meter tests under controlled conditions with CO₂ mixtures containing only non-condensables, and CO₂ content measured with a $\pm 0.027\%$ accuracy. Higher uncertainties are not only possible but often reported in the literature. The variations among the reported uncertainties stem from different metering principles and manufacturers, operating conditions, accuracy of the reference laboratory, and of the reference thermophysical properties.

Research, calibration, and custody infrastructure

There is a lack of traceable facilities able to calibrate CO₂ flow meters at an industrial scale. Few facilities can operate at large scale, but only in the gas phase, none with liquid/dense CO₂. Small- and medium-scale research facilities for CO₂ metering have been identified. Various groups in Europe have planned the development of facilities traceable to a primary reference in the coming years.

Offline analysis will be needed to measure the composition of CO₂ streams accurately. CO₂-rich streams from different emitters yield mixtures that can react chemically. Such chemical reactions, along with those occurring with the materials inside the storage cylinders and or sampling transport vessels, must be considered. **Limited experience in short-term (<6 months) stability of binary CO₂ mixtures has provided positive initial results. Nevertheless, material compatibility and vessel selection for storing reference**



materials must be carefully addressed for every mixture. Further work on SI-traceable reference materials to ensure global comparability is needed.

Novel technologies to assist fiscal metering

Some novel technological developments have the potential to contribute to overcoming some shortcomings of existing fiscal metering technologies. **Promising technologies** identified encompass (i) the **reduction of pressure drop in Coriolis-like devices** and (ii) **multimodal methods to identify the formation of a second phase or to compensate for measurement errors deriving from it**; such multimodal methods combine traditional fiscal meters with capacitance or ultrasonic devices; and (iii) **accurate inline density measurements to decrease volume-to-mass conversion uncertainties.**

Efficient implementation of fiscal metering in challenging environments

Challenges with fiscal metering related to technology complexity, interference with the fluid flow and cost of implementation and maintenance are amplified in inaccessible environments that impose harsh conditions, such as subsea installations. In such environments, higher requirements for robustness, reduced complexity and costs of the meters are imposed. **Some metering technologies have better adaptability to harsh environments than others. For example, non-invasive solutions, like clamp-on ultrasonic devices or small and non-complex technologies, like Orifice Plates, have lower implementation and maintenance costs at the expense of increased uncertainty.** Arguably, accuracy is of slightly less importance because subsea flow meters are envisioned to serve as monitoring tools for the flow into the storage site, to e.g., control the flow of CO₂ and avoid undue pressure build-up in the reservoir or formation. One **alternative cost-reduction solution is based on (i) reducing the number of fiscal metering** units serving multiple wells via manifolds and estimating – using flow models – the injection rates. Alternatively, (ii) **virtual flow measurements can help remove flow metering subsea altogether.** This philosophy, however, relies heavily on accurate flow models, which, in time, need accurate information on, e.g. heat transfer and friction coefficients. Better model accuracy could be obtained if the behaviour of the subsea system is thoroughly accounted for, e.g., by using optic fibre pressure and temperature sensors.

Uncertainty reduction methods

Flowmeters are inherently susceptible to both random and systematic errors, which can impact the accuracy of mass flow rate measurements. Calibration techniques are typically employed to mitigate systematic errors, though residual errors often require further correction. A key focus is the use of filtering techniques, particularly the Exponential Moving Average (EMA) filter, to address random errors. The EMA filter smooths out noise by applying exponentially decreasing weights to past data, enabling more accurate real-time measurements. The filter's performance is highly dependent on the tuning of its forgetting factor, which must strike a balance between bias and variance. **Two filtering approaches are introduced for systems with multiple adjacent flowmeters.** The first approach combines weighted averaging of individual flowmeter readings with subsequent EMA filtering. In contrast, the second approach averages the results of individual EMA filters applied to each flowmeter. **These methods effectively reduce the overall variance of the measurements, thereby potentially improving accuracy.** The former method generally offers better reliability in reducing measurement errors. Other techniques, such as Holt-Winters, Kalman filters, and deep learning architectures, are potential alternatives for further error reduction. However, complex methods

need to be employed with care. Additionally, ensuring optimal filter performance involves careful parameter tuning, consideration of sampling frequencies, and effective management of noise correlations.

Regulatory framework

The global normative landscape for CCUS is constantly evolving, with different regions at different stages of development. Regarding the groundwork for a regulatory framework for CCUS, Europe stands at the forefront. The region has made significant strides in streamlining the CCS permitting process, with some countries having more advanced national CCS policies than others. Other regions worldwide are also making progress, albeit at different rates. In the Middle East, Africa, and Asia Pacific, advancements have been made, but the region still shows limited improvement in the CCUS normative framework, which is broadly lacking.

Similarly, **there is a lack of a repeatable, harmonised, agreed, and documented way of metering CO₂ for the upcoming international CCUS market.** Uncertainty requirements for flow measurements of CO₂ in the different phases are dispersed among various regulatory, standard and best practices documents. Overall, the minimum accuracy of the complete measuring systems is 1.5 %, and of the individual meter 1%. For captured CO₂ in gas form, the minimum uncertainty in flow is 2.5%, although lower uncertainties are found in regulations for gas measurements that do not explicitly specify CO₂ as a working fluid.



1 Background

Meeting the Paris Agreement goals implied reducing the global CO₂ emissions by 50-85 % by 2050. For this, widespread Carbon Capture, and Storage (CCS) is needed. The mass of CO₂ that will be transported and stored to meet the International Energy Agency (IEA)'s Sustainable Development Scenario is of a similar scale to the current global natural gas use which accounted for ~3GT/y in 2023 [1, 2]. Trading such amounts of CO₂ requires significant technological, financial, and regulatory efforts.

Although the perspective for CCUS market growth is promising, given the recognition that achieving net-zero greenhouse gas (GHG) emissions is increasingly urgent, the technological and regulatory pace requires an exponential increase in CCUS business to meet the IEA's scenario (see Figure 1). Additional measures are needed to continue reducing and managing carbon emissions, especially in hard-to-abate sectors.

Currently, the main business drivers for CCUS are carbon taxes (e.g., in the USA) and emission trading schemes (in Europe – EU ETS, UK ETS). ETS caps the total level of GHG that can be emitted and allows industries with low emissions to sell their extra allowances. The supply and demand of emission allowances create a market price for CO₂ emissions. The ETS enables the subtraction of emissions captured and stored in long-term geological storage sites. However, according to the current EU ETS regulation, the capture site can only deduct the CO₂ from its reported emissions once transferred to a pipeline transport network or a storage site. In this context, thorough CO₂ accounting is vital. Fiscal metering allows verification of compliance with the ETS, thus generating revenue. Accurate fiscal metering is critical for developing confidence in trading and ensuring regulation compliance.

Reaching the required widespread levels of CCUS requires overcoming the existing technological, economic, and regulatory challenges. The ZEP report [3] on Trans-European CO₂ Transportation Infrastructure for CCUS underlined some of the technological challenges for the development of future CCUS transportation infrastructure (see Figure 2). Relevant to the present report are the challenges associated with network and monitoring, in particular, those regarding (i) real-time composition and monitoring plans, but also those regarding (ii) models for phase equilibria, database and validation, and (iii) test facilities for metrology.

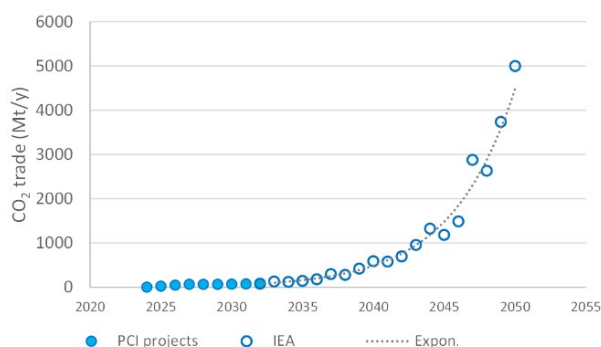


Figure 1. Yearly CO₂ trade showing PCI projects from lists of 2019 and 2021 and extrapolation to meet the 2050 IEA sustainable development scenario



Measurement needs related to (i) above in particular, have been emphasized in previous works [4-6]. Most benchmark studies have focused fiscal metering technologies [7-9]. There are, however, broader measurement and analysis needs for CO₂ streams that have, so far, only been superficially addressed in the literature. Furthermore, the information is scattered and in need of an expert eye to sort and critically review.

Also pertinent to (i) is the evolution of CCUS business models from single-source-to-sink transport towards capture clusters, yielding various CO₂-rich mixtures. Hard-to-abate sectors, e.g., cement and steel production, as well as the petrochemical industry, waste incineration, and natural gas reforming, require varied CO₂ capture technologies. Diverse capture processes, yielding from the varied CO₂ sources, lead to an assortment of impurity species and concentrations. Further, the CO₂ transport networks downstream of the capture plants will need to be designed and operated, accounting for dynamic operational conditions. That is, the intermittency of the capture processes will yield planned, and unplanned, temporal and spatial variations in pressure, temperature, flow rate, and stream composition.

Such variations in compositions, flow rates, and operational conditions may yield off-spec streams with the possibility of forming an impurity-rich second phase, precipitation and accumulation of corrosive liquids, and the shift of the bubble point curve towards higher pressure caused by non-condensable gases. It is thus paramount to appropriately design the transport infrastructure and use models and technologies that decrease the risks of, for example, operation in the two-phase gas-liquid region that, among many unwanted consequences, results in higher uncertainties for fiscal meters. Flow variations also require careful meter selection with appropriate turn-down ratios. Using volumetric flow meters necessitates density knowledge for volume-to-mass conversions, the appropriate selection of the equation of state, or understanding the added uncertainty of density measurements for the custody transfer operations is critical.

Awareness of the current state of the art and a clear outline of the future pathways of CO₂ fiscal metering have significant implications for the developing CCUS. The present work addresses such aspects from an integral perspective, encompassing at least three key fields, i.e., metrology, thermodynamics, and the regulatory domain. The remainder of the report is structured in three sections. After an introductory Section 1, which provides an overview of the application niche of this research and describes the motivation of the present work, Section 2 establishes the current state of the art, relevant for CO₂ fiscal metering. In this sense, Section 2 investigates potential traceability chains for CO₂ flows, TRL of fiscal metering technologies and their expected accuracies. A review of relevant equations of state and their applicability to CO₂ streams is also provided. The need for fiscal metering facilities to calibrate fiscal meters and laboratories to keep reference materials is also discussed towards the end of Section 2.

CCUS metrology is at an early stage of development; thus, Section 3 provides an outlook. There, novel technologies and their ability to improve metering and close gaps are provided. Special attention is dedicated to cost-effective fiscal metering and error reduction. Finally, an overview of the existing regulatory framework is provided in Section 4, where gaps in international standards are discussed.

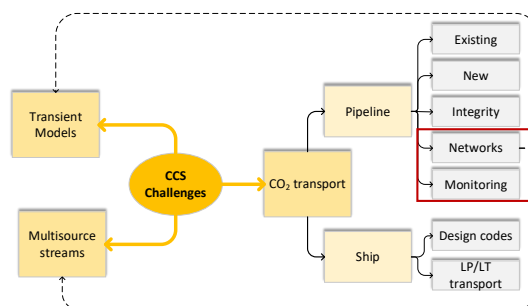


Figure 2. CCS challenges identified by the ZEP showing in red the areas directly targeted by the current project

2 Current state of the art

2.1 Fiscal metering framework

The CCUS industry is at an early stage of maturity, thus publicly available information is sparse. The present work will focus on the operating conditions of the projects that have a more advanced stage of maturity, and where information is readily available (see Appendix A).

Figure 3 illustrates the CCS value chain and main metering points. CO₂-rich streams will be metered and analysed throughout the transport chain from the outlet of the capture plant (node 3) to the injection well (node 9). Further details on the flow metering nodes can be found in [4] and references therein.

In the field, fiscal meters will measure the flow rate of the CO₂-rich stream, yet in general, the commodity in CCS is pure CO₂ or CO₂ above a set purity level. Thus, to report the stored CO₂ to regulating bodies, the CO₂ mass needs to be computed from combined mass flow rate measurements and stream composition. In-situ density is also necessary if volumetric meters are used.

The predominant phase state throughout is illustrated in Figure 3 by the colour of the pipelines, and correspondingly in the accompanying phase diagram. The nodes where changes in compositions are expected are indicated by the ‘unique composition’ icon. According to the operation conditions, gas meters will be needed at the outlet of capture plants and onshore networks, and liquid-service meters in export pipelines, loading and off-loading terminals, and injection wells.

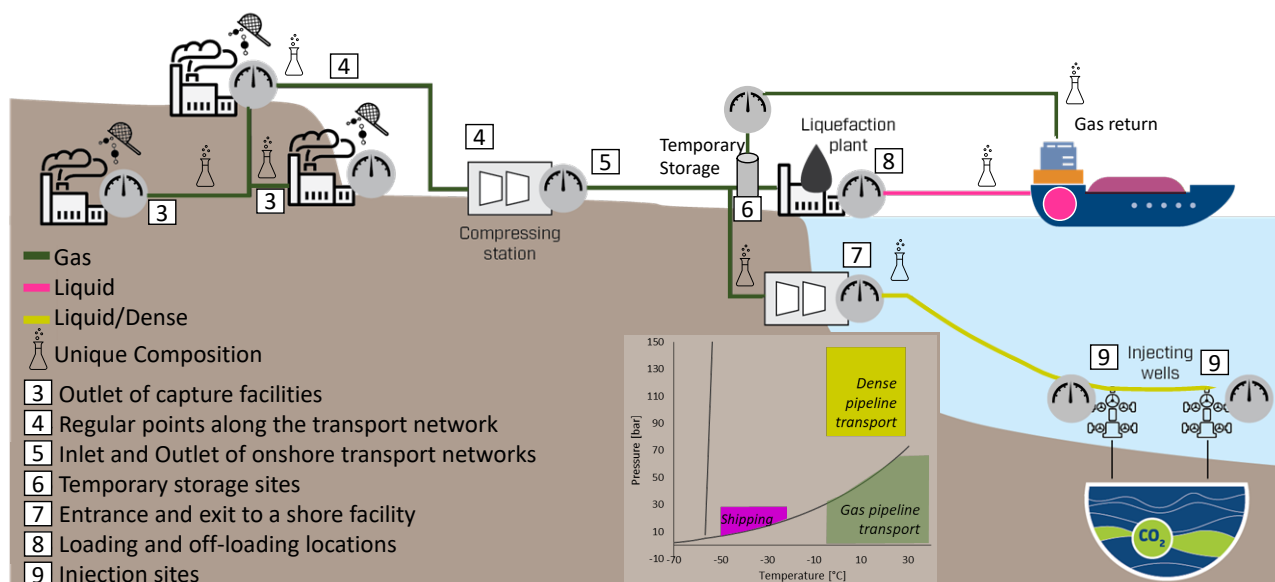


Figure 3. CCS value chain showing post-capture measurement nodes and varying stream composition and typical transport conditions in the CO₂ phase diagram. Modified from [10]¹

¹ Measurement technologies for pipeline transport of carbon dioxide-rich mixtures for CCS by Y. Arellano, et al., licensed under CC BY 4.0



Relevant transport states are close to the vapour-liquid equilibrium curve of CO₂. That is, shipping of subcooled CO₂ is undertaken close to the triple point, whereas the pipeline transport conditions occur close to the critical point, where fluid properties change rapidly with temperature and pressure. Moreover, the presence of impurities in the CO₂ stream yields changes in the physical state of the mixture, e.g., non-condensable gases increase the pressure level of the bubble curve. The presence of impurities modifies the phase envelope of the mixture, causing changes in the thermophysical state of the stream at operating conditions different from that for pure CO₂. Further, impurities can promote the formation of a second phase. Yet, impurities are not the only cause for phase changes in the value chain; unintended shutdown sequences can also yield two-phase (liquid-gas) flow in export CO₂ pipelines [11]. Consequently, ensuring single-phase flow, on which fiscal metering technologies depend, can be challenging in transport networks. This is especially true for intermittent streams and long pipelines affected by changes in terrain and ambient conditions.

The flow rates in export pipelines and offloading terminals can be roughly estimated based on the number of pipelines and the target storage capacities of the various CCS projects (See Appendix A). The expected conditions of the different measurement points with CO₂ transport are summarised in Table 1.

Table 1. Measurement points and conditions

Metering point	Condition	Pressure (bar)	Temperature (°C)	Flow rate (tonne/h)	Ø (inch)
Onshore pipeline	Gas	15-70	Ambient	450-1150	24, 42
	Dense	120	Ambient	690	36
Outlet of the capture Plant	Gas	2-50	30-40	31-160	N/A
Various points in networks (manifolds, compression stations, buffer storage, etc)	Gas	See conditions above			
Loading & off-loading terminals	Liquid	10-22	-30 to -21	340-570	N/A
Export pipeline (compression station)	Gas	50	Ambient	570	24
	Liquid/Dense	85-120	-2 to 8	450-1700	12-30
Injection in wellheads	Liquid/Dense	See conditions above			

2.2 Measurement technologies

The challenges and needs of CO₂ measurement have been underlined in several works [4-6]. Benchmarked technologies have shown promise for accurate flow measurement of CCUS [7, 8, 10, 12]. The market for CO₂ monitoring technology is, however, relatively new. To overcome some knowledge gaps, several groups have undertaken experimental tests on fiscal metering techniques for CO₂ service at different conditions. A single technology for flow measurement or method for analyses of impurities in the CCUS stream is currently unavailable. Several analytical techniques would be required throughout the CCS value chain.

2.2.1 Flow measurement

Initial assessments [10, 13-15] indicate that existing commercially available meters can partly address some measurement needs of CCUS. A brief summary of the metering principles of the most promising technologies and their use in CO₂ service follows.

Coriolis flow meters consist of measuring tubes which vibrate at their natural frequency. The forces exerted by the tubes on the fluid flowing internally are proportional to the inertia and to the mass flow through them. Algorithms are used to compensate for stiffness resulting from the process fluid temperature.

Differential pressure meters encompass among other devices, orifice plate meters. In orifice plate meters, a difference in pressure is related to the flow rate across an orifice of known geometry. The accuracy of these meters depends on the accuracy of the differential pressure measurements and of the accuracy of fluid properties, like the density.

Ultrasonic flow meters measure the volumetric flow from the fluid velocity. Ultrasonic meters use opposed-facing transducers to emit and receive ultrasonic pulses. The difference between the contrapropagating transit times over a known path length is used to measure the fluid velocity. The process conditions and the fluid properties, i.e., fluid viscosity and acoustic signal attenuation, impact the measurements.

Turbine meters translate the mechanical action of an axial turbine rotating inside the flow stream into a volumetric flow rate. The rotation speed is proportional to the fluid velocity.

Non-SI-traceable tests of the above meters have found different niches within CCS applications. Table 2 summarises the available technologies with potential for CCS fiscal metering, including the latest developments and experimental experience. The TRL of the technologies are given as per their documented use in Enhanced Oil Recovery (EOR), or pure CO₂ use. The current stage of development of CCS results in a TRL of 4-5 for CO₂ mixtures and conditions relevant for CCS service, with the lack of large-scale facilities being the main limiting factor to advance TRL.

2.2.2 Stream analysis

Elemental analysis is a process where a sample of a material is analysed to determine its chemical composition. Here, the elemental analysis of CO₂ streams is referred to as stream analysis. Stream analyses can be performed offline, where the stream is sampled and sent for analysis to a laboratory; or online, via a continuous measurement system and a sampling line to in-situ analysers. The former is mostly suitable for batch transportation. For pipeline transport, on the other hand, online analysis of the stream is preferred. Alternatively, non-critical impurities can be measured offline at a regular frequency.

A thorough desk study on measurement technologies for impurities in CCS gas streams is presented in [16], for details of relevant methods, the reader is referred to the study and references therein. Given the variety of impurities and concentrations in CO₂ streams at a given time, multiple analytical methods are needed.

**Table 2. Flow measurement technologies with the potential for CCUS (modified from [12])**

	Coriolis	Ultrasonic	Differential Pressure	Turbine
Measurement range (10")	~1,000 tonnes/hr (nominal)	1824 m ³ /hr	Similar to Coriolis, but small turndown permissible without affecting accuracy	200-4000 m ³ /hr
Process pressure limit	SS316, 100 barg, SS318 / Hastelloy C22 200 barg	No fundamental limit for clamp-on for liquid or inline (>176 bar installed).	Not a limitation in practice	100 barg
Process Temperature range	Sufficient (commercial models can be specified from -200 to +400 °C)	Sufficient (-190 to +500 °C depending on options and models)	Pressure transducer dependent, but little flexibility once calibrated for a fluid	-25 to +70 °C
Composition ranges	In principle, unlimited and flexible as long as single-phase is ensured, but must be verified	Higher impurity level can give higher signal strength, but more uncertain density (if based on EOS)	In principle, unlimited and flexible as long as single-phase is ensured, but more uncertain density (if based on EOS)	In principle, unlimited and flexible as long as single-phase is ensured, but more uncertain density (if based on EOS)
Pressure drop	Yes	Can be negligible	Yes, and it could be strongly tied to accuracy	Yes
Multi-phase	To a limited degree and with lower accuracy	Normally not	No	No
Density relation	The meter can inherently also be used as a densimeter, but density does not have a first-order effect on the mass flow measurement	First-order impact, external measurement, or model estimate required	First-order impact, external measurement, or model estimate required	First-order impact, external measurement, or model estimate required
Weight and footprint (10")	~900 kg, 0.85 m ²	, 0.09 m ² / 4 beams ~530 kg	Relatively small	220 kg, 0.25 m ²
Flange dimension	10" may be a practical limit for the purpose	TBC, most likely no limitations	Any	TBC, most likely no limitations
Minimum Error in non-SI-traceable tests ² [14, 17]	Gas: ±0.25% pure CO ₂ & CO ₂ -mix Liquid: ±0.16 % pure CO ₂ – ±0.25 % CO ₂ - mix	Gas: ± 0.2% CO ₂ -mix Liquid: ±0.65 % CO ₂ -mix	Gas: ±0.2% pure CO ₂ – ±0.67% mixture containing CO ₂ Liquid: ±1.3% pure CO ₂	Gas: ±0.15% pure CO ₂ & CO ₂ -mix Liquid: ±1.5 % pure CO ₂
Knowledge gaps	Verification at varying conditions	Properties, especially attenuation, transients	Properties	
TRL (CO ₂ - EOR)	9 [18]	6 [19]	9 [20]	9 [20]
Comments	More extensive experimental body of knowledge with CO ₂ compared to the other technologies. Tests suggest the technology is suitable for liquid and dense-phase CO ₂ applications.	Limited body of knowledge for liquid/dense phase. Notable advantageous due to large size and minimal pressure drop.	Applicable for gaseous CO ₂ . Volume-to-mass conversions remain a concern	Suitable for gaseous CO ₂ under controlled environments such as laboratories or test centres, where mechanical integrity is of lesser concern

² Unless otherwise stated the expanded uncertainties provided here and the rest of the document correspond to $k = 2$ (at a 95 % level of confidence)



Stream analysers often require skilled operators, and equipment and maintenance are costly. Therefore, such equipment is seldom found on site. Offline analyses can give rise to challenges regarding the method of sampling, which can influence the outcome, as well as the stability of the samples during transport and storage [21] (refer to Section 2.7.2 for consideration regarding custody of reference materials). Further, sampling material compatibility to avoid reactions between sample materials and analyser components is paramount. During the selection, design, and configuration of the analysis technologies to service a given mixture, a thorough pre-feasibility study based on the species present and accuracy requirement is necessary.

From the existing body of knowledge and relevant stakeholders' experience [10, 16, 22-24], it is evident that multimodal configurations that leverage the potential of two or more measurement principles are the most viable method for CO₂ stream analysis. In this sense, gas chromatography (GC) with thermal conductivity detection (GC-TCD), and absorption spectroscopy with Fourier-transformed infrared (FTIR) or enhanced with optical feedback cavity (OFCEAS) are some of the most promising multimodal configurations. Together with GC, mass spectroscopy (MS) is also recommended for CO₂ analysis by DNV [24].

GC-TCD combines physical and chemical separation processes with an analytical method. In a GC, the separation takes place in the analytical column, which is usually held within a GC oven. The primary separation mechanism of the components within the column is volatility. The temperature could be kept constant; however, often a temperature program of the oven will be preferred for a sufficient separation of the peaks while keeping the run time of the analysing method down. A detector responds to the components, producing a chromatogram. The chromatogram plots peaks of the retention time of every component, with the area under each peak proportional to the concentration of the given compound. The choice of the GC detector varies depending on the impurities present. TCD is a near-universal detector, where the sensitivity depends on the difference in thermal conductivity between the component and the carrier or reference gas. GC-TCD optimised for CCS-relevant impurities is customary in dedicated laboratories with reported uncertainties below 0.03% ($k=2$)³ [25, 26]. GC combined with a TCD can measure all the major impurities expected in the CO₂-rich stream [14, 16]. However, for components like NH₃, amines, and glycols, other GC detectors different from TCD are recommended in [16] (see also Table 3). The time of online analysis with a GC-TCD varies between 20 seconds (with a micro-GC) and up to 20 minutes for complex mixtures [14]. The GC needs to be calibrated for each mixture composition via calibration curves made from analysing various, typically 3 to 5, different sample compositions. Further, repeatability must be ensured via numerous analyses.

The absorption spectroscopy principle measures the concentration of impurities in the CO₂ gas stream. In an absorption spectroscopy system, light in the infrared region (IR) induces molecular vibrations, causing absorption at wavelengths that are unique for each gas [27]. Virtually all organic compounds absorb IR radiation, however, since the compounds are not physically separated (like in a GC), overlapping spectra between the different impurities can occur, affecting the measurement accuracy. Such an overlapping effect is documented in Figure 4, from the work in [27]. The plot shows the wavelengths of CO₂ and other components (N₂, NO, SO₂, H₂S, O₂, NO₂, H₂O and H₂) at concentrations relevant to CCS. A list of sensor

³ Unless otherwise stated the uncertainties provided in this document correspond to $k=2$ (at a 95 % level of confidence)



considerations for various impurities is provided in [16].

FTIR and OFCEAS are faster than a GC and, thus, better suited for the measurement of critical trace impurities where fast measurements are required. These technologies have a low detection limit, in the order of 1 ppm. Yet speed can come at the expense of lost accuracy, with measurement uncertainties of OFCEAS in CO₂ concentrations of $\pm 2\%$ relative [28]. Mass and absorption spectroscopy is a well-established technology in various industrial processes, at conditions similar to what is required for CCS. GC-MS and FTIR, for example, have been employed at Technology Centre Mongstad (TRL 6), with good results. Yet building good models for FTIR is reportedly time-consuming and expensive [23]. Such deterrents can be prohibitive for streams with varying compositions.

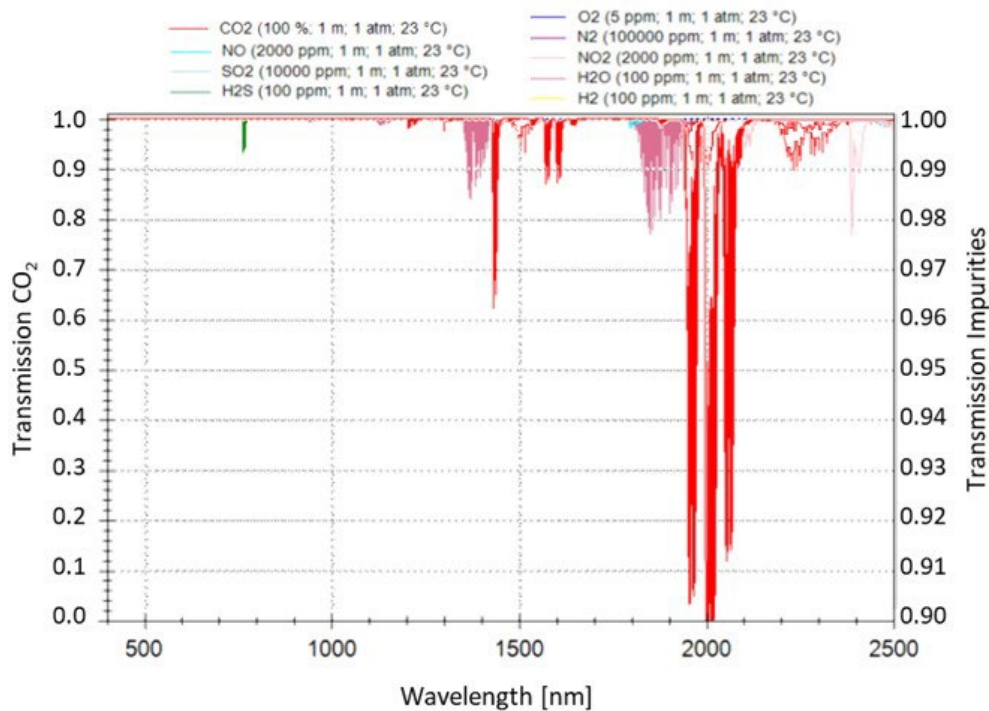


Figure 4. Rate of transmission spectra for 1 m path length for CO₂ and CCS-relevant impurities. Assuming a bleeder system is used at atmospheric conditions (1 bar, 23 °C). The transmission coefficients were estimated using HITRAN database [28] at wavelengths between 400 and 2500 nm. Source: [27]⁴

The authors in [16, 29] recommend various analytical instruments for measuring selected impurities in CO₂ for quality assurance purposes. For materials that cannot be analysed by the methods or detectors discussed above, the instruments in Table 3 are suggested in [29]. For more information on the technologies, the reader is referred to the original work and references therein.

⁴ Measurement technologies for pipeline transport of carbon dioxide-rich mixtures for CCS by Y. Arellano, et al., licensed under CC BY 4.0

**Table 3. Overview of alternative instruments for analysis of impurities in CO₂ (modified from [29])**

Material	Upper limit ($\mu\text{mol}\cdot\text{mol}^{-1}$)	Analytical instrument
H ₂ O	300	Cavity ringdown spectroscopy (CRDS), Quartz crystal microbalance
H ₂ S	5	GC with sulphur chemiluminescence
O ₂	100	GC with pulsed discharge helium ionisation detector
SO _x	0.5	Ultraviolet fluorescence spectroscopy
NO _x	0.5	Chemiluminescence analyser, CRDS, Cavity attenuated phase shift spectroscopy
HCl	1	CRDS
HCN	0.9	GC with flame thermionic detector, Selected-ion flow-tube mass spectrometry
Hg	0.002	Atomic absorption spectrometry
Amines	1	GC with nitrogen chemiluminescence detector
Glycols	0.046	Scanning Mobility Particle Spectrometer, GC with flame ionisation detector

2.3 Thermodynamic models

The thermodynamic properties of CO₂ streams relevant to metering fall into two categories:

- Calculation of phase boundaries: This amounts to determining at which states a new phase becomes thermodynamically stable.
- Calculation of single-phase properties: This involves calculating the properties of the CO₂-rich phase, such as its density and enthalpy.

Phase boundaries

To calculate phase boundaries an equation of state (EoS) must be able to represent both the CO₂ stream and the new phase. Since flow metering technologies generally require that the CO₂ stream exists in a single phase, an EoS must be sufficiently accurate to ascertain whether the operating point is in the single-phase or multi-phase region.

The appearance of an unwanted vapour phase in the CO₂ stream is a common problem for metering technologies. The major impurities in CO₂ streams are typically non-condensable such as nitrogen, oxygen, argon, methane, carbon monoxide, hydrogen, and helium. If the total concentration of these impurities becomes too high, a gas phase will appear. Fortunately, the thermodynamics of CO₂ streams containing only these impurities are now well understood, and equations of state such as EOS-CG-2021 [30] can calculate these phase boundaries accurately. Other impurities are generally present in concentrations of a few hundred ppm, and thus their impact on the thermodynamic properties of the CO₂-rich phase is usually small, as discussed further below. The simplest approach to dealing with these minor impurities is to disregard them.

For condensed phases, the phase boundaries are generally harder to predict compared to vapour phases. A typical unwanted condensed phase is an aqueous phase, which can accumulate in pipes or equipment and cause corrosion. For the binary system CO₂-water the phase boundaries are well-known, but in generic CO₂ streams this is complicated by the presence of impurities such as acids that can stabilise an aqueous phase

at lower humidity levels [31]. While these phases are usually present in very small quantities, if they accumulate over time, significant inaccuracies may ensue.

Single-phase properties of the CO₂ stream

The most relevant single-phase thermodynamic properties are density, speed of sound, and the Joule-Thompson coefficient. The thermodynamic properties of the CO₂-rich phase can generally be determined with high accuracy, apart from certain operating regions. Near the critical point, thermophysical properties are highly sensitive to variations in temperature, pressure, and composition. The critical point connects to the Widom line, given by $\max(\partial\rho/\partial P)_T$. Flow metering that depends on accurate thermophysical properties should avoid operating close to the critical point and the Widom line. In these regions, equations of state will inevitably be less accurate.

Viscosity is another central property for flow metering and is needed to calculate the Reynolds number of the flow. Viscosity is a transport property, and hence cannot be calculated by an equation of state. The choice of viscosity model for CO₂ streams is not treated here, but is evaluated and discussed in e.g. [32].

Multiparameter equations of state: EOS-CG-2021 model

No single equation of state is appropriate for all modelling purposes [33]. Generally, multiparameter equations of state are the most accurate and are applicable across all fluid phases [34]. Their accuracy results from a correlation procedure that demands extensive experimental data on thermodynamic properties, and these EoS may not be developed for mixtures that contain rare impurities. For CCS mixtures, however, extensive work has vastly improved the situation in recent years.

The EOS-CG-2021 model is a multiparameter EoS reported by Neumann et al. [30], which extends previous works [35-37]. It is valid for systems containing the following components:

- Carbon dioxide (CO₂)
- Nitrogen (N₂)
- Oxygen (O₂)
- Argon (Ar)
- Water (H₂O)
- Carbon Monoxide (CO)
- Hydrogen (H₂)
- Methane (CH₄)
- Hydrogen sulphide (H₂S)
- Sulphur dioxide (SO₂)
- Monoethanolamine (MEA)
- Diethanolamine (DEA)
- Hydrogen Chloride (HCl)
- Chlorine (Cl₂)
- Ammonia (NH₃)
- Methyl diethanolamine (MDEA)

The EOS-CG-2021 model is furthermore compatible with the GERG-2008 EoS [35], meaning that they can be combined into one EoS applicable to mixtures with components that at least one of them caters for. Such a combined EoS will additionally cover helium and additional hydrocarbons.

To illustrate the accuracy of the EOS-CG-2021 model, let us consider the CO₂-N₂ system, where nitrogen (N₂) is selected as it is typically the predominant impurity. This binary model was developed as part of the GERG-2008 initiative, and had approximately 5,000 measurements from 25 sources available for its development. The model's indicative uncertainties are 0.3% for vapour density, 0.5% for liquid density, and 1% for supercritical density. Additionally, it reproduces measured speed of sound data within 1% for pressures up to 100 bar.

Note that for some of the binary subsystems and for most ternary and higher-order subsystems, there are no validation data available, and the accuracy of EOS-CG-2021 is unknown. From a thermodynamic viewpoint, the EoS should remain accurate for the calculation of single-phase properties if it is accurate for the majority of the binary interactions. In a CO₂ stream the intermolecular interactions will be predominantly between CO₂ and itself, between CO₂ and non-condensables, and to a smaller extent between non-condensables. Interactions with the remaining impurities will have less effect on thermodynamic properties. Although single-phase properties should remain accurate, phase boundaries may not.

A method to handle impurities for which the EoS has not been developed is also needed. Impurity concentration limits for various projects (see Appendix A) indicate that non-condensable impurities are generally present at only a few hundred ppm or less. If these levels of non-condensable impurities are added to a CO₂-N₂ stream, their impact on the thermodynamic properties will typically be much smaller than the uncertainties indicated for the CO₂-N₂ system. Therefore, as long as phase separation does not occur, the uncertainty associated with such trace impurities will typically be dwarfed by other uncertainty sources. Unless their impact on thermodynamic properties is known, trace impurities should simply be disregarded in EoS calculations.

Engineering equations of state

If the multiparameter EoS, for some reason, cannot be used, an alternative is to utilise a simple engineering equation of state. When fitted to the same data, these will always be less accurate than multiparameter EoS. However, they are simpler, easier to fit, often simpler to solve in a numerically robust way, and computationally cheaper [33]. Their accuracy can be excellent if they are fit to the operating region of interest.

The state of the art for cubic EoS is the translated-consistent Peng-Robinson EoS (tc-PR) [38]. A key feature of tc-PR is its good performance for mixtures where some components are supercritical, which is the case for non-condensable impurities (N₂, O₂, Ar...) in CO₂ streams in CCS. Cubic EoS can be used with various mixing rules, but the most accurate results for CCS streams are generally obtained with excess Gibbs mixing rules [26, 39, 40]. If hydrogen-bonding components are present, the CPA equation of state or the members of the SAFT-family of EoS can be considered [39].

If there is certainty that the flow is always in the single-phase region, the EoS will only need to be accurate for compositions close to pure CO₂, which simplifies the process of developing the EoS. In this case the extended corresponding state EoS framework [41] [33] like SPUNG [42], can be utilised to obtain an equation that reduces to the Span-Wagner EoS [43] for pure CO₂, but that retains most of the simplicity, robustness and computational speed of cubic EoS.

An oft-overlooked issue is the importance of an accurate underlying ideal-gas heat capacity model. Most equations of state are given as expressions for the pressure as a function of temperature, volume, and composition, $P(T, v, \mathbf{z})$. Such a relation is not enough to calculate property changes between states at different temperatures; it must be supplemented with an equation for the ideal gas heat capacities for each component. Wilhelmsen et al. [40] used the process simulator HYSYS V10 for isentropic compression of pure CO₂ from 1 bar and 298.15 K to 2 bar. Due to the inaccurate ideal gas model used by HYSYS, the final temperature was off by 1 K compared to using the same model but with the state-of-the-art ideal gas model. When using engineering equations of state, it should be ensured that the most accurate ideal-gas heat capacity models are used, which are typically those that are used for the multiparameter EoS by default.

Summary: recommendation for equation of state

The EOS-CG-2021 is recommended for all systems where it is applicable and can be supplemented by other multiparameter equations of state, such as GERG-2008, if needed. The mathematical formulation of these multiparameter EoS is modular, so that it should be updated whenever a new component or a new binary system is fitted. The concentration of other impurities should be set to zero for the EoS calculations.

2.4 Traceability

Traceability is the foundation of fiscal metering. To ensure fair trade and decreased financial exposure, it is key to precisely trace the mass flow measurement of CO₂ back to a standard or references linked to the International System of Units (SI) for time and mass.

Bootstrapping calibration uses transfer references calibrated against a primary reference. Such chain calibration often relies on incremental capacities of the secondary reference meters. The primary standard apparatus provides traceability and dictates the base calibration accuracy. The primary flow standard links national standards and the transfer flow standards used in calibration laboratories for meters deployed in the field.

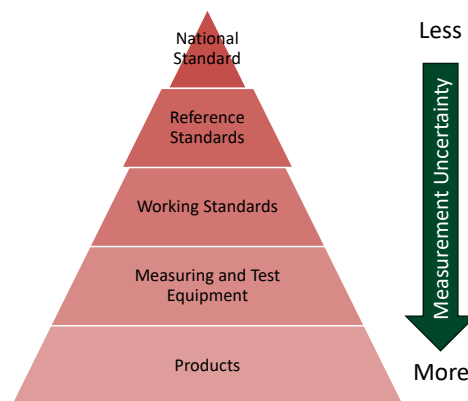


Figure 5 Traceability pyramid

Two basic flow reference principles exist: (i) gravimetric (only suitable for liquids), in which flow is diverted to a closed container, and (ii) volumetric, without stream diversion. Gravimetric reference is the most used calibration method for liquid flows at low pressures like water. In gravimetric calibrations, the flow is diverted to a closed container where it is weighed. Using this method for large-scale CO₂ flows would require advanced pressure control at the inlet of the tank inlet to maintain the pressure. Yet, large pressure drops



of liquid CO₂ can yield dry ice formation. Thus, during operation, the pressure should be maintained above the boiling point to avoid fast boil-off. Further, tight control of the fluid temperature warrants uniform stream composition through the system. As per the available literature, there is one small-scale rig that uses gravimetric reference for CO₂ [44].

For liquid and gaseous CO₂, combined volumetric primary reference and mass calculation is a feasible possibility. Volumetric proving in the form of small volume provers (SVP) [45] has been long implemented in other industries. SVP use a travelling piston to measure volume flow where the position of the piston is correlated to a calibrated volume. Using accurate density, pressure, and temperature measurements grants mass flow estimates from the measured volume flow. Meter provers are regulated by the API standard chapter 4 [46], developed for the oil and gas industry. Therein the overall minimum uncertainty is required to be less than $\pm 0.01\%$, including contributions from all measurements relating to meter proving, e.g., temperature, flow, and pressure. Care must be taken to ensure that the fluid is in single phase and that the density is determined by an accepted practice, such as an appropriate equation of state (see Section 2.3 on thermodynamics).

SVPs are manufactured for applicable flow rates and pressures and are available on the market. Reported Calibration and Measurement Capability (CMC) uncertainties for water laboratories using provers are in the order of ± 0.02 to $\pm 0.04\%$ ($k=2$) [47, 48]. Yet, the accuracy and repeatability of SVP with CO₂ is still an open question. Efforts to quantify the uncertainty of a liquid CO₂ calibration facility using bootstrapping and particularly with volume provers as primary reference are documented in [9, 49], and summarised in Section 2.5 below. Ongoing research aims to build a traceability chain for CO₂ in the coming years. In this sense, the MetCCUS⁵ project is developing primary standards for gaseous CO₂. There, TÜV SÜD NEL (NEL), INRIM, VSL, and FORCE work on building volume provers for intermediate scale ($<50 \text{ Sm}^3/\text{h}$) and large scale ($<400 \text{ m}^3/\text{h}$) CO₂ flows. For liquid and supercritical CO₂, NEL via the ENCASE⁶ project and SINTEF, as part of PREFERENCE⁷, are developing primary standards.

2.4.1 Alternative pathways

Following the traceability path in Figure 5, it is evident that the meters deployed in the field require calibrations that can be traced to national standards. Calibrating CO₂ at close-to-operation conditions is typically preferable and, in some industries, often required by regulatory authorities. Such a strategy reduces the effects that fluid properties and process conditions have on measurement accuracy. However, calibration facilities for CCUS meters are a recognised limitation to calibrate with process fluid [3], as primary standards are just being developed. But even if facilities were in place, matching process and stream compositions with precision and performing calibrations at all relevant process conditions can be time-consuming and expensive. Two alternative pathways are discussed below.

2.4.1.1 Calibration with proxy fluids

Various works outline the performance of flow meters for CO₂ services [4, 7, 22, 27, 49]; from them and the references therein, a summary of the transferability considerations is summarised in Table 4.

⁵ <https://metccus.eu/>

⁶ <https://www.encase-eu.com/>

⁷ <https://www.sintef.no/en/projects/2022/preference-primary-flow-reference-for-ccs/>

Table 4. Relevant fiscal metering technologies for CCS and considerations for CO₂ service

Technology	Transferability considerations	Relevant experience
Coriolis	The calibration of Coriolis meters requires matching flow rates. Density output should typically be corrected for pressure and temperature effects. Thus, calibration across the expected operational range of pressure and temperature is recommended. Transferability in Coriolis, characterised by the effects of low Reynolds numbers for viscous fluids, does not apply to CO₂ [14]. Note that the Reynolds number for gaseous CO₂ is two to three times higher than for nitrogen or methane for a given volumetric flow rate. For liquid CO₂ at conditions relevant to CCS, the Reynolds number is between 4 and 18 times that of water at the same flow rate [14]. Such a difference should be reflected in the maximum calibration volumetric flow rate with the proxy fluid of choice.	Tests with gaseous and liquid/dense CO₂ at three different institutes suggest the feasibility of using water as a calibration fluid, with deviations of within ± 0.5 % to the reference flow rates [8, 50]. Performance shifts above critical temperature have been reported [14], so care is advised until more analysis is undertaken. Intercomparison tests with an orifice meter showed 0.35 % agreement for the liquid and dense phases [17]
Differential Pressure	Transferability of calibrations of DP meters is customary by using the discharge coefficient-Reynolds number curve for the specific meter geometry. The discharge coefficient depends on the meter geometry and Reynolds number of the flowing fluid. As such, calibration is not required as per ISO 5167, but is preferred for lower measurement uncertainties [49]. Calibration with alternative fluids should be suitable for CO₂, subject to experimental evidence, which is still pending. Correction of the Young's modulus value and the thermal expansion is, expectedly not an issue for meters operating with subcooled CO₂, yet experimental proof is required [14].	No uncertainty analysis and comparisons of water calibrations to liquid CO₂ calibrations for DP meters have been reported. Still, in [17] the authors use an orifice flow meter calibrated on water and nitrogen as a reference in a relative error assessment of meters for liquid CO₂. The estimated uncertainty is approximately ± 0.35 % ($k=2$), as per the meter uncertainty budget to account for the transferability of calibration from water to CO₂.
Ultrasonic	Transferability of water-to-fluid calibrations is more challenging than for other technologies scalable with Reynolds numbers. Acoustic attenuation is fluid-dependent; it peaks for gaseous CO₂ in the frequency range typically used in ultrasonic flowmeters [51]. The speed of sound of liquid CO₂ can be between 40 and 75% lower than that of water, with inversely proportional transit times. Flow rate measurements are geometry-dependent and linked to variations between calibration and operation conditions. Such differences can reach up to 50 K for liquid CO₂ service; yielding a change in path length of over 0.10 % [49].	No extensive data exists to compare water calibrations to liquid CO₂. Intercomparison tests of ultrasonic meters calibrated in water with a reference orifice meter showed a 0.5 % difference for the liquid phase and 1.5 % for the supercritical phase, using 500 kHz transducers. The error in liquid CO₂ reached 3 % with 1 MHz transducers. No reading was feasible in the supercritical phase [17]. The effect of improper insulation on ultrasonic meters for cryogenic service has been reported, with up to 2.5% deviation in mass flow rate under uninsulated conditions [52]. For liquid CO₂, water calibration and temperature corrections are only viable so long as actual traceable data is available.



Turbine	The flow rate measurement error of turbine meters is typically characterised by the Reynolds number. Calibration with a proxy fluid is feasible, as long as the Reynolds number from the calibration can be matched. In [49], the authors discuss that uncertainties should be considered due to (i) the determination of the Reynolds number, (ii) the linearity of the meter curve, and (iii) bearing friction. Regarding the latter, compensation based on the extended Lee model has not been verified for low-viscosity fluids like liquid CO₂. Other concerns relate to the effect of CO₂ on the bearings and the thermal expansion of the meter body [49].	Uncertainty analyses and comparisons of water-to-CO₂ calibrations for turbine meters are lean in the literature. Turbine meters calibrated in natural gas have been used with gaseous CO₂ with reported uncertainties of less than 0.25% ($k=2$) [8, 53]. Intercomparison tests of a turbine meter calibrated in water with a reference orifice meter showed a difference of up to 2.3% with liquid and supercritical CO₂ [17]. The authors argue that at a given Reynolds number, the K-factor (pulses per litre) as obtained on water does not completely coincide with the K-factor on CO₂, and thus, proxy calibration is not recommended.
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Overall, documented test outcomes for the gaseous phase suggest that turbine meters and Coriolis meters are in better agreement and have a higher potential for being calibrated using alternative fluids – provided influential factors, such as temperature and pressure coefficients, density and Reynolds numbers are correctly accounted for. For liquid and dense phases, initial results at a small scale indicate that calibration transferability using alternative fluids is achievable for Coriolis meters. However, further investigation is required, especially at temperatures close to or above the critical temperature.

2.4.1.2 Non-flow verifications

Challenges associated with high costs and the lack of - or limited access to traceable calibration facilities can be partially eased by verification techniques in controlled static conditions. Such an alternative can be helpful in assessing the performance of the meter in operational settings relevant to CCS transport. Examples of such assessments for ultrasonic metering technology are discussed and demonstrated in [15, 51] respectively. The work in [51] focused on assessing the meter self-diagnostic routines, signal-to-noise ratio, gain, accuracy of speed of sound measurement, and inter-channel variance. For Coriolis meters, zero stabilities, analyses of vibration and signal frequencies could be undertaken [15, 54]. It is noteworthy that this alternative technique is in no way a substitution for traditional flow calibration, as dynamic process conditions and effects from flow profiles, to name a few aspects, cannot be accounted for.

2.5 Calibration uncertainty

2.5.1 Primary reference (volume prover)

In [49] the calibration uncertainty of a CO₂ liquid calibration facility using an SVP is exemplified following the API Manuals of Petroleum Measurement Standards (MPMS) method and applies the GUM [55]. The calibrated reference volume $V_{F,ref}$ at the reference meter in the test facility is expressed as:

$$V_{F,ref} = \frac{BPV_p \cdot CTS_p \cdot CPS_p \cdot CTL_p \cdot CPL_p}{CTL_m \cdot CPL_m} \quad (1)$$

where BPV_p is the base prover volume, CTS and CTL are correction factors for the temperature of the steel and the liquid, respectively. CPS and CPL are correction factors for the pressure of the steel and the liquid, respectively. Subscript m and p refer to the location, i.e., meter un tests or prover, respectively.

BPV_p is typically determined via water calibration against volumetric or gravimetric methods traceable to primary standards with a direct link to SI-units of measurement. The uncertainty of the reference (base) volume at test facility conditions is expected at $\leq 0.03\%$ according to [49], although no experience operating SVP with CO_2 has been documented yet.

Additional uncertainty contributors listed in [49] are low-temperature effects, high pressure, repeatability, volume between the SVP and reference flow meter, pulse interpolation, and time and pulse measurement uncertainty. Regarding the former two factors, both for low-temperature conditions and for high-pressure CO_2 , the dominant measurement uncertainty sources influencing $V_{F,ref}$, besides BPV_p , are the temperature correction terms pertaining to the liquid, i.e., CTL_p and CTL_m . Thus, to reach a flow measurement uncertainty of 0.25% in the calibration of the reference flow meter by the SVP, the authors in [49] estimate that the overall accuracy of the temperature measurement of the liquid at the SVP and the reference flow meter must be at $\pm 0.2\text{ }^\circ\text{C}$ or smaller.

For high-pressure applications, an added uncertainty source is density calculations. If an equation of state is used, the density depends on the local temperature, pressure, and composition (and their respective measurement uncertainties). The sensitivity of the CO_2 density to pressure and temperature from pure CO_2 based on EoS-CG was investigated in [56] with the propagation of uncertainties defined in Equation (2)

$$U^*(\rho) = \sqrt{[S_p^* U^*(p)]^2 + [S_T^* U^*(T)]^2 + \sum_i [S_i^* U^*(x_i)]^2}, \text{ with } S_y^* \equiv \frac{y}{\rho} \frac{\partial \rho}{\partial y'} \quad (2)$$

where U^* is the relative uncertainty, S_p^* and S_T^* are relative sensitivities of density to pressure and temperature, respectively. x_i is the mole content of the substance i in the mixture. y stands for the variables p, T or x_i .

The authors in [56] analysed the relative sensitivity of temperature and pressure on density for pure CO_2 , using the EOS-CG. Disregarding the term $\sum_i [S_i^* U^*(x_i)]^2$ in Equation (2), the sensitivity factor for pressure, S_p^* , was found to range between 1 and 2 for gaseous form, around 3 near the critical point, and up to 8 at supercritical conditions. The sensitivity factor for temperature S_T^* was one order of magnitude larger than that for pressure, reaching its maximum (-35) around the critical point. The implication of this is that even far away from the critical point, for example for liquid CO_2 transport via pipelines, for every temperature degree change, or temperature measurement uncertainty, variations between 6.5 kg/m^3 and 9 kg/m^3 (around 1%) are expected in the density estimations [57].

2.5.2 Bootstrapping

In calibration experiments, several measurements of known flow rates are used to establish the relationship between a measured response and operating conditions. The bootstrap method offers the opportunity to use meters as secondary or transfer standards that can be scaled with the flow, thus providing flexibility. The calibration uncertainty increases with bootstrapping and is dependent on the configuration. A preliminary uncertainty analysis was performed in [9] for a bootstrapping array where all secondary references are placed in parallel to measure the maximum flow (see case A in Figure 6). Case A ensures direct reference calibration of all the secondary reference meters, thus somewhat decreasing the overall calibration uncertainty; compared to increased calibration stages (see Figure 7).

The authors in [9] considered that the meters of each reference stage i have a relative repeatability of $u(i)$, with an uncertainty contribution for each meter of $\sqrt{2}u(i)$. The total relative uncertainty contribution of a single calibration stage N_s (as illustrated in Figure 6) is then in the interval $\sqrt{2}u(i) \left[\frac{1}{\sqrt{N_{p,i}}} \quad 1 \right]$, where $N_{p,i}$ is the number of parallel arms of stage i .

Assuming that the relative repeatability of the meters of each stage is the same, $u = u(1) = u(2) \dots$, and the number of parallel meters in each stage is the same, $N_p = N_{p,1} = N_{p,2} = \dots$ yields the results in Table 5. Expanding the work in [9, 58], let us consider Case B in Figure 7, a configuration with two stages of three parallel arms. In Case B, the number of secondary meters is reduced by a factor of up to 2, thus potentially reducing the CAPEX. However, such a configuration would unavoidably require chain calibration, increasing measurement uncertainty, as evidenced by the ratio of $\frac{u(A)}{u(B)}$ in Table 5.

The maximum relative uncertainty contribution of the calibration stages occurs when the fluctuations of the meters in the arms of the stage have a correlation of 1. The minimum value when the fluctuations of the stage meters are independent of each other. The real case is probably somewhere in between. The optimum configuration is a trade-off between CAPEX, OPEX, and targeted uncertainty.

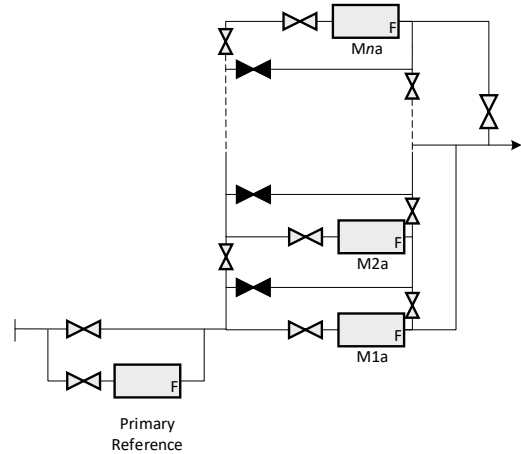


Figure 6 Measurement arrays showing single stage Bootstrap of n number of meters (Case A)

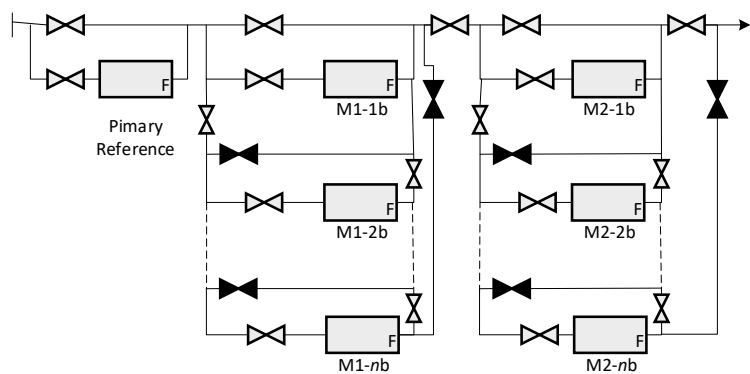


Figure 7 Measurement arrays showing Bootstrapping (Case B) with n meters in each of the two stages

Table 5. Preliminary uncertainties of secondary reference

Case		Independent arms & stages	Independent arms, correlated stages	Correlated arms, independent stages	Correlated arms & stages
		$\sqrt{\frac{2N_s}{N_p}}u$	$N_s \sqrt{\frac{2}{N_p}}u$	$\sqrt{2N_s}u$	$N_s \sqrt{2}u$
A	$N_s = 1$	$\sqrt{\frac{2}{9}}u = 0.47u$	$\sqrt{\frac{2}{9}}u = 0.47u$	$\sqrt{2}u = 1.41u$	$\sqrt{2}u = 1.41u$
	$N_p = 9$				
B	$N_s = 2$	$\sqrt{\frac{4}{3}}u = 1.2u$	$2 \sqrt{\frac{2}{3}}u = 1.6u$	$2u$	$2\sqrt{2}u = 2.8u$
	$N_p = 3$				
$\frac{u(A)}{u(B)}$		$\frac{1}{\sqrt{6}} \approx 0.41$	$\frac{1}{2\sqrt{3}} \approx 0.29$	$\frac{\sqrt{2}}{2} \approx 0.71$	0.5

2.5.3 Reported uncertainty of calibration facilities

There is limited public information on the calibration uncertainty of CO₂ facilities. Yet a non-thorough review of existing facilities follows to shed light on the accuracy levels that could be expected for the calibration of CO₂ fiscal meters.

- (1) The small-scale CO₂ loop at Tianjin University [44] counts with two calibration references. One primary weighing reference and one secondary master meter reference. The reported uncertainty of their weighing system is 0.06% ($k=2$) for liquid CO₂ and of their master meters of 0.16% ($k=2$) for CO₂ liquid flows, and 0.3% ($k=2$) for CO₂ gas flows.
- (2) The transfer package used in [17] has an uncertainty in mass flow rate of $\pm 0.08\%$ ($k=2$), calibrated at NEL water facility. NEL water facility, in time, reports an uncertainty in mass flow rate of $\pm 0.15\%$ ($k=2$).
- (3) Also relevant for CO₂ calibration is the experience from VSL for liquified natural gas (LNG). VSL reports SI-traceable calibration uncertainty of 0.3% ($k=2$) on the reference mass flow rate [59]. Added uncertainties for volume-to-mass conversions, when using volumetric meters – stemming from temperature and pressure measurement uncertainties and the density equation of state – should also be considered. For LNG, VSL estimates an increased uncertainty up to $\pm 0.35\%$ when converting to volume flow.

2.6 Fiscal metering uncertainty

2.6.1 Brief overview of uncertainty requirements

Currently, there is no unified set of regulations for CCUS projects globally. A review of the current global regulatory framework for CCUS is provided in Section 4 where country-specific advances on the matter are discussed. Also, see the work in [9, 49].

To provide a framework for the uncertainties discussed in the following subsections, a summary of existing uncertainty requirements per fluid phase is provided in Table 6. Overall, the precision required for flow meters varies depending on the governing regulating body and the measurement objective. The strictest accuracy requirements currently enforce 1% per metering unit. This applies to fiscal meters in the liquid phase. However, exceptions are permitted if meeting the highest accuracy tier is technically or financially impractical.

**Table 6 Summary of current uncertainty requirements in percentage of the reading (modified from [14])**

	Measuring system uncertainty	Flow meter uncertainty	Phase
EU ETS[60] UK ETS[61]	2.5 %	Not specified	Any phase
NIST [62]	1,5 %	Not specified	Liquified carbon dioxide
EU MID (Directive 2014/32) [63] OIML R 117 [64]	1.5 %	1 %	Liquified carbon dioxide Liquified carbon dioxide
OIML R 137 [65]	1.5 % - 3 % (depending on flow rate)	Not specified	Gas
OIML R 140 [66]	0.9 % - 2% (depending on flow rate)	Not specified	Gas (>1000m ³ /h)

2.6.2 Meter uncertainty

The uncertainty of flow meters is determined by calibration tests. Periodic recalibration avoids measurement drifts over time. Meter uncertainty estimations must consider the reference uncertainty of the calibration facility, including, but not limited to, the uncertainty of the reference instrumentation, the composition, and the I/O of choice. As previously mentioned, calibrations should ideally be performed using the actual process fluid under conditions that match those at which the meter operates, as sometimes required by regulatory authorities and operators [14, 67]. However, costs and infrastructure limitations on calibration facilities operating with CO₂ at conditions and flow rates relevant to CCUS applications open the opportunity to use proxy fluids in meter calibrations (see Sections 2.4.1 and 2.7). Such a method, however, yields increased uncertainties. Sufficient experimental evidence is needed to demonstrate the feasibility of calibrating with proxy fluids, meters that will service CO₂-rich streams. Such evidence is technology-specific and requires extensive systematic experimental campaigns involving numerous metering technologies of representative sizes; and relevant CO₂-rich mixtures. Considerations of calibration with proxy fluids for various metering technologies, as well as an overview of initial transferability studies for CO₂ service, are given in [14, 17, 49] and included in Table 4.

An effort was made to summarise information deriving from experimental campaigns to understand the minimum meter uncertainty as per relevant laboratory experience. This is, however, not an easy task as the available data is dispersed. Also, the literature encompasses tests performed at independent laboratories with different fluids, capacities, conditions and different equipment of varying dimensions. No laboratory intercomparison tests have thus far been undertaken for CO₂ or CO₂-mixtures, which could shed light on the accuracy of the test facilities and the metering technologies under the same controlled conditions. In the MetCCUS project the first laboratory intercomparison tests will be undertaken for CO₂ in gas phase. Such experience will provide a clearer picture of metering uncertainty for low and medium-scale flows. The time horizon for liquid flow is more uncertain, as primary references and test facilities are only being developed [68] .

As per the available resources and existing literature, Table 7, extended in Appendix B, gathers the minimum metering error for CO₂ flow discretised by measurand, i.e., mass $\dot{m}$ or volume $\dot{Q}$ flow rate. The provided figures in the table are referential only as they are minimum values only where higher values are reported in the literature. Overall, the lowest measurement errors for mass measurements were $\pm 0.25\%$ and $\pm 0.16\%$ for gas and liquid, respectively, as per independent Coriolis meter tests. The minimum deviation in volume flow was $\pm 0.15\%$ from a turbine meter in the gas flow, with no available reports for pure CO₂ mass flow rates in liquid conditions.

Table 7 Minimum metering uncertainty reported in the literature (see Appendix B for extended data)

Minimum reported uncertainty	P (bara)	T (°C)	Flow rate	Composition	Original work
$u(\dot{m}_{CO_2})_{m_{gas}} \geq \pm 0.25\%$	27/37	Ambient	5688 -44010 kg/h	Pure CO ₂	Chinello and Brown [69]
$u(\dot{m}_{CO_2})_{m_{liq}} \geq \pm 0.16\%$	<72	20 – 30	250 - 3600 kg/h	Pure CO ₂	Sun et al. [44]
$u(\dot{Q}_{CO_2})_{m_{gas}} \geq \pm 0.15 \%$	3 - 32	N/A	N/A	Pure CO ₂	George et al. [53]

2.6.3 System uncertainty

The uncertainty of the mass flow rate of CO₂ in a CO₂-rich stream at a given time is obtained by appropriately combining the uncertainty of each of the measurements in the system. The uncertainties in mass depend on the type of meter used, i.e., direct mass flow meters or volumetric flow meters. Regarding the former, the mass over a period that CO₂ flows through a mass flowmeter is the product of the measured mass flow rate of such stream ($\dot{m}_{mix}$) by the mass fraction of the CO₂ ($x_{CO_2,wt}$), see (3). The mass flow rate uncertainty is given by Equation (4).

$$\dot{m}_{CO_2} = (\dot{m}_{mix})_m \cdot (x_{CO_2,wt})_m \quad (3)$$

$$u(\dot{m}_{CO_2}) = \sqrt{[u(\dot{m}_{mix})_m]^2 + [u(x_{CO_2,wt})_m]^2} \quad (4)$$

If a volumetric flow meter is used, uncertainties yielding from volume-to-mass conversions should also be included, see Equation (6)

$$\dot{m}_{CO_2} = (\dot{Q}_{mix})_m \cdot (\rho_{mix})_{m,EoS} \cdot (x_{CO_2,wt})_m \quad (5)$$

$$u(\dot{m}_{CO_2}) = \sqrt{[u(\dot{Q}_{mix})_m]^2 + [u(x_{CO_2,wt})_m]^2 + [u(\rho_{mix})_{m,EoS}]^2} \quad (6)$$

where the subscript m refers to measured variables, and EoS to the quantities computed from Equations of State. Note that if the density is calculated and not measured, $(\rho_{mix})_{EoS}$, the uncertainties of the stream pressure, temperature, and composition, are intrinsic terms of the density uncertainty per Equation (2).

In (3)–(6), the CO_2 mass fraction, $(x_{CO_2,wt})_m$, is the concentration of CO_2 in the CO_2 -rich stream over the sum of the concentrations of the components in the stream, i.e.,

$$x_{CO_2,wt} = \frac{(y_{CO_2})_m \cdot M_{CO_2}}{\sum_{i=1}^n [(y_i)_m \cdot M_i]} \quad (7)$$

where y_i is the concentration in %mol of impurity i , M_i and M_{CO_2} is the molar mass of impurity i and of CO_2 respectively (kg/kmol), n is the number of impurities.

For a given mass flow rate measurement, the uncertainty sources identified above are summarised in Table 8. If a volumetric flow meter is used, uncertainties yielding from volume-to-mass conversions should also be included – See Equation (5). Note that, as with results in Table 7, the reported uncertainties in Table 8 are based on non-SI traceable tests as reported in the literature for various metering technologies and phases. A more comprehensive overview of the original work is reported in Appendix B and the references therein. The measurement uncertainties reported in Table 8 refer to the deviations in measurement of the tested meters when compared to reference figures. Such references comprise various reference equipment traceable to a given working fluid or EoS-derived values. The uncertainties reported in the literature vary significantly, depending on multiple factors, including the metering principle, operating condition, and accuracy of the reference laboratory, instrument or EoS, among others. Further, the uncertainties in Table 8 are the minimum uncertainties achieved as per the consulted literature; larger errors are often reported. Also, the uncertainties of the reference equipment or the experimental facilities where tests were undertaken, are not accounted for in the summary in Table 9. The figures provided below are referential, and an uncertainty budget should be developed for every project.

Based on the minimum uncertainties reported in Table 8 for the terms in Equations (4) and (6), the minimum expected system uncertainties in per cent of mass when volumetric or mass meters are used in CO_2 -rich streams are summarised in Table 9.

Table 8 Referential uncertainty terms and minimum reported uncertainties

Eq	Terms	Reported uncertainty	Notes & references
(4)	$u(\dot{m}_{mix})_m$	$u(\dot{m}_{mix})_{m_{gas}} \geq \pm 0.25\%$	All mass uncertainties correspond to tests with Coriolis meters.
		$u(\dot{m}_{mix})_{m_{liq}} \geq \pm 0.35\%$	Uncertainties for liquid are based on intercomparison tests or comparisons with small-scale gravimetric references [8] [17] [69] [44] [14]
(6)	$u(\dot{Q}_{mix})_m$	$u(\dot{Q}_{mix})_{m_{gas}} \geq \pm 0.2\%$	Ultrasonic meter. Adjusted K-factor [14]
		$u(\dot{Q}_{mix})_{m_{liq}} \geq \pm 0.65\%$	Uncertainties are based on intercomparison tests [17]



(4), (6)	$u(x_{CO_2,wt})_m$	$u(x_{CO_2,wt})_m \geq 0.027\%$	Gas chromatography [26]
(6)	$u(\rho_{mix})_m$	$u(\rho_{mix})_{m_{gas}} \geq \pm 1\%$	Coriolis measurements compared to GERG-2008 [8].
		$u(\rho_{mix})_{m_{liq}} \geq \pm 0.2\%$	Coriolis measurements compared to GERG-2008 for the given mixture [17]
(6)	$u(\rho_{mix})_{EoS}$	$u(\rho_{mix})_{EoS} \geq \pm 0.08\%$	The reported accuracy is the minimum Mean Average Absolute Deviation for two datasets (CO ₂ – Ar and CO ₂ – N ₂). Large deviations were evidenced in mixtures with H ₂ , the Weighted Arithmetic Mean for 8 datasets. is 1.18% [70]

Table 9 Minimum expected mass flow uncertainties in a measurement system with current state-of-the-art technologies

Measurement variable	Phase	Mass flow uncertainty with measured density	Mass flow uncertainty with estimated density ^a
			$u(\dot{m}_{CO_2})$
Mass flow rate	Gas		$\pm 0.25\%$
	Liquid		$\pm 0.35\%$
Volume flow rate	Gas	$\pm 1.02\%$	$\pm 0.22\%$
	Liquid	$\pm 0.68\%$	$\pm 0.66\%$

^a The density uncertainty used is as reported in Table 8. However, the uncertainty of the density from EoSs is correlated to the uncertainty in temperature, pressure and composition, see Equation (2), as well as the choice of the equation as discussed in Section 2.3.

2.7 Infrastructure

Several factors determine the demand for CO₂ flow meter calibration facilities. Regulations, for example, will indirectly determine whether dedicated CO₂ facilities are required. Complementary to this section is the size of the fiscal metering market in Section 3.4. An overview of existing and planned facilities for CO₂ flow meter testing and calibration is presented below, followed by considerations for reference material keeping.

2.7.1 CO₂ flow test facilities

The increased development of CCS is also evidenced in the metrology field. An initial screen of CO₂ sites from 2020, based on literature and direct enquiries, found limited CO₂ meter calibration capabilities [13]. Only the facility at Fortis BC in Canada, could calibrate meters for gas phase CO₂. An updated overview from 2024 is presented in [14], listing six facilities able to operate with CO₂ and/or CO₂-rich mixtures. Yet to this date, the conclusions from [13] stand, as no SI-traceable full-scale facility that could perform calibration in gas-, dense-, and liquid phase exists. Table 10 below is an extension of the work in [14] considering also smaller-scale facilities and planned large-scale infrastructure.

Table 10 highlights besides the lack of SI-traceable facilities to calibrate CO₂ flow meters at industrial scale, few facilities can operate at large scale, but lack the possibility to operate with liquid, dense, and multi-phase CO₂. The authors are familiar with three planned liquid CO₂ facilities traceable to a primary reference, namely one at TÜV-SÜD NEL in the UK, one at SINTEF Energy Research in Norway, and one at DNV in the Netherlands.



The former two are planned to start operation in 2025 and 2027, respectively, whereas the latter depends on an imminent investment decision.

2.7.2 Laboratories for analyses and custody of reference materials

Offline analysis will be needed to accurately measure the composition of CO₂ streams. For method verification, equipment calibration, and quality control, among others, reference materials are key. Reference materials are, as per definition by ISO Guide 30:2015, 2.1.1, sufficiently homogeneous and stable with respect to one or more specified property values, which have been established to be for its intended use in a measurement process [71]. It is customary for metrology institutes to prepare certified reference mixtures with metrological traceability. However, as the existing body of knowledge shows, most of the publicly available studies on these reference materials for CCS are based on large fractions of inert gases in CO₂ to support fluid property measurements [72].

CO₂-rich streams from different emitters yield mixtures that can react chemically, establishing a new chemical equilibrium downstream of the mixing point that may form acids or elemental sulphur [73]. Understanding and characterising such chemical reactions in CO₂ streams are not only relevant to ensure the integrity of CCUS processes and operations but must also be considered in primary reference material keeping. Early experiences at NPL with the stability of reactive mixtures are documented in [74], where an increase in carbonyl sulphide (OCS) in the chromatogram series after 12 and 18 months from preparation was evidenced in cylinders containing a mixture of gases, including CO₂. Unstable H₂S due to possible reactions with either CO₂ or CO was reported. The work on chemical reactions in [73] influenced the revised set of specs for the Northern Light CCS project [75]. There, the authors recommend stringent control and monitoring for impurities that (i) influence the phase envelope and trigger drop out of a water-rich liquid phase – e.g. methanol and glycol, (ii) trigger or enhance rapid degradation or cracking like H₂S, O₂ and CO, (iii) can react with each other to form strong acids and elemental sulphur that can drop out from bulk (H₂O, O₂, SO_x, NO_x and H₂S), and (iv) influence degradation [73].

Further reactions can also occur with the vessel material, where samples are transported for offline analysis. Special care is required for reactive gases such as sulphur compounds or ammonia, which could be adsorbed onto, or react with the vessel surface. Reactions within the sampling vessel can lead to inaccurate and unreliable analysis results. The suitability of the storage vessel can be determined by measuring the recovery yield and storage stability for a given compound [16]. Sampling vessel selection depends on the nature of the impurity, its stability and ability to interact with the walls of the containers, and the sampling temperature, pressure, and concentration. A good practice guide for the sampling of CO₂ in CCUS process is provided in [76]. Further, storage stability studies with limited compounds are available in the literature, e.g., for cylinders in the presence of eleven components, including CO₂, see the work in [77], and for bags when methanol, acetaldehyde, ethanol, and acetones are present in the mixture, see [78]. The adsorption effects of different species in the vessel materials create the need for a fit-for-purpose strategy. Hence, CO₂ sampling will likely involve collecting the gas in several types of vessels [79]. The work in [16] summarises various stability studies performed on sampling cylinders, sorbent tubes, sampling bags and canisters. In general, aluminium gas cylinders with internal passivation treatment show better long-term stability for reactive gases in low concentrations in different matrix gases. However, to determine suitable sampling vessels, the authors in [16] and [79] recommend further stability studies under identical conditions and possible interactions between species present potentially simultaneously in the CO₂.

Table 10: CO₂ flow facilities. The table is extracted and expanded from [14].

Facility	Diameter (inch)	Temperature (°C)	Pressure (bar)	Flow rate (Am ³ /h)	Flow rate at 20 °C (Mt/tpa)	Phase	Fluid	Traceability
Existing facilities								
Fortis BC (CA) [80]	12	4 – 40	8 – 16	16 bar: max 3 400 8 bar: max 6 510	16 bar: max 0.94 8 bar: max 0.86	Gas	Pure CO ₂	Turbine master meters calibrated in natural gas at accredited laboratory
TÜV-SÜD NEL (UK) [81, 82]	8	4 – 30	6 – 46	20 – 1 600	0.002 – 1.27	Gas	Pure CO ₂ , inert impurities	Reference orifice meter calibrated in water and nitrogen at accredited laboratory
DNV (NL) ⁸ [84]	6	Ambient	6 – 36	50 – 1 000	0.007 – 0.67	Gas	Pure CO ₂ , CO ₂ /natural gas mixtures	Reference sonic nozzles calibrated in air and natural gas at accredited laboratory.
Equinor P-lab (NO) [85]	3	4 – 105	100 max	Gas: 0 – 70 Dense: 0 – 50		Gas, dense		
IFE Falcon (NO) [14, 86]	2	-150 – 50	20 – 150	Gas: 0 – 30 Liquid/dense: 0 – 20	Gas: 0.0006 – 0.019 Liquid/dense: 0.0006 – 0.19	Gas, dense, liquid, multiphase	Pure CO ₂ , CO ₂ rich mixtures (e.g., N ₂ , CH ₄ , O ₂ , H ₂ O)	Master meters factory calibrated with a proxy fluid
SINTEF FloMet (NO) [51]	5/6 - 8	-40 – 35	90 max	0/1.2	Liquid /dense 0.005	Liquid, Dense	Pure CO ₂ , CO ₂ and N ₂	Gravimetric (Static bench) or Coriolis for flow tests
SINTEF DeFacto (NO) [87]	5/8 - 1 1/4	-80 – 60	160 max	0-5000	Gas: Max 4.2 Liquid/dense: 5.2	Gas, dense, liquid, multiphase	Pure CO ₂ , CO ₂ rich mixtures	Coriolis
Herriot-Watt Univ (UK) [88]	1	17 - 30	65-85		0.000005 – 0.005	Liquid, dense	Pure CO ₂	Gravimetric reference
Tianjin Univ (CH) [44]		~20	58 max		Max 0.03	Two-phase	Pure CO ₂	Gravimetric reference
Primary flow standards under development/upgrade								
VSL (NL) [89]	N/A	N/A	64	5-230		Gas	nearly pure CO ₂	Piston prover
FORCE (DK)	4	N/A	3-65	20-340		Gas	99.7% CO ₂	Piston Prover
INRiM (IT)	2	15-25	atm	Up to 30		Gas	Pure CO ₂	Piston Prover
Planned facilities⁸								
TÜV-SÜD NEL (UK), 2025 [14]	3	4 – 50	1 – 201	0.7 – 70	0.005 – 0.6	Dense	Pure CO ₂ , CO ₂ rich mixtures	Primary standard (piston prover)
SINTEF (NO), 2027	2	-20 – 20	120		Max 0.13	Liquid, dense	Pure CO ₂ , CO ₂ and N ₂	Primary standard (bespoke design)

In this sense, the metrology-focused projects EMPiR JRP 20IND10 Decarb and 21GRD06 MetCCUS are pioneers in the development of new standards and measurement methods to support the CCS industry and meet the technical specifications. In MetCCUS, reference primary mixtures were prepared by the project

⁸ There is ongoing work to establish a facility at DNV for liquid and dense CO₂ in the Netherlands [83] P. Sall, "DNV leads global joint industry project to set standards for crucial CO₂ flow meter traceability and accuracy in CCUS," ed, 2024., although no information of the flow capacity and dimension are publicly available.



partners, who will undertake stability studies over the course of two years to detect possible degradation. The stability of binary mixtures of CO₂ and low levels of SO₂, H₂O, NO₂, DMS, and EtOH, is being investigated. Early results show that most mixtures remain stable after six months [90]. Nevertheless, material compatibility and vessel selection for the storage of reference materials need to be carefully addressed for every mixture [91, 92].

The certification of the composition and purity of the CO₂ streams requires measurements that are traceable to the SI units. Such traceability grants accuracy and ensures global comparability [29]. Thus, primary reference materials, calibration gas mixtures, and purity methods are required to measure the very low-level impurities specified by CCUS operators (Appendix A). As per the early stability tests and limited data on reactions with vessels, the CCS industry would benefit from further work on traceable primary reference materials.

3 Outlook

3.1 Novel technologies to bridge current gaps

Improving the accuracy and extending the applicability of flow measurement technologies is beneficial for CCS development. Novel technological developments have the potential to overcome some shortcomings of existing fiscal metering technologies. Here, the focus is on sensor principles that are known or are in industrial use elsewhere and that can assist in bridging current technology gaps.

Coriolis meters, which were seen to provide some of the most accurate measurements, are, however, limited by pipe diameters and have internal pressure drop, which challenges operations close to saturation conditions. A new technology under development in Norway can help overcome this limitation. The mass flow meter being developed by Cignus Instruments is, based on the effect the inertia of the flowing fluid has on vibrating systems, as in traditional Coriolis meters. The novel concept is based on a suspended torsion element within a straight pipe and permanent magnets that generate torsional vibration. The registered time difference in fluctuation is proportional to the mass flow in the pipe [93]. The technology has been recently tested in a CO₂ environment in P-lab, reaching TRL 4/5 [94].

Recent research has also investigated fiscal metering-related challenges involving online stream analysis, second phase identification, and sensor fault identification [10, 95, 96]. Fiscal meters that are composition-sensitive or that are operated close to saturation conditions, as in the case of ship offloading, can present lower accuracies if a second phase is formed. An unwanted second phase can arise due to normal operation conditions, e.g., pressure constraints, or in unintended shutdown sequences, as well as from terrain topography favouring liquid deposition in low points, or evaporation of components from the CO₂-rich liquid stream [27]. If operational conditions are such that a single-phase state cannot be ensured during the normal operation of the metering system, technological solutions are required to minimise metering uncertainty and warrant the health of the meters.

The above issues become particularly challenging if the two-phase character of the flow is not detected at all. Particularly for Coriolis meters the presence of a second phase can severely affect the measurement



accuracy. The formation of a second phase in the Coriolis flow tubes yields non-homogeneities, changes in compressibility, and shifts in the centre of mass. This results in errors in the reported mass flow and density, stemming from deviations from single-phase calibrations. The presence of bubbles in liquid flow yields two error mechanisms, i.e., decoupling and compressibility, which are directly proportional to the gas void fraction, and the square of the reduced frequency [97]. To overcome this, multimodal configurations with the colocation of a second technology able to identify a second phase, in the proximity of a fiscal meter can be advantageous. For this, an acoustic-augmented Coriolis meter developed by CorVera can be promising [98]. The technology utilises pressure sensors ported into the process piping upstream and downstream of the traditional Coriolis meter to provide a real-time measurement of the sound speed of the process fluid. The process fluid sound speed and measurements from the existing Coriolis meter are used as inputs to an empirical model of bubbly flows within the Coriolis meter to decrease the errors in mass flow and density [98]. The application of these combined technologies has, however, not been tested for CO₂, thus the TRL remains at 3.

Concentrations of minor species are commonly measured offline by sampling-based technologies. Yet, as discussed above, analysing equipment can be expensive and require regular calibration and skilled personnel. To avoid sampling, which is prone to non-representative consideration of different phases, particularly for very small volume fractions, inline solutions are preferred. Inline phase detection has been long used in other industries [99, 100]. The applicability of some of these commercially available sensors for CO₂ transport was theoretically assessed in [10, 96]. Limited operational experience for CCS was reported. Dielectric measurements are one of the promising principles for the identification of composition changes and second-phase formation [10, 27, 96]. Capacitance-based measurement is a well-established measurement principle [101-107]. The technology has a high TRL in other industries and proven accuracy down to 2% for measurement of volumetric fractions of contrasting permittivity of oil-gas mixtures [108, 109] which could be leveraged for high-contrast species like CO₂ and O₂, N₂, Ar, H₂, CH₄, and/or H₂O [96]. Two electrical permittivity technologies were recently tested for identification and measuring contaminants in liquid CO₂; for this, two independent low-frequency electrical permittivity electrodes and microwave sensors were installed in a CO₂-N₂ mixture stream. The early results showed a good correlation between measured and theoretical permittivity values for every given condition and composition [110]. The sensitivity of the impurity measurements is dependent on the accuracy of the permittivity measurement and the contrast between the permittivity of the impurity and CO₂. Thus, the results suggest that the tested technologies (TRL 4 for CCS) are highly sensitive to impurities having a high contrast in permittivity compared to CO₂ [101-107].

Volume-to-mass flow rate conversion are required from most fiscal meters. For this, quantification of the density is needed. While the lowest density uncertainties result from using EoS, accurate composition knowledge is needed. Varying stream composition makes the volume-mass relationships less simple to estimate, thus increasing the instantaneous density uncertainty [7, 111]. Also, discrepancies in flow measurements when density is Coriolis-measured or EoS-computed in liquid CO₂ tests were reportedly above 0.2% [17]. In such scenarios, therefore, actual density measurements of the CO₂ stream could be beneficial. The density can be measured either in a laboratory following a process of field sampling or inline via a densimeter measurement. The former method has the drawback that it is not representative of the dynamics of CO₂ networks [112], hence the focus here is on the latter. A previous benchmark study [113] summarises potential density measurement technologies for CCUS based on those identified by the American Petroleum Institute (API) [114]. Technologies with the highest potential for CCS, as prioritised by stakeholders [115] were (i) Coriolis meters, in which the natural frequency of the measuring tube is

proportional to the density of the fluid in the tube; (ii) resonators where the resonant frequency of the resonator is proportional to the density; and (iii) nucleonic densimeters where the radiation from a radioactive source is partially absorbed by the fluid– the amount being proportional to its density. All the three principles were tested with pure CO₂. The Nucleonic and Coriolis meters showed the lowest errors when compared to Span-Wagner EoS, i.e., $\pm 0.3\%$ and $+0.8\%$, respectively [57].

3.2 Cost-efficient implementation

Challenges with flow and fiscal metering related to technology complexity, interference with the fluid flow and cost of implementation and maintenance are amplified in environments that are inaccessible or impose harsh conditions. The subsea environment is an example of conditions where installation is more challenging, maintenance is more expensive, and the conditions of the fluid flow may be less controllable than in an onshore or topside setting. Consequently, higher requirements for robustness and reduced complexity are imposed, yielding increased costs for the metering systems. In the following, the applicability of both mature and novel technologies for the implementation of flow and fiscal metering under challenging conditions is discussed with a focus on the subsea environment. For the different technologies, the following factors were considered

- Complexity of the technology; a low complexity facilitates installation and deployment.
- Robustness, e.g. to corrosion; high robustness yields decreased maintenance frequency and increased lifetime.
- Cost of technology and/or maintenance; low costs are desirable if a higher frequency in replacement and/or maintenance is expected due to decreased lifetime brought on by the environment.
- Interference with the CO₂ stream. Little interference avoids phase and flow regime changes.

In the analysis below, the accuracy of the flow meter technologies is not explicitly accounted for here since only technologies deemed appropriate for CO₂ service, as discussed in the previous sections are included. Furthermore, the accuracy is of slightly less importance because subsea flow meters will rarely be used as fiscal meters [116] even though flow metering on the injection point is required as illustrated in Figure 3. Instead, subsea flow meters are envisioned to serve as monitoring tools for the flow into the storage site, important, e.g., to control the migration of CO₂ and avoid undue pressure build-up in the reservoir [117].

A factor not included in the assessment of the specific technologies, relates to the number of required subsea flow measurements. In Figure 3, measurements are depicted at each well into the reservoir, but one flow meter can serve a single well, or multiple wells if the meter is installed on the subsea manifold [118]. Flow rates in the individual wells must then be estimated from the overall flow rate, measurements of the pressure and temperature at the individual well heads and information on the properties, lengths and diameters of the pipelines stretching from the manifold to the wellhead using flow models [119]. The advantage of this latter philosophy is the reduced cost from decreasing the number of flow meters required. The disadvantage is the increased uncertainty of the flow rate of the single wells arising, e.g., from uncertainty in the flow model, and uncertainties related to measurements of the initial pipeline roughness and the evolution of the roughness in the pipelines [120]. These uncertainties increase the longer the pipelines between the manifold and the individual wells are. Thus, measurements on single wells may be appropriate if the wells are spread out. Consequently, assessments of whether one or multiple subsea flow meters are required must be performed individually for each injection site and are, to a certain degree,



independent of the meter technology chosen, even if higher costs of the technology, installation, and maintenance increase the threshold for installing multiple meters.

Below, the capabilities of various metering methods for subsea CO₂ injection are discussed. Relevant for them all is the uncertainty of how often deinstallation, recalibration and maintenance will be required. As indicated in Section 4.2.5, recalibration may have to be performed at a minimum every fifth year, but more frequent maintenance and recalibration are not inconceivable since some of the known factors causing drift in the meters may be amplified subsea. Other installation requirements such as long, straight upstream and downstream pipelines add costs to the overall injection system [121]. It should also be noted that all technologies rely on electrical signal communication. As such, a subsea control module must be installed alongside the meter, and sufficient protection of the system from the external saline environment (e.g., to avoid corrosion of the electrical wires) must be in place. These are, however, not unique considerations for the flow meters but apply to all subsea electrical equipment, such as electrical valves.

Coriolis mass flow meters bear the promise of reducing the complexity of the total measurement system since additional density and/or temperature and pressure measurements are not required. Coriolis meters are conventionally intrusive, thus associated with relatively high internal pressure drops, if compared to ultrasonic meters, for example. They can also have high installation and maintenance costs based on experience in the oil and gas industry. However, the associated costs of maintenance are expected to be lower in CO₂ injection service since the stop of operation is not associated with a loss in revenue to the same degree as in oil and gas fields. Both temperature and pressure fluctuations impact the properties of the materials in the Coriolis meter, causing drift in the measurements over time [122]. Added drift can also arise from corrosion and erosion of the meters caused by multi-phase flow [123], drop-out of corrosive phases and solid formation [124]. It is a concern that these phenomena will be more frequent in subsea applications than onshore or topside, especially under transient situations when the system is operated closer to the critical pressure. The above factor results in a less attractive view of Coriolis meters for subsea applications unless special requirements regarding uncertainty outweigh the added costs associated with subsea applications of this technology.

Various *differential pressure* technologies are applicable for subsea CO₂ flow measurements. Orifice plates and Venturi meters are habitually used in the oil and gas industry and are associated with lower costs than Coriolis meters due to the reduced complexity of the meters themselves. Similarly to Coriolis meters, differential pressure devices are intrusive, and thereby subject to corrosion and erosion and consequent degradation of their performance over time. The *orifice meters* lead to the largest pressure drop but have the advantage of being less complex and with less expensive implementation. Orifice plate meters do not require calibration as per ISO 5167, meaning that the need for recalibration and maintenance is potentially smaller than for other types of flow meters [125]. In general, *Venturi* meters have lower pressure drops and are more robust than orifice meters, but require calibration and their performance with CO₂ lacks documentation [14]. Even if differential pressure meters had higher measurement uncertainties than the Coriolis meters, they may be more appropriate for subsea applications due to their lower complexity and lower costs of technology, installation and potential maintenance.



The remaining technologies assessed for subsea applications are all volumetric flow meters, meaning that additional pressure and temperature sensors, or density meters, are required to convert from volumetric to mass flow. Although using additional pressure and temperature sensors in combination with an EoS will increase the uncertainty of the mass flow rate, there is abundant experience with subsea pressure and temperature sensors. This indicates that the costs of the sensors and maintenance will be small compared to the flow meters. Therefore, these solutions seem attractive for subsea applications, especially in the view that the uncertainty is of slightly lower importance and that pressure and temperature sensors may be necessary, anyhow, to keep control of the flow conditions of CO₂. That said, the accuracy of the EoS also depends on accurate information on the composition of the CO₂ stream. As indicated in the previous sections, composition measurements are complex even topside, and less than attractive to perform subsea. Normally, it is a valid assumption that the composition does not change downstream of the onshore or topside injection point although reactions in the downstream pipelines can lead to changed composition of the flow over time, which may result in changed density and erroneous mass flow estimations. As such, direct density measurements may increase the precision of the mass flow calculations and may be beneficial if the risk of changed composition downstream of the injection point is high, even if the cost of the overall system increases.

Ultrasonic meters have been proven for CO₂ flow measurements. Ultrasonic meters are highly sensitive to the flow regime and rigorous requirements are imposed, which may increase system costs [121]. However, ultrasonic meters are non-intrusive and do not induce pressure drops, and thus are advantageous for large flow rates and diameters, particularly relevant for injection manifolds. Another benefit of ultrasonic meters for subsea applications is that they exist in clamp-on modules, with increased flexibility compared to other inline meters, at the expense of reduced accuracy [126].

Turbine flow meters have traditionally been used in oil and gas installations but have more limited and uncertain applicability in injection systems. Turbine meters are both invasive and intrusive; they are complex with moving parts directly in contact with the process fluid. For subsea applications, these represent obvious limitations associated with drift and calibration requirements, which can yield maintenance requirements prohibitive in subsea environments.

Similar to the approach of limiting the number of meters per reservoir or formation using one on the main flow line, and calculating the flows for each well, one can envisage that all subsea flow meters are removed altogether and that *virtual* flow measurements relying on flow models and proxy data (e.g. subsea temperature and pressure) are used. While this will reduce the costs of the subsea system, the models rely on accurate information on, e.g., the friction coefficients and heat transfer, which are related to the pipeline roughness and design, and their development must, therefore, be monitored over time. An option that would give more information on the behaviour of the subsea system and modify the models to increase their accuracy, is to utilise optic fibre strain, pressure and temperature sensors [10, 127]. Another option is to use single flow measurements, e.g., by use of clamp-on ultrasonic meters, to (regularly) calibrate the models. With the increased use of artificial intelligence and neural network modelling in the process industry, such measurement-enhanced models may gain traction, and help decrease uncertainties of the virtual meters [95, 128, 129].

3.3 Measurement error reduction strategies

The uncertainty in fiscal meters has been addressed in previous sections. Various calibration techniques that use reference flowmeters are available and can significantly help reduce and quantify the overall measurement uncertainty. Measurement errors can be divided into two categories, i.e., random error or uncertainty and systematic errors or bias. The residual, post-calibration error, although within the recommended values, might still compromise the quality of the overall fiscal transaction, leading to undesired outcomes. It is, therefore, desirable to introduce additional techniques that can help the involved parties further reduce the uncertainty by employing statistical and machine learning methodologies. This section is dedicated to the study and the outline of techniques that can be implemented to improve the flowmeter's readings.

For the sake of simplicity, here it is assumed that the measurement has already been transformed into a mass flow rate value.

3.3.1 Single flowmeter measurement and errors

Whenever a flowmeter acquires a measurement, it can be expressed as $\dot{m} = \theta + w$, where θ is the true value of the mass flow rate, $\dot{m}$ is the measured value of θ (its estimate), and w is the error contribution.

In general, a typical loss function used to quantify errors is the *mean square error* (MSE), which has the following mathematical form [130]:

$$\text{MSE}(\dot{m}) \triangleq \mathbb{E}[(\dot{m} - \theta)^2] = \mathbb{E}(w^2) = \text{Var}(w) + \mathbb{E}^2(w) = u_\theta^2 + b_\theta^2 \quad (8)$$

where $\mathbb{E}(\cdot)$ and $\text{Var}(\cdot)$ indicate the expected value and the variance, respectively. Note that the subscript in u_θ and b_θ indicates a possible dependency on the true value of mass flow rate θ . This equation squares the difference between the mass flow rate's reading $\dot{m}$, and its true value θ , and it allows us to decompose the error into two different contributions, which are characterized by their distinct nature into:

- $u_\theta \triangleq \sqrt{\text{Var}(w)} = \sqrt{\text{Var}(\dot{m})}$ represents the measurement's standard deviation, which is a measure of *random errors*.
- $b_\theta \triangleq \mathbb{E}(w) = \mathbb{E}(\dot{m}) - \theta$ represents the measurement's bias, which indicated the *systematic errors*.

Because random errors represent the instrument's measurement noise and the bias depends on the true (and unknown) value of the flow rate θ , it is typically impossible to nullify their contributions.

3.3.2 Offline systematic and random error assessment for single flowmeters

A corrective offset can be employed during the calibration stage to reduce the systematic error of a flowmeter. However, such an offset cannot guarantee its efficacy over the range of all possible values of θ . Among the potential strategies to select the appropriate offset value, one can assume a plausible range of



values $[\theta_{\min}, \theta_{\max}]$ and minimise the systematic error within such a range. It is here recommended that such an interval corresponds to the recommended flowmeter's operating limits. The procedure is outlined in Appendix C. This procedure assesses the average bias b that can be used as an offset to correct possible systematic errors that might occur during the metering process, resulting in a corrected measurement of the form: $\dot{m}_{\text{corrected}} = \theta + w - b$. This presents a reduced systematic error which now has become $\mathbb{E}(\dot{m}_{\text{corrected}} - \theta) = b_{\theta} - b$. The systematic error can theoretically be entirely removed when b_{θ} is constant for all values of θ . In such a case, $b = b_{\theta}$, allowing $\mathbb{E}(\dot{m}_{\text{corrected}} - \theta) = 0$.

Unlike systematic errors, random errors cannot be corrected by applying a correction to a single measurement to adjust their unwanted effects. However, an offline assessment of the magnitude of such errors is possible which is helpful to develop online techniques. As before, our quantification process must account for different values of θ . The proposed procedure is an adaptation of what was presented when assessing the systematic error and is also included in Appendix C. The method estimates the average variance u^2 and can be performed simultaneously with the bias assessment as they share most of the procedure except for the calculations involved.

3.3.3 Online filter for single flowmeters (EMA filter)

The previous sections illustrate how to quantify systematic and random errors. Moreover, it was shown how a bias correction can reduce systematic errors. Regarding random errors, a solution is the use of filtering techniques to address the measurement's volatility. To provide a practical introduction to the theoretical benefits of measurement filtering, the *exponential moving average* (EMA) filter is described following. The limitations, and further techniques to allow more robust results are also discussed [131, 132].

For this application, it is convenient to express the flow rate's measurement at the generic N^{th} discrete-time as $\dot{m}[N] = \theta[N] + w[N]$. To facilitate the statistical analysis, it is assumed that:

- $\theta[N]$'s are deterministic and unknown values of mass flow rate;
- $w[N]$'s are noise samples with $\mathbb{E}(w[N]) = 0$, $\text{Var}(w[N]) = u^2$, $\text{Cov}(w[N], w[M]) = 0$, for all N and M , with $N \neq M$, where $\text{Cov}(\cdot, \cdot)$ stands for the covariance. The assumption that $\mathbb{E}(w[N]) = 0$ and $\text{Var}(w[N]) = u^2$ implies that $b = b_{\theta}$, for all values of θ , (which allows to remove the systematic error perfectly) and that $u^2 = u_{\theta}^2$, for all values of θ , respectively. Note that here the notation $\dot{m}_{\text{corrected}}[N]$ is dropped in favour of the simpler $\dot{m}[N]$. However, the reader should remember that the bias correction has been applied. $\text{Cov}(w[N], w[M]) = 0$ means that the noise is uncorrelated. Therefore, the flowmeter's samples are uncorrelated: $\text{Cov}(\dot{m}[N], \dot{m}[M]) = 0$.

The goal of a filter, at the N^{th} discrete-time, is to provide an estimate $\dot{m}_{\text{filter}}[N]$ such that $\dot{m}_{\text{filter}}[N] - \theta[N] \approx 0$. To this end, it is more desirable to develop a filter that can exploit the vector of all past measurements up to the N^{th} instant: $\dot{\mathbf{m}}[N] \triangleq [\dot{m}[1] \ \cdots \ \dot{m}[N]]^T$. Using this vector for filtering purpose means to develop the function $\dot{m}_{\text{filter}}[N] = f_n(\dot{\mathbf{m}}[N])$. Specifically, for the case of the EMA, the following filtering function yields:

$$\dot{m}_{\text{EMA}}[N] \triangleq \lambda \sum_{n=1}^N (1 - \lambda)^{N-n} \dot{m}[n] + (1 - \lambda)^N \dot{m}[1]$$

or recursively:

(9)

$$\dot{m}_{\text{EMA}}[N] = \begin{cases} \dot{m}[1], & N = 1 \\ \lambda \dot{m}[N] + (1 - \lambda) \dot{m}_{\text{EMA}}[N - 1], & N > 1 \end{cases}$$

The EMA is a data smoothing technique commonly used in time series analysis to remove noise and highlight trends in data. It is particularly useful in scenarios where more recent observations are considered more relevant than older ones, allowing the filter to adapt more quickly to changes in the data. The EMA filter applies exponentially decreasing weights to past data points, meaning that the most recent data points have the most significant influence on the average. In contrast, older data points have progressively less impact. The weighing is done by setting an appropriate value of $\lambda \in (0,1)$. This differs from a simple moving average, which equally weighs all data points within a specified window. Table 11 summarizes the results discussed above.

Per se, the EMA filter does not guarantee a performance improvement. While the estimate's variance improves, the bias increases as the flow rate tends to vary with time. For this reason, it is important to tune the coefficient λ properly. Low values tend to assign higher weights to past measurements while higher values to recent ones. The limit cases are when $\lambda = 0$ and $\lambda = 1$ are selected, resulting in $\dot{m}_{\text{EMA}}[N] = \dot{m}[1]$ (high bias, low variance) and in $\dot{m}_{\text{EMA}}[N] = \dot{m}[N]$ (low bias, high variance), respectively. For the application of flowmeters, we recommend avoiding values of λ that would result in a filter that cannot process flow rate changes correctly. This situation exemplifies a bias-variance trade-off scenario where the bias lowers as $\lambda \rightarrow 1$, and the variance lowers as $\lambda \rightarrow 0$. Appendix C provides a data-driven approach to this tuning problem.

Table 11. Summary of the statistical properties of the Exponential Moving Average (EMA)

Flow rate value	True value	Direct measurement (with bias correction)	EMA filter		
			General	Steady-state	Switch to steady-state
Symbol	$\theta[N]$	$\dot{m}[N]$	$\dot{m}_{\text{EMA}}[N]$		
Expected value	$\forall N$	$\theta[N]$	$\lambda \theta[N] + (1 - \lambda) \cdot \mathbb{E}(\dot{m}_{\text{EMA}}[N - 1])$	$\theta[N]$	$\theta + (1 - \lambda)^{N-M+1} \cdot (\mathbb{E}(\dot{m}_{\text{EMA}}[M - 1]) - \theta)$
	$N \rightarrow \infty$				$\theta[N]$
Bias	$\forall N$	0	$(1 - \lambda) \cdot \mathbb{E}(\dot{m}_{\text{EMA}}[N - 1] - \theta[N])$	0	$(1 - \lambda)^{N-M+1} \cdot (\mathbb{E}(\dot{m}_{\text{EMA}}[M - 1]) - \theta)$
	$N \rightarrow \infty$				0
Variance	$\forall N$	u^2	$u^2 \left(\frac{2 (1 - \lambda)^{2(N-1)}}{2 - \lambda} + \frac{\lambda}{2 - \lambda} \right)$		
	$N \rightarrow \infty$		$u^2 \frac{\lambda}{2 - \lambda}$		

3.3.4 Online filter for multiple flowmeters

When multiple meters are installed with the purpose of providing mass flow rate θ_t , for any continuous time t , the measurement of the generic i th flowmeter can be reformulated, with $i = 1, \dots, I$: $\dot{m}^{(i)}[N_t^{(i)}] = \theta_t +$

$w^{(i)} \left[N_t^{(i)} \right]$, where $N_t^{(i)}$ is the number of measurements done by the i th flowmeter as of time t , with uncorrelated noise samples $w^{(i)} \left[N_t^{(i)} \right]$'s between the flowmeters.

Two methods are proposed in Appendix C, one where the flowmeter's measurements are averaged, and a second where the EMA's filters associated with each flowmeter are averaged. In the first method, the weighted average of the measurements $\hat{m}_t^{(\text{mean})}$ are defined as the weighted average of the flowmeter's last available reading using the inverse of the flowmeter's variances as weights. This allows handling flowmeters with different sampling frequencies. Of course, forcing $\hat{m}_t^{(\text{mean})}$ to be the average of readings taken at various times adds an unknown bias contribution to the estimator. This is not the case for steady-state conditions or perfectly synchronized flowmeters, and it becomes negligible at sufficiently high sampling frequencies. See Figure 8 for a schematic representation of the method.

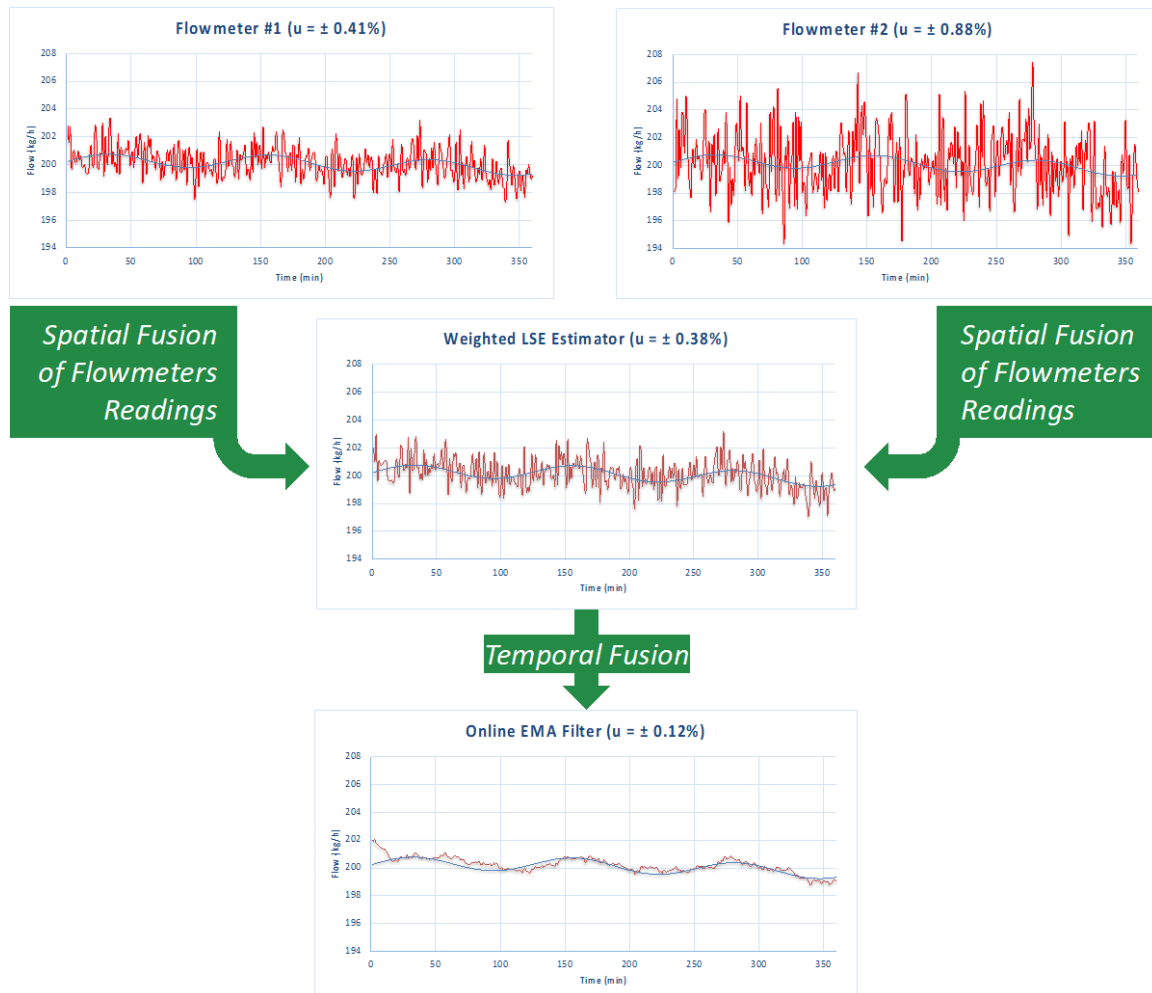


Figure 8. The scheme shows an example with two flowmeters providing real-time flowrate measurements with uncertainty $\pm 0.41\%$ and $\pm 0.88\%$. The readings are fused in real-time via weighted LSE estimation, providing an estimate with uncertainty $\pm 0.38\%$. Finally, an EMA filter is used to further reduce the uncertainty to $\pm 0.12\%$. The smooth blue line represents the true value of flow rate.

Averaging the EMA's filter (second method) allows handling flowmeters with different sampling frequencies. Forcing the value $\dot{m}_{\text{EMA},t}^{(i)}$ to be constant in the time interval that goes from the $(N_t^{(i)})^{\text{th}}$ to the $(N_t^{(i)} + 1)^{\text{th}}$ measurement adds an unknown bias contribution to the estimator. Analogously to the first method, this is not the case for steady-state conditions or perfectly synchronized flowmeters, and it is negligible for high sampling frequencies. Also, if no significant additional bias is generated via ensuring sufficiently high sampling frequencies (or perfectly synchronized flowmeters), the decrease in variance is sufficient proof to state that averaging the filter's results is a possible way to reduce measurement errors. This method has the advantage of being able to be implemented on the fly as it merely averages independent filters' outputs, making it a flexible option. However, it is expected to be less reliable than the first method.

3.3.5 Other real-time techniques

The methods previously shown are all based on the EMA filtering technique. This technique is a common way to handle noisy time series and assumes an ARIMA(0,1,1) model [132]. This model is far from capturing all the statistical characteristics of the flowmeter's measurements, even more so when multiple flowmeters are involved. The choice of displaying such an algorithm lies in its ability to combine ease of implementation and effectiveness, both extremely important in critical applications such as fiscal metering.

Alternatively, the latest trends in artificial intelligence (AI) show promising results in time series processing when handled with *artificial neural networks* (ANN) [133], especially when equipped with many layers, also known as *deep neural networks* (DNN) [134]. These can learn underlying statistical patterns without being limited by linearity, independence, or normality constraints. The *universal approximation theorem* justifies the outstanding performances of such neural network-based solutions. When handling time series, deep learning algorithms that are known to be able to process them effectively are mainly of the family of *recurrent neural networks* (RNN), of which *long short-term memory* (LSTM) networks represent the state-of-the-art. Current trends show excellent results when using *transformers*, which are architectures widely used in large language models (LLM) and show higher performances and shorter training times than LSTM networks [135]. Deep learning strategies are highly data-driven and require massive data to exploit their full potential. Thus, carefully choosing the algorithms based on the amount and quality of the available data is suggested.

Other techniques that can be exploited to reduce the measurement errors further, often to be paid with more complex algorithms comprise: the Holt Linear Method [132], the Holt-Winters Method [132, 136], stochastic time-series models [137], recursive least square filter [138], and the Kalman filter [130]. For an overview of these techniques refer to Appendix C and references therein.

3.3.6 Note on correlations and sampling frequency

The analysis previously described often assumed uncorrelated noise in the recorded measurements. This means that the noise samples are uncorrelated in time and among flowmeters. Moreover, it was assumed that each flowmeter is attempting to measure the same value of mass flow rate $\theta[N]$ implying that the



flowmeters are placed at a negligible distance from one another. When this last assumption holds, assuming uncorrelated measurement noise between the flowmeters is fair. However, it is still plausible that the noise is correlated in time within a single flowmeter. To correctly account for these contributions, the user should estimate the autocovariance when carrying out the offline assessments of b and u^2 . This allows using this additional statistical property when selecting the appropriate value of the coefficient λ for the EMA filters (or when training machine learning algorithms) by simulating a more realistic measurement noise. If the covariance matrix is obtained, it can also be exploited when designing algorithms that necessitate its use (e.g., Generalized Recursive Least Squares Filter and Kalman Filter). Regarding this possibility, after estimating the covariance matrix C_w , it is recommended to convert the corresponding correlation matrix R_w , then fixing a lower and upper threshold to its non-diagonal values, and finally converting the newly built correlation matrix R_w^* into a new covariance matrix C_w^* . This procedure allows for low correlations to be discarded as they could be caused by estimation errors and, by discarding high correlations, ensures the covariance matrix invertibility. The situation in which the assumption of uncorrelated measurements might hold is when the sampling frequency is low enough. However, this is not a desirable situation as information on the noise auto-correlation is inevitably lost and the underlying trend of the mass flow rate. For this reason, a high sampling frequency is desirable.

3.4 Estimated fiscal metering market for 2030 and 2050

It is challenging to estimate the number of flowmeters deployed in the emerging CO₂ market. There are several sources listing CCS projects that are operating, under construction, or in planning. For example, the Global CCS Institute is tracking 41 operating projects and 391 projects in development [139], numbers that are rapidly increasing year by year. The IEA has an overview of 844 projects in different phases of development and operation [140]. Common for both is that there are uncertainties related to which projects will be commissioned, they comprise capture projects, transport projects, storage projects, and combinations of these. It is also not possible to quantify with certainty the number of flow meters for different project types, as it depends on several factors, e.g., number of border crossings, number of emitters connected to a project, etc.

Another approach is to look at transport projects or CO₂ network projects. The EU updates a list of Projects of Common Interest (PCI) and Projects of Mutual Interest (PMI) every other year. The list includes projects that are important for the energy infrastructure in the EU that are also border crossing (PCI) or even connected outside the union (PMI). In the 2024 version, there are 14 such projects listed for CCS-related infrastructure [141]. Still, this only gives data for one region, and it is not trivial to estimate the number of flow meters even for only one of the projects. Finding similar lists worldwide and investigating metering needs for each project is a comprehensive task, with little gain, that will not be attempted here.

In this work, two approaches are used to estimate the size of the fiscal metering market in the future. They take projections for CCS deployment in 2030 and 2050 by the amount of CO₂ captured and stored. The total is used to estimate the number of flow meters needed for each megatonne (Mt) of CO₂ captured and stored. The two methods, including the calculations, are explained in the following. Different projections and scenarios for CCS deployment are given in Table 12. Based on these figures, the calculations use a total capacity of 200 Mtpa in 2030 and 1000 Mtpa in 2050. This is a conservative estimate, as it takes the minimum value from the listed scenarios.

Table 12. CCS scenarios for 2030 and 2050.

Source	2030 scenario (Mtpa)	2050 scenario (Mtpa)
IEA Net Zero Roadmap 2023 update [142]	400	1000
IEA Net Zero Roadmap [143]	1670	7600
DNV Energy Transition Outlook 2023 [144]	200	1200
Global CCS Institute – Global Status of CCS 2023 (Announced capacity 2023) [139]	350	
Basis for analysis	200	1000

3.4.1 Method 1

In this method, the number of flow meters is calculated based on the number of capture facilities and wells required to reach the capture rates defined. The following assumptions are made for the number of flow meters required for each facility:

- Each capture unit requires *one flow meter*.
- Each injection well requires *one flow meter*.
- Flow meters through the transportation networks (e.g., at pipe junctions, border crossings, or at ownership changes) equals the *average of flow meters required for capture units and injection wells*.

The number of capture facilities is estimated by taking the average size of capture facilities in the IEA database for CCS [140] facilities for operational and ongoing projects. The list is assumed to be representative of the range of scales CO₂ capture units will have in the future. The average capture capacity is found to be 1.35 Mtpa. By dividing the total amount of CO₂ to be stored in the 2030 and 2050 scenarios by the average capture capacity, the number of facilities is found. The required number of capture facilities and connected flow meters for 2030 and 2050 become approximately 150 and 750, respectively. This is also a conservative estimate as it presumes all capture facilities to operate continuously at full capacity.

The injection capacity of a well depends on the reservoir conditions. In the Northern Lights project, a single injection well will have a capacity of 1.5 Mtpa [145]. The well from Sleipner, injected at a rate of *circa* 1 Mtpa [146]. Whiriskey [147] argues that the Sleipner CO₂ well is in the upper injectivity range and suggests using an injectivity of 0.6 Mtpa. Thus, considering the former is the most conservative figure, the number of required wells can be found. For the 2030 and 2050 cases, the number of wells with connected flow meters becomes approximately 130 and 650, respectively. As with the capture facilities, this number presumes continuous operation at full capacity, an unlikely scenario, such that more wells should be expected.

Taking the average of the number of flow meters for the capture facilities and the wells, 140 and 700 flow meters are required for the 2030 and 2050 scenarios, respectively. The number of flow meters in the transportation network is a low estimate, as there will probably be required meters at border crossings, junctions, where flows from more than one source are combined, changes in transportation method (e.g., pipeline to ship), whenever the CO₂ shifts owner, and intermediate storage terminals all probably will require fiscal metering (see Figure 3). Although several of these might overlap, and for some cases, there might not

be a need for any flow meters in the transport network, it should not be expected that less than one meter on average is sufficient.

By these estimates, at least 420 and 2100 flow meters will be operating in 2030 and 2050, respectively.

3.4.2 Method 2

In the second method, the estimates are based on a specific project and its need for CO₂ flow meters. The Northern Lights project will be used as the reference case due to its development maturity and availability of open information. According to a report from 2019 [148], flow meters will be utilised at the following locations:

- At the loading location of the ship.
- At the subsea location near each well.

Fugitive emissions will be estimated by measuring the liquid level and conditions in the tanks on the ship and intermediate storage facility. The report also mentions allocating space for a fiscal metering system at the offloading site to facilitate the measurement of third-party volumes and at the outlet of the intermediate storage facility to meter the export for injection.

In a more recent presentation, Northern Lights shows the usage of three fiscal meters at the offloading position at the intermediate storage facility, as well as one meter measuring the flow rate in the gas return to the ship [149]. Table 13 summarises the amount of flow meters needed for the 5 Mtpa capacity of Northern Lights based on the presented references.

Table 13. Number of flow meters required for Northern Lights.

Location	Number of flow meters	Flowmeter type if specified	Comment
Ship loading	5		Ships will be loaded at various locations. Five locations is a conservative estimate.
Ship offloading	4	Ultrasound, turbine, coriolis.	Three flow meters that can be configured in parallel or series. One flow meter of unknown type for the gas return.
Intermediate storage outlet	1		Might or might not be installed.
Seabed	4		One per well, four wells are required for 5 Mt/year capacity.
Sum	14		

This estimate gives 14 flow meters for 5 Mt of injected CO₂ annually. For the 200 and 1000 Mtpa scenarios the sum is then 560 and 2800 in 2030 and 2050, respectively.

The results for both estimation methods are shown in Table 14. Being rough estimates of the number of flow meters requirement, the two methods provide results that agree reasonably well.

Table 14. Estimation of operating flow meters by the two presented methods

Method	2030 scenario (200 Mtpa)	2050 scenario (1000 Mtpa)
Method 1	420	2100
Method 2	560	2800

By dividing the number of operating flow meters by the calibration interval, the average number of flow meters that require calibration a given year can be estimated. Based on the few references given on calibration intervals (see Section 4.2.5) and assuming (i) a 5-year calibration interval, (2) the total amount in meters calculated as per Method 1 – most conservative figure, yields that in 2030 and 2050, 84 and 420 flow meters will require calibration, respectively. It is noteworthy that the calibration intervals might vary between countries and regions due to notably different regulations. Further, it is still uncertain to which extent regulating bodies will enforce calibrations must be performed with the actual process fluid, CO₂ with impurities, pure CO₂, or with a proxy fluid.

The estimates above carry high uncertainty but gives a rough idea of the amount of the fiscal metering market and calibration needs. The estimates are thought to be relatively conservative. The most conservative estimates in scenarios, estimations, and calibration interval have also been utilised. On the other hand, the IEA scenarios are based on reaching net-zero emissions by 2050. The efforts for the deployment of CCS must still increase significantly to be in line with these ambitions (see Figure 1).

3.5 The value of decreased calibration uncertainty

One of the main economic drivers of the CCUS business, and thus fiscal metering, is the price of carbon. Currently, such price is set in different countries by a choice between (or a combination of) Emission Trading Systems and carbon taxes. The price of CO₂ from the EU ETS over the last two years has been consistently above 60 €/t [150]. The highest taxation per tonne of CO₂ is implemented in Switzerland and Liechtenstein, with taxes above 120 € [151]. Considering the amount of CO₂ to be yearly transported and stored by 2050, according to the IEA [152] is 5000 Mtpa, a conservative CO₂ price of 50 €/t, yields a value in the CO₂ traded of 250,000M€/y. The value of the uncertainty in measurement devices (per every 1%) is 2500M€/y.

Uncertainty results in a financial exposure of either part in the custody transfer process, depending on the + or – error. Thus, the largest impact of uncertainty in fiscal metering within CCS is related to the allocation of revenue. Rightful allocation is, expectedly, of even larger relevance for cross-border CCS projects. The diagram in Figure 9 shows the value network of a large-scale CO₂ fiscal metering calibration facility as designed by SINTEF [67]. The value network maps the inter-organisational exchange foreseen to take place and provides insight into the interactions between a calibration lab and stakeholders as well as among the stakeholders themselves. In the network, stakeholders often hold two or more dimensions simultaneously, i.e., customers, suppliers, or competitors. The value network in Figure 9, built under Parolini's approach [16], can also be seen as a set of economic entities connected through the transfer of offerings.

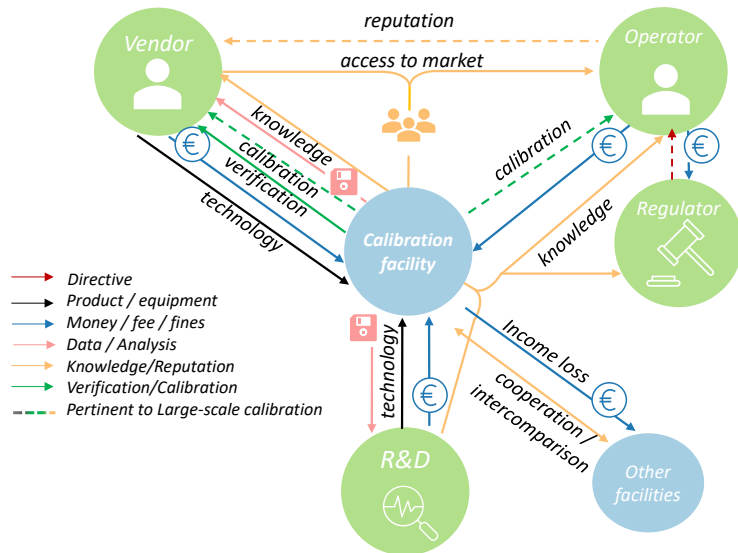


Figure 9. Value network of a large-scale calibration facility (modified from [67])

The resulting network possesses a structure so that it delivers a common value proposition to a specified stakeholder or market. Focusing on the end users, the objective to determine the suitability of technologies for CCS can only be met by a calibration facility operating at conditions as close as possible as in the field. Hence, if the end consumer were to pivot the analysis, it would automatically set the boundaries of the required size and functionalities of the calibration infrastructure. The development of various calibration facilities constitutes opportunities for cooperation and intercomparison, as being considered in Europe by the ECCSEL ERIC [68].

4 Regulatory framework

Robust international standards are imperative to ensure the efficient and effective global deployment of CCUS technologies. In 2022, the International Energy Agency (IEA) released the CCUS Handbook: Legal and Regulatory Frameworks for CCUS [28], which provides a comprehensive overview of global legislation, encompassing different countries and regions that have developed their specific regulatory frameworks. In the following, an overview of the current framework relevant to fiscal metering is provided. Key areas where standards must be developed or enhanced to address the challenges and opportunities within the CCUS value chain are discussed.

4.1 Legislation

Four macro-regions are addressed: Europe, Asia Pacific, the Middle East and Asia, and the Americas. Each macro region presents unique challenges and opportunities in deploying CCUS technologies, requiring tailored standards and guidelines to address specific needs. This structured approach allows for a tailored

analysis of each region's requirements and priorities, which can ultimately aid in the development of robust and harmonised international standards that promote the widespread trust around and adoption of CCUS technologies worldwide. Each region has been analysed to the depth allowed by the study frame and the progress made. Europe shows the most significant progress so far, followed by North America.

One of the critical barriers to deploying CCUS is the transboundary transport of CO₂, which requires the ratification of the 2009 amendment to the London protocol at a national level, followed by bilateral agreements with other nations. To date, Belgium, Denmark, Estonia, Finland, Iran, South Korea, the Netherlands, Norway, Sweden, and the United Kingdom have ratified the amendment to enable the export of CO₂ for storage purposes.

4.1.1 Europe

Europe stands at the forefront of the preparatory normative framework for the emerging CCUS technology. In 2023 and 2024, several advancements were made for CCS in Europe. At the European Commission level, for example, the Net Zero Industry Act with specific targets for the deployment of CCS across Europe [153] was adopted. Also, a state aid scheme to support the roll-out of biogenic carbon dioxide capture and storage to produce negative emissions was approved by the European Commission [154]. Further, the Commission has been working on updating the Guidance Documents for the CCS Directive to better support operators and authorities in the practical implementation of permitting procedures. This includes addressing technical and market developments, documenting best practices, and removing ambiguities identified by stakeholders and Member States.

National policy developments and bilateral agreements have been announced in countries like in Denmark, Norway, and the Netherlands [155] as well as Belgium, France, Germany, Iceland, Sweden, Switzerland, and the UK among others [155]. Outside northern Europe, countries Bulgaria, Greece, the Czech Republic, Poland and Romania are also advancing in the implementation of CCS projects [156].

Current normative framework.

In Europe, the *CCS Directive* [157], officially known as the directive on the geological storage of CO₂, sets out regulations for the safe storage of CO₂ in geological formations. It applies to all CO₂ storage activities within the EU and throughout the entire lifespan of storage sites. It also includes guidelines for monitoring and the capture and transportation aspects of CCS, primarily governed by existing EU environmental laws like the EID Directive and the Industrial Emissions Directive, with modifications made by the CCS Directive.

The *EU ETS* [158] holds polluters accountable for their greenhouse gas emissions by requiring payment for the emitted CO₂, aids in reducing emissions and provides funding for the EU's eco-friendly transition, is active in all EU member states, as well as Iceland, Liechtenstein, and Norway (EEA-EFTA nations), and encompasses emissions from approximately 10,000 facilities in the energy and manufacturing sectors, along with airlines operating within the EU and flying to Switzerland and the United Kingdom—equating to about 40% of EU emissions. The UK has its own *UK ETS system* for carbon reduction and trading for UK businesses [61]. The

UK ETS operates in a very similar way to the EU ETS scheme, with slightly different approaches to emissions reduction over time [159, 160].

Industrial facilities and airline operators under the ETS must have an approved monitoring plan for tracking and reporting their yearly emissions. This plan is a vital component of the operating permit required for industrial facilities. Annually, operators must submit an emissions report, which must be verified by an accredited verifier by March 31st of the following year. Once verified, operators must surrender the corresponding number of allowances by April 30th of that year.

The regulations governing the EU ETS compliance cycle are outlined in two laws:

- Monitoring and Reporting Regulation (MRR) [161]
- Accreditation and Verification Regulation (AVR) [162]

According to these directives, accurate and traceable CO₂ measurements are required for fiscal and operational purposes across the CCUS value chain. In Europe, fiscal metering is regulated through the ETS by the *ETS M&R Regulation 2018/2066* [163]. The EU ETS requirements encompass thorough monitoring of CO₂ flows and leakages across the entire value chain. Currently, the accuracy requirements for CO₂ measurement are dictated by the European Commission's Measuring instruments directive (MID) (*Directive 2014/32*) [63]. Existing metrology standards are discussed in a separate section below.

The newly introduced EU *Industrial Carbon Management Strategy* highlights the need for coordination, contract and price transparency and timely permitting to ensure a non-discriminatory, open-access, transparent, multimodal, cross-border CO₂ transport and storage infrastructure [164]. CCUS projects are heterogeneous, and there is a lack of standardisation among them. The EU Carbon Management strategy [164] recognises the need for ambitious and well-coordinated policies at the national level and strategic infrastructure planning at the EU level. To further the development of CCUS, a shared framework among industry and research sectors concerning CO₂ accounting along the CCUS chain is needed. Although the EU normative framework is comprehensive, the EU directives must be implemented nationally

4.1.2 Middle East and North Africa (MENA)

The International Energy Forum (IEF) published two reports on carbon management in the MENA region [165]. These reports support countries in expanding the deployment of CCUS and achieving their climate goals from the regulatory and market-growth perspective. Many MENA countries, including Saudi Arabia and the UAE, have a well-established track record. The Middle East region already accounts for around 8% of global capture capacity across three large-scale commercial CCS facilities: Uthmaniyah CO₂-EOR Demonstration Project in Saudi Arabia, Al Reyadah CO₂-EOR Project in Abu Dhabi and Ras Laffan CCS Project in Qatar.

The 2050 and 2060 net zero targets by the UAE and Saudi Arabia, respectively, and the UAE hosting COP28 have boosted the interest in CCS technologies in the region. In Qatar, for example, a 4.3 Mt expansion of carbon capture capacity at QatarEnergy's Ras Laffan LNG complex has taken place.

In Africa, Kenya has announced its second Direct Air Capture (DAC) facility and first megaton-scale DAC project, to capture 1Mton CO₂ by 2028. Egypt on its side, brought CCUS within the scope of the nation's single approval system via its law No.72 of 2017.

Overall, some progress has been made in the region. However, the area still shows limited improvement in the CCUS normative framework. Further work will be needed to support the deployment of CCUS in the region.

4.1.3 Asia Pacific

In 2023, several advancements were made in the normative for CCUS in the Asia Pacific region, including Australia [166]. Asia Pacific has over 1,300 emitters and the potential for over 20 hubs. Currently in the region are nine operative CCUS facilities, mainly in Australia and China. The focus of such facilities is on sequestration emissions from natural gas processing and the chemical sector. However, to unlock its CCUS potential, an exponential growth of its current operational CCUS-related projects should take place.

Australia is in the top five of the countries with the highest CCUS readiness rating in the world, according to the Global CCS Institute [167]. It has developed a detailed regulatory framework, including for potential leaks associated with CCS projects.

At least seven large-scale CCUS projects are in the early planning stages in Southeast Asia. Indonesia and Malaysia have improved their readiness for CCUS with the introduction of CCUS-specific legislation related to storage. Specifically, the Malaysian state of Sarawak has passed legislation to regulate CCS activities. The government plans to deploy CCUS domestically in Japan to achieve a substantial storage capacity by 2050. South Korea has committed to developing national legislation to support CCUS, although the promise has yet to materialise.

Despite these advancements, there are still challenges. The Global CCS Institute readiness index scores the Asia Pacific countries 35 on average [168]. This suggests a lack of supporting regulations and incentives in the region.

4.1.4 Americas

America is split concerning CCUS regulation, with the North actively improving its regulatory framework within CCUS and the South lagging [139].

In the United States, although CCUS has been promoted by the federal government, reaching the ambitious domestic climate goal of net-zero emissions by 2050 is challenging, given the significant quantities of carbon that will need to be captured and stored. The incentives on the Infrastructure Investment and Jobs Act and the Inflation Reduction Act reflect the recognition of the importance of CCUS to the US Congress. However, policies needed to facilitate CCUS deployment in the US need to take place on a state-by-state level. As per the CCUS State Legislative Tracker [169], which assesses the legal readiness of CCUS at a state level in the USA, identified in August 2024, 33 states with significant legislation on the matter. This is a substantial improvement from January 2023, when only 15 states had CCUS legislation in place.



Canada has also been active in promoting CCUS technologies. The Canadian government has implemented several policies and regulations to encourage the development and deployment of CCUS technologies. These include financial incentives, such as tax credits for carbon capture and storage, and regulatory measures to ensure the safe and effective operation of CCUS projects. The Canadian region of British Columbia has also implemented CCUS-specific regulations to clarify the technology's approval process. Alberta's Technology and New emissions regulation included provisions for CCS projects.

The normative landscape for CCUS in South America is still in its early stages. Brazil has recently passed new legal framework for CCS, focusing on regulation and inspection of activities throughout the value chain [170]. While there is growing interest in CCUS technologies, the development and implementation of these technologies are not as advanced as in other regions such as North America, Europe, or Asia Pacific.

The regulatory framework for CCUS is still under development in many South American countries. Clear and supportive regulations are needed to encourage investment in CCUS technologies. Further, Infrastructure for CCUS, such as transportation and storage facilities, is limited. Significant infrastructure development is required to increase the capture capacity of facilities.

Public understanding and acceptance of CCUS technologies in the region are relatively low compared to others. Efforts are needed to address public concerns and increase awareness about the benefits of CCUS. Additionally, the economic viability of CCUS technologies is a significant challenge. Policies that make CCUS economically attractive are needed.

Despite these challenges, there are signs of progress. Some South American countries have started to explore the potential of CCUS technologies and consider them in their climate change mitigation strategies. However, more work is needed to realise the potential of CCUS in South America fully.

Summary: State of legislation for CCUS

Europe is at the forefront of preparatory legislation for CCUS deployment. The region has made significant strides in streamlining the CCS permitting process, with countries like Denmark, Norway, the Netherlands, and the United Kingdom leading the way in national CCS policy developments and supporting CCS projects. The European Commission has also been proactive in updating the Guidance Documents for the CCS Directive to better support operators and Competent Authorities in the practical implementation of permitting procedures. Still, gaps remain concerning the implementation of European regulations by the member states and clarity in the regulatory and permitting framework, especially regarding the transfer of liability from operators to the states.

Other regions worldwide are also making progress, albeit at different rates. In the Middle East, Africa, and Asia Pacific, advancements have been made, but the regions still show limited improvement in the CCUS normative framework, which is broadly lacking. There is a clear need for further work.

The global normative landscape for CCUS is constantly evolving, with different regions at different stages of development. Continued progress in this area will be crucial for successfully deploying CCUS technologies and achieving global climate goals.

4.2 Global regulations and standards relevant to CO₂ fiscal metering

4.2.1 General uncertainty requirements in flow measurement

The current basis for fiscal metering in Europe is provided by the Emission Trading systems EU ETS and UK ETS. The ETS M&R Regulation 2018/2066 [163] Article 49, regulations for the transfer of CO₂, and Annex VIII, Section 1, Tier 4 (which superseded Commission Decision 2010/345) establish an accuracy for measurement net captured CO₂ mass in ± 2.5 %. It is important to note, however, that the EU ETS was developed for emission monitoring with Continuous Emission Monitoring System (CEMS), *i.e.*, for flue gas conditions. It is discussed in [171] CEMS are applicable when CO₂ is transferred out of a capture site, which usually takes place at pressures close to atmospheric. Unlike operation conditions in the transportation network, at injection or during shipping. As such, the ± 2.5 % requirement fails to cover the need for technology deployed in the CCS value chain [171]. Further, stricter accuracy requirements can be expected. That is, for example, the EU taxonomy report [172] requires leakages to be kept below ± 0.5 % from the capture point to the injection point to meet the “do no significant harm” criteria. Documenting this will need even higher accuracy than the regulations require.

The EU MID (Directive 2014/32) [63] harmonises the laws of the EU and EEA member states on the subject of measurement devices. Annex VII MI-005 applies to continuous measurements of liquids other than water. Under the EU MID, the accuracy of liquified carbon dioxide is classified under Class 1.5. Class 1.5 establishes a maximum permissible error (MPE) of ± 1.5 % for the measurement system, and ± 1 % for the flow meter. There is no explicit mention of CO₂ gas [171]. The EU MID Annex IV MI-002 classifies industrial gas measurements fall under Class 1.5, meaning that the gas meter should have a MPE of ± 1.5 % for flow rates between Q_t and Q_{max} (“upper zone”), and ± 3 % between Q_{min} and Q_t (“lower zone”) where Q_t is the transitional flow rate ($Q_t \leq Q_{max}/10$).

The recommendations from the International Organization for Legal Metrology in the OIML R 117 ‘Dynamic measuring systems for liquids other than water’ [64], classifies the accuracy classes as per four fields of applications. Similar to the EU MID, measuring systems for liquefied CO₂, which fall under Accuracy Class 1.5, require an MPE of ± 1.5 %. Under the same class, the maximum permissible error for a meter under rated operating conditions is ± 1 %. It is noteworthy that neither the MID nor the OIML makes reference to the stream composition, contrary to EU ETS which refers to pure CO₂ [171].

The US National Institute for Standards and Technology (NIST) Handbook 44 – 2017, section 3.38 covers measuring devices for liquid CO₂ [173]. The measurement of liquid CO₂ is classified as Accuracy Class 2.5 with an acceptable tolerance for the measuring devices of 1.5 %. The standard requires the test liquid to be CO₂ in a compressed liquid state.

4.2.2 Project-specific uncertainty requirements in flow measurement

Measurement uncertainty specifications are also part of contractual agreements for ongoing CCS projects. In this sense, the Dispatchable Power Agreement for Net Zero Teeside in the UK [174], specifies

measurement uncertainty requirements of $\pm 1.0\%$ for CO_2 and $\pm 1.5\%$ for CO_2 -rich mass flow measurement. The Porthos project in the Netherlands states that the overall uncertainty on mass CO_2 shall not exceed $\pm 1.5\%$. [175]. Neither the monitoring plan nor contracts for the Northern Lights project are publicly available, yet to the authors' knowledge as per communications with Northern Lights stakeholders, the commercial agreements for custody transfer in the project comprise measurement uncertainties of $\pm 1.5\%$ for dynamic measurements and $\pm 0.5\%$ static measurements.

4.2.3 Technology-specific standards

There are several ISO standards that address particular metering technologies. An overview of CCS-relevant standards is provided in [15, 121] and references therein. It is noteworthy that some of the technology-specific standards are instead very detailed, while others only cover high-level guidance as is the case of the ISO 10790:2015 [176] for Coriolis meters. Differential pressure devices for gas and liquid flow are covered by ISO 5167-2:2003 [177]. Ultrasonic meters for liquids and gas flows, are governed by the ISO 12242:2012 [178] and ISO 17089-2:2012 [179] standards, respectively. ISO 9300:2005 specifies the geometry and method of Critical Flow Venturi nozzles for a mass flow rate of gas streams, yet its validity for CO_2 rich mixtures is not proven. Turbine meters are covered by ISO 2715:2017 for use with liquid hydrocarbons and by ISO 9951:1993 for gas flow measurement. The latter one is, however, obsolete, with the BS EN 12261:2018 being a more updated alternative [14].

4.2.4 Other relevant standards

For volume-to-mass conversions using density meters, the table 4 of Annex VII section 2.6 of the MID [63] is relevant. The MID specifies a density accuracy of $\pm 2 \text{ kg/m}^3$ for Class 1.5. The OIML R117-1 [64] has a similar requirement in section 2.7.2.2 table 5.2, but it is stated only for mass-to-volume conversions. It is, however, reasonable to expect a similar requirement for volume-to-mass conversions. The API provides guidelines on continuous density measurement – particularly in the selection and testing of density meters – and on installation configurations [114].

The ISO/TR 27921:2010 addresses likely compositions of the CO_2 captured and identifies potential impacts of the impurities downstream of the capture process. ISO 27913:2016 outlines requirements and provides guidance for CO_2 pipeline transport. As per the analysis in [121] none of the above standards address the effect of impurities in flow meters and methods to identify impurities in the CO_2 stream are meagrely defined. Knowledge often precedes the development of standards. Thus, the above gaps could be due to the current lack of technical knowledge linked to limited operative experience, and of research facilities worldwide.

From a system perspective, the ISO/TS 21354 discusses the benefits of using model test fluids that are normally well-behaved and whose PVT properties are well-known, which allows to reduce uncertainties regarding PVT properties to a minimum; especially given the wide range of fluid compositions in the field, a range which cannot be fully replicated in experimental flow-loops. Such claims reinforce the need to develop EoS that accurately describes the behaviour of CO_2 -rich mixtures and the verification of the capabilities of various sensor technologies on their own and or as part of an MFPM system with pure CO_2 and with mixtures of interest.

ISO/TS 21354:2020 addresses the measurement of multiphase fluid flow targeting oil, water, and gas mixture streams. However, the high-level considerations might still stand for the application of interest. At a device level, multiphase flow meters are systems that combine various individual sensors. Surely, all of these sensors and transmitters directly influence the overall quality of the measurements. The ISO recognizes the significant differences between multiphase and single-phase flow meters. The largest uncertainty contributor in multiphase meters relates to the variability in fluid dynamic process conditions and fluid properties. Hence, to use a multiphase flow meter in a CCUS stream, a combined expanded measurement uncertainty should be assessed.

4.2.5 Calibration frequency

Regarding flow calibration, the ISO/IEC 17025:2017 [180] establishes the general requirements for the competence of testing and calibration laboratories. Article 42 in the EU ETS [163] states that the operator shall ensure that laboratories carrying out measurements, calibrations and relevant equipment assessments for CEMS are accredited in accordance with the aforementioned ISO/IEC 17025. The US EPA Federal Register Vol. 74, states that all measurement devices must be calibrated according to the recommended procedures by the manufacturers, an appropriate industry consensus standard, or a method therein specified. The calibration accuracy of all measurement devices should account for a 5% accuracy. Flow meters based on differential pressure (e.g. orifice and Venturi meters) are exempted from this rule and may be verified by means of a DP-sensor calibration. Most ISO standards on flow metering technology require calibration under ISO 17025. Generally, only orifice meters can be exempted from calibration under flowing conditions if manufactured in compliance with ISO 5167.

The calibration methodology and frequency are regulated by Article 60 in the ETS M&R Regulation 2018/2066 [163]. The operator is responsible for calibrating, adjusting, and checking the measurement equipment at regular intervals in a manner traceable to international measurement standards. This procedure is performed at least annually in conjunction with the ETS compliance cycle, but shorter intervals may be required to comply with EN 14181.

EN 14181 regulates the calibration procedure according to quality assurance levels (QALs). For the calibration of the meters after installation in the field, QAL2 and QAL3 are relevant. To achieve QAL2, calibration in a certified calibration centre at least every fifth year is required, while QAL3 monitors measurement drift and thereby ensures that the measurement accuracy is maintained during operation. Notably, QAL3 is performed continuously during operation, and does not necessarily involve a certified calibration centre, but if the QAL3 tests reveal increased measurement drift and uncertainty, QAL2 calibration is required. In addition, annual surveillance tests (ASTs) are performed by certified calibration personnel. Although resembling QAL2, the AST may be performed on-site provided the on-site calibration yields a satisfactory uncertainty. As per the above, if the meter performance is stable with time, calibration in a certified calibration facility may not be required more than every fifth year.

Only scarce information of calibration intervals is given in the literature. In the Porthos project, flow meters should be calibrated within two years of entering operation, and if the drift is below 0.3% within that period, it should be recalibrated with a 4-6-years interval [175]. Furthermore, not specifically mentioning CCS, a

calibration frequency of five years is accepted for O&G fiscal meters in Norway [181]. However, consultations with the Norwegian regulatory body and various European metrology institutes report that requirements for CCS operation at the highest tier, i.e., strictest accuracies, are already in place [67]. Yet, regulatory provisions can grant reduced calibration frequencies under ETS MR Article 18, Paragraph 3, provided the calibration costs (at the specified frequency) are unreasonable. Equation (10) is used to estimate the benefits of the calibration frequency. The improvement factor is the difference between the uncertainty currently achieved and the uncertainty threshold of the higher tier multiplied by the average annual emissions over the three most recent reporting periods.

$$Benefit = Improvement\ factor \times Reference\ price \quad (10)$$

The lack of large-scale traceable CO₂ calibration laboratories exempts vendors and operators from calibrating according to the highest tier and at realistic operating conditions. Despite the above opening in the regulations, technological advancement within CCUS flow metering is expected to precede the enforcement of higher-tier compliance.

4.2.6 Advances in Standard Bodies

Although experimental feasibility and uncertainty validation precludes standard creation or enforcement, recently the CEN/TC 474 Technical Committee CCUS and carbon accounting approved a new work item proposal on Carbon dioxide quantification and verification across the CCS Value Chain. The work item aims to develop a standard that delineates the methodologies and requirements for quantifying the mass of CO₂ and CO₂ stream, as well as for quality assurance and verification [182].

Summary: State of CO₂ metering regulations

As evident from the regulatory review above, there are currently no dedicated international standards covering the technical requirements for CO₂ measurement devices, encompassing flow and composition measurements. A common measurement framework is key towards establishing a standardised accounting and verification of CO₂ metering. Such standardised procedures would provide fair and consistent custody transfer operations, reduce operative costs, and provide trust in CCUS business models and liability compliance. Because under ETS normative, allowance credits are awarded to emitters based on the CO₂ stored, accounting requires an all-encompassing value chain accounting, that is, from source to sink. Failures to implement standard accounting methodology across the chain could yield measurement inaccuracies, with the associated unwanted financial exposure to the trading parties. A first working item has been established at the CEN/TC 474 Technical Committee CCUS to tackle this gap.

5 Conclusions

To achieve the announced net-zero targets, global CCUS capacity must grow more than a hundredfold in the longer term, reaching up to 5 gigatonnes of CO₂ per year by 2050 and decarbonising around 15 to 20 per cent of today's energy-related emissions. This requires a significant acceleration compared to the current situation. Fiscal metering of CO₂ streams will be critical to support trade, protect consumers, build



confidence, facilitate taxation and fulfil treaty obligations. The aim of this work was to document the current state of the art, the challenges and opportunities of fiscal metering for CCS, and to provide an outlook from a technological and regulatory perspective.

Four technologies have been shown to have a high potential for use in CO₂ fiscal metering. Coriolis, Differential Pressure, Turbine, and Ultrasonic meters have been tested for CO₂ and CO₂-rich mixtures. The tests, conducted by different groups, took place in laboratory environments and resulted in a TRL of 4/5 for CCS applications. The reported measurement uncertainties vary considerably and depend, among other things, on the principle, the test conditions, the accuracy of the reference laboratory and the composition of the fluid. Comprehensive inter-laboratory comparison campaigns are required for CO₂ or CO₂-rich mixtures. Such comparative studies would help to clarify the accuracy of the metering technologies under the same controlled conditions.

One of the main inhibiting factors for TRL progress is the limited availability of infrastructure for researching and calibrating fiscal meters on a large scale. An alternative calibration strategy could be the use of traceable proxy fluids instead of CO₂ mixtures. The effectiveness of such a method for meters operating in CO₂ streams is sparsely documented. Laboratory tests indicate that this strategy is more promising for some technologies than others. Further research is needed.

Important challenges unique to CCS arise from the presence of impurities in the CO₂ stream. Impurities may lead to changes in the physical state of the mixture. The precise characterisation of such impurities and the understanding of their effects is of utmost importance for transport and, not least, for fiscal metering. For the latter, the use of the EOS-CG-2021 is recommended, but it should be checked whether the impurities present are part of the systems to which the EoS applies. A characterisation of the CO₂ stream is essential for this.

Stream analysis is also the key to the fiscal metering for CO₂ mass accounting. The mass of CO₂ stored must be reported to regulators, but the field measurements relate to the flow rate of the CO₂-rich stream. Combined bulk mass flow rate and stream composition are required to calculate the net CO₂ mass flow. Knowledge of the in-situ density is also required when volumetric meters are used. Chemical characterisation of the stream usually requires several analytical methods. The highest accuracy can be achieved by analysing samples with equipment such as GC, which is expensive, time-consuming and requires skilled technicians. Characterisation of critical impurities that need to be measured faster could benefit from other methods such as mass spectroscopy, FTIR and OFCEAS.

Stream analysers require calibration, which is carried out using traceable reference materials. In addition, representative samples must be collected, transported and stored for each analysis to characterise CO₂ streams. Chemical reactions in the storage cylinders or the transport containers for the samples must be avoided. Instabilities or degradations are undesirable for the storage of primary reference material in metrology institutes or for calibrations. Some research efforts have already been made to understand the stability of CO₂ samples. Nevertheless, further work on SI-traceable reference materials is needed to ensure global comparability. It is also recommended to carefully consider material compatibility and the choice of vessels for storage of reference materials for each mixture.

After determining the current state of the art, this study provided an outlook on the fiscal metering of CO₂. To this end, the study focussed on novel methods to close existing technological gaps, cost-effective



solutions for subsea fiscal metering and methods to reduce measurement errors. Regarding the first point, novel technological developments were investigated to identify technologies that can help overcome some of the shortcomings of existing fiscal metering technologies. The identified advances in Coriolis, Capacitance, Ultrasonic, and Gamma-ray technologies may hold promise for overcoming some of the shortcomings of conventional fiscal measurement devices. The four novel technology applications can help improve pressure drop in intrusive meters, detect second-phase formation, reduce measurement error due to gas-in-liquid phases, and reduce uncertainties in volume-to-mass conversion.

The use of technologies in difficult environments places higher demands on robustness and reduced complexity and costs. For offshore use, two alternative solutions for cost reduction were analysed. These solutions are based on (i) reducing the number of fiscal metering units serving multiple wells via manifolds, and (ii) estimating injection rates and virtual flow measurements that eliminate subsea flow metering altogether. However, the latter requires accurate flow models. Finally, to reduce the residual error after calibration of the metering, various filtering techniques were introduced. These may help in reducing the overall variance of the measurements and thus improve accuracy.

From a technological point of view, there are great opportunities for fiscal metering of CCS. The challenges and solutions identified require further research to reach the required level of deployment. Data sharing, comparative studies and close collaboration between researchers, technology developers, and operators are of paramount importance given the short timeframe for achieving net zero targets.

The legal framework for CO₂ fiscal metering is still under development. The lack of traceable chains for CO₂ services may prevent providers and operators from calibrating to the highest tier and under realistic operating conditions in accordance with current regulations. Technological progress in CO₂ fiscal metering is expected to precede the enforcement of higher-tier compliance. This is an opportunity to shape the relevant legislation and standardised practices for the benefit of fair business. A repeatable, harmonised, agreed, and documented way of metering CO₂ for the upcoming international CCS market is needed.

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APPENDIX A – CO₂ stream specifications of current CCS projects

Table B.1 Typical impurities concentration limit. Note that specifications are subject to potential changes over time. Source: Modified from [14, 183]

Component	Unit	Gas Pipeline (HyNet UK)	Gas Pipeline (Porthos NL)	Dense Phase Pipeline (East Coast Cluster, UK)	Dense phase pipeline (Aramis, NL)	Ship (Northern Lights NO)	Ship (Aramis, NL)
CO ₂	mol%	≥95	≥95	≥96	≥95	≥99.8	balance
N ₂	mol%	4	0.24	4	2.4	0.005	Meet total inert limit
H ₂	mol%	0.75	0.75	0.75	0.75	0.005	0.005
Ar	mol%	4	0.4	4	0.4	0.01	Meet total inert limit
CO	mol%	0.2	0.075	0.2	0.075	0.01	0.12
CH ₄	mol%	4	1	N/S	1	0.01	Meet total inert limit
Ethane C ₂ H ₆	mol%	4	N/S	N/S	N/S	0.0075	N/S
Propane & Other Aliphatic Hydrocarbons	mol%	0.15 in total	0.12 in total (including Ethane)	N/S	1.2	Total amount < 1100 ppm-mol C ₃ < 1100 ppm-mol, C ₄ -C ₅ < 815 ppm-mol, C ₆ -C ₇ < 75 ppm-mol, C ₈ -C ₉ < 8 ppm-mol. C ₁₀ + not allowed	N/S
H ₂ O	ppm mol	50	70	50	70	30	30
O ₂	ppm mol	10	40	10	40	10	10
NO _x	ppm mol	10	5	10	2.5	1.5	1.5
SO _x	ppm mol	10		20	20 total for H ₂ S+CO ₂ +SO _x +D	10	10
H ₂ S	ppm mol	5	20 (on which H ₂ S≤5)	5	5	9	5
CO ₂	ppm mol	5 in total		N/S	see SO _x	N/S	N/S
CS ₂	ppm mol			N/S	N/S	N/S	N/S
NH ₃	ppm mol	10	3	10	10	10	10
BTEX	ppm mol	15 in total	0.1	N/S	N/S	0.5	N/S
Methanol	ppm mol	350	620	500	620	30	40
Ethanol	ppm mol	N/A	20	500	20	1	20
Solid Particulates	mg/Nm ³	1 in total	N/S	1	Max size 1 µm	Max size 1 µm	1 micron cut-off diameter
Toxic Metal (Ash, dust, Na, K, Mg, Cr, Ni, Cd, Hg, Ti, Pb, As & Se)	mg/Nm ³	0.15	N/S	N/S	N/S	Hg: 0.0003 ppm mol 0.03 ppm mol in total Cd+Ti	Hg: 0.03 ppm mol 0.03 ppm mol in total Cd+Ti
VOCs (formaldehyde, acetaldehyde dimethyl sulfide ethanol)	mg/Nm ³	48 in total	10 in total	N/S	10 ppm	Total ≤10 ppm mol 20 ppm mol of formaldehyde 20 ppm mol of acetaldehyde 1-propanol < 1 ppm-mol, 2-butanol < 1 ppm-mol, 1,2,4-trimethylbenzene < 5 ppm-mol, Methyl acetate < 10 ppm-mol, Acetone < 10 ppm-mol, Hexanal < 10 ppm-mol, Diethyl ether < 10 ppm-mol, Acetonitrile < 10 ppm-mol	20 ppm mol of formaldehyde 20 ppm mol of acetaldehyde
Acid Forming Compounds (Cl ₂ , HF, HCl, HCN)	mg/Nm ³	150 in total	2ppm mol HCN	N/S	2 HNC	N/S	N/S
Amines (MEA, MDEA, DEA, AMP, piperazine)	ppb mol	100 in total	1000 in total	N/S	1	0.01 in total	10000 in total
Glycols (TEG, MEG DEG, propylene glycol, dimethyl ethers of polyethylene glycol)	ppm mol	NIL	follow dewpoint specification (<-10°C at 20 bar)	NIL	follow dewpoint specification (<-10°C at 20 bar)	MEG: 0.005 ppm mol TEG: Not allowed	N/S
Nitrosamines and Nitramines (NDMA, NMEA, NDEA, NDELA NPIP, NMor)	µg/Nm ³	3 in total	N/S	N/S	N/S	N/S	N/S
Naphthalene	ppb mol	100	N/S	N/S	N/S	N/S	N/S
Dioxins and Furans (PCDD, PCDF)	ng/Nm ³	0.02 in total	N/S	N/S	N/S	N/S	N/S
Ethylene	ppm mol	N/S	N/S	N/S	N/S	0.5	N/S
Hydrogen Cyanide	ppm mol	N/S	N/S	N/S	N/S	100	N/S

APPENDIX B – Minimum reported metering uncertainty

Table B.1 Test conditions of minimum reported fiscal metering uncertainties for CO₂ service

Minimum reported uncertainty	P (bara)	T (°C)	Flow rate / Density	Composition	Reference Equipment	Original work	Notes
$u(\dot{m}_{mix})_{m_{gas}} \geq \pm 0.25\%$	16 – 34	Ambient	50 - 1000 m ³ /h 550 - 60000 kg/h	(a) 95 % CO ₂ + 5 % NG (b) 99.3 % CO ₂ with 0.7 % NG	Secondary working standards	van Putten et al. [8]	All mass uncertainties correspond to tests with Coriolis meters. Uncertainties for liquid are based on intercomparison tests or comparisons with small-scale gravimetric references [14]
$u(\dot{m}_{mix})_{m_{liq}} \geq \pm 0.35\%$	26/71/ 91	-20/20/40	4464 – 16200 kg/h	99.82 vol% CO ₂ , 0.13 vol% O ₂ , 0.03 vol% CH ₄ , 0.02 vol% H ₂ O	Orifice meter traceable to water	Brown and Chinello [17]	
$u(\dot{m}_{CO_2})_{m_{gas}} \geq \pm 0.25\%$	27 and 37	Ambient	5688 -44010 kg/h	Pure CO ₂	Secondary working standards	Chinello and Brown [69]	
$u(\dot{m}_{CO_2})_{m_{liq}} \geq \pm 0.16\%$	<72	20 – 30	250 - 3600 kg/h	Pure CO ₂	Gravimetric primary standard	Sun et al. [44]	
$u(\dot{Q}_{mix})_{m_{gas}} \geq \pm 0.2\%$	28 and 38	Ambient	65 – 750 m ³ /h	99.82 % vol CO ₂ , 0.13 % O ₂ , 0.03 % CH ₄ , 0.02 % H ₂ O.	Turbine meter traceable to natural gas	Chinello et al. [14]	Ultrasonic meter. Adjusted K-factor [14]
$u(\dot{Q}_{mix})_{m_{liq}} \geq \pm 0.65\%$	25-70	-20 – 20	75 – 270 kg/h	99.82 % vol CO ₂ , 0.13 % O ₂ , 0.03 % CH ₄ , 0.02 % H ₂ O.	Orifice meter	Brown and Chinello [17]	Ultrasonic meter. Uncertainties are based on intercomparison tests [17]
$u(\dot{Q}_{CO_2})_{m_{gas}} \geq \pm 0.15\%$	3 - 32	N/A	N/A	Pure CO ₂	Sonic nozzles traceable to a gravimetric system	George et al. [53]	Turbine meter [17] [14]
$u(x_{CO_2,wt})_m \geq 0.027\%$	7 – 182	-50 - 30	N/A	57-100 % mol CO ₂ 43 – 0 % mol N ₂	GC calibrated against gravimetrically prepared calibration gas mixtures	Westman et al. [26]	Gas chromatograph [14]
$u(\rho_{mix})_{m_{gas}} \geq \pm 1\%$	16 – 34	Ambient	50 - 1000 m ³ /h 550 - 60000 kg/h	(a) 95 % CO ₂ + 5 % NG (b) 99.3 % CO ₂ with 0.7 % NG	Secondary working standards	van Putten et al. [8]	Coriolis meter tests compared to GERG-2008 [8].



$u(\rho_{mix})_{mliq} \geq \pm 0.2 \%$	25-70	-20 – 20	800-1020 kg/m ³	99.82 % vol CO ₂ , 0.13 % O ₂ , 0.03 % CH ₄ , 0.02 % H ₂ O.	Orifice meter	Brown and Chinello [17]	Compared to GERG-2008 for the given mixture [17]
$u(\rho_{CO_2})_{m_{gas}} \geq \pm 7.7\%$	11-49	17-21	9-127.4 kg/m ³	Pure CO ₂	GERG EoS (validated for mixtures with an Anton Parr density meter at a 2.8 % AARD in gas)	Nazeri et al. [184]	Average Absolute Relative Deviation (after corrections) from GERG EoS [184] The reported errors are higher than reported for mixtures. Thus when more experimental information is available, the uncertainty figure should be revised.
$u(\rho_{CO_2})_{mliq} \geq \pm 0.3\%$	30-80	-6 – 21	814 – 976 kg/m ³	Pure CO ₂	Span-Wager EoS	Arellano et al. [115]	CO ₂ calibrated gamma densitometer measurements compared to S-W EoS [115]
$u(\rho_{mix})_{EoS} \geq \pm 0.08 \%$	1 – 700	-10 – 150	N/A	8 datasets with 28 mixtures containing CO ₂ , H ₂ , N ₂ , Ar, CO, O ₂ , SO ₂ CH ₄ – iC ₄ H ₁₀	GERG-2008	Vitali et al. [70]	The reported accuracy is the minimum Mean Average Absolute Deviation for two datasets (CO ₂ – Ar and CO ₂ – N ₂). Large deviations were evidenced in mixtures with H ₂ , the Weighted Arithmetic Mean for all 8 datasets. is 1.18% [70]
$u(\rho_{CO_2})_{EoS} \geq \pm 0.03\%$	5 - 73	-56 – 31	14 - 382 kg/m ³ (gas) 507 - 1177 kg/m ³ (liq)	Pure CO ₂	Measuring cell and saturated densities method by Duschek et al [185]	Span Wager EoS [43]	Test conditions from Duschek <i>et al.</i> [185] used to develop the saturated Liquid and vapour density equations for W-S EoS

APPENDIX C – Measurement error reduction methods

Offline systematic and random error assessment for single flowmeters

This appendix reports the proposed method to assess the magnitude of the systematic and random errors offline.

The following proposed procedure allows the user to assess the systematic error of a single flowmeter:

- 1) Select a sufficiently high number of flow rates' values K to be tested.
- 2) Let $k = 1$.
- 3) Randomly select a value of flow rate θ_k within the interval $[\theta_{\min}, \theta_{\max}]$.
- 4) Test the flowmeter at θ_k by acquiring J_k measurements $\dot{m}_{j,k}$, with $j = 1, \dots, J_k$.
- 5) Estimate the bias corresponding to the mass flow rate θ_k :

$$b_{\theta_k} \approx \frac{1}{J_k} \sum_{j=1}^{J_k} \dot{m}_{j,k} - \theta_k$$

- 6) Let $k \leftarrow k + 1$.
- 7) If $k \leq K$, return to point 3; otherwise, proceed to point 8.
- 8) Compute the approximated expected bias:

$$b \approx \frac{1}{K} \sum_{k=1}^K b_{\theta_k}$$

This is equivalent to assuming a *prior probability density function* $p(\theta)$ and setting the corrective factor equal to the expected bias. Such a prior does not reflect the actual behaviour of θ and must be interpreted as a subjective belief [186]. It is here recommended to assume $\theta \sim \mathcal{U}_{[\theta_{\min}, \theta_{\max}]}$, meaning a *continuous uniform density function* with support $[\theta_{\min}, \theta_{\max}]$. What just described is the step-by-step procedure necessary to approximate the expected bias, which has the following shape:

$$b = \mathbb{E}(b_{\theta}) = \int [\mathbb{E}(\dot{m}|\theta) - \theta] p(\theta) d\theta \approx \frac{1}{K} \sum_{k=1}^K \left(\frac{1}{J_k} \sum_{j=1}^{J_k} \dot{m}_{j,k} - \theta_k \right)$$

where $\mathbb{E}(\cdot | \cdot)$ is the conditional expected value. Such a mismatch between the theoretical and the experimental value becomes negligible as the overall number of tests increases.

On the other hand, the proposed procedure for the offline assessment of the random errors is the following:

- 1) Select a sufficiently high number of flow rates' values K to be tested.
- 2) Let $k = 1$.
- 3) Randomly select a value of flow rate θ_k within the interval $[\theta_{\min}, \theta_{\max}]$.
- 4) Test the flowmeter at θ_k by acquiring J_k measurements $\dot{m}_{j,k}$, with $j = 1, \dots, J_k$.
- 5) Estimate the variance corresponding to the mass flow rate θ_k :

$$u_{\theta_k}^2 \approx \frac{1}{J_k - 1} \sum_{j=1}^{J_k} \left(\dot{m}_{j,k} - \frac{1}{J_k} \sum_{j=1}^{J_k} \dot{m}_{j,k} \right)^2$$

- 6) Let $k \leftarrow k + 1$.

- 7) If $k \leq K$, return to point 3; otherwise, proceed to point 8.
- 8) Compute the approximated expected variance:

$$u^2 \approx \frac{1}{K} \sum_{k=1}^K u_{\theta_k}^2$$

As before, we have assumed a prior probability density function $p(\theta)$. This was the procedure to approximate the expected variance, which has the following shape:

$$u^2 = \mathbb{E}(u_{\theta}^2) = \int \text{Var}(\dot{m}|\theta) p(\theta) d\theta \approx \frac{1}{K} \sum_{k=1}^K \left[\frac{1}{J_k - 1} \sum_{j=1}^{J_k} \left(\dot{m}_{j,k} - \frac{1}{J_k} \sum_{j=1}^{J_k} \dot{m}_{j,k} \right)^2 \right]$$

where $\text{Var}(\cdot | \cdot)$ is the conditional variance. Also here, the mismatch between the theoretical and the experimental value becomes negligible as the overall number of tests increases.

Online filter for single flowmeters (EMA filter)

This appendix analyses the statistical properties of the EMA filter when applied to a single flowmeter. At the generic N th instant, the EMA filter for single flowmeters provides a value of $\dot{m}_{\text{EMA}}[N]$ that depends on all the values in the vector $\dot{\mathbf{m}}[N]$. This means that $\dot{m}_{\text{EMA}}[N]$ is an attempt to estimate the true value $\theta[N]$ even by taking advantage of measurements that were recorded when the flow rate was different from $\theta[N]$. This typically results in a biased estimate, meaning that $\mathbb{E}(\dot{m}_{\text{EMA}}[N]) \neq \theta$, for any $N > 1$:

$$\mathbb{E}(\dot{m}_{\text{EMA}}[N]) = \begin{cases} \theta[1], & N = 1 \\ \lambda \theta[N] + (1 - \lambda) \mathbb{E}(\dot{m}_{\text{EMA}}[N - 1]), & N > 1 \end{cases}$$

Two main considerations regarding the biased nature of the filter can be made. First, let us rewrite the algorithm at a generic instant $N \geq M > 1$:

$$\dot{m}_{\text{EMA}}[N] = \lambda \sum_{n=M}^N (1 - \lambda)^{N-n} \dot{m}[n] + (1 - \lambda)^{N-M+1} \dot{m}_{\text{EMA}}[M - 1]$$

If the flow rate at the M th instant has stabilized at a constant value θ , then we have the following expected value:

$$\begin{aligned} \mathbb{E}(\dot{m}_{\text{EMA}}[N]) &= \lambda \sum_{n=M}^N (1 - \lambda)^{N-n} \mathbb{E}(\dot{m}[n]) + (1 - \lambda)^{N-M+1} \mathbb{E}(\dot{m}_{\text{EMA}}[M - 1]) \\ &= \lambda \theta \frac{1 - (1 - \lambda)^{N-M+1}}{\lambda} + (1 - \lambda)^{N-M+1} \mathbb{E}(\dot{m}_{\text{EMA}}[M - 1]) \\ &= \theta + (1 - \lambda)^{N-M+1} (\mathbb{E}(\dot{m}_{\text{EMA}}[M - 1]) - \theta) \end{aligned}$$

where the constant flow rate allowed us to write that $\mathbb{E}(\dot{m}[n]) = \theta$, for all $n \geq M$, and where we exploited the presence of a geometric series. From this result, one can see that the bias at the N th instant is proportional to the expected error between $\dot{m}_{\text{EMA}}[M - 1]$ and θ , with $(1 - \lambda)^{N-M+1}$ as a proportionality coefficient. This leads to the conclusion that when the flow rate stabilizes, the EMA filter becomes asymptotically unbiased:

$$\lim_{N \rightarrow \infty} \mathbb{E}(\dot{m}_{\text{EMA}}[N]) = \lim_{N \rightarrow \infty} [\theta + (1 - \lambda)^{N-M+1} (\mathbb{E}(\dot{m}_{\text{EMA}}[M - 1]) - \theta)] = \theta$$

This leads to the second, now more intuitive observation that, for the case of a constant value of flow rate $\theta = \theta[1] = \dots = \theta[N]$, the filter is always an unbiased estimator. This can be easily

proven by direct application of the expected value to the filter's function:

$$\mathbb{E}(\dot{m}_{\text{EMA}}[N]) = \begin{cases} \theta, & N = 1 \\ \lambda \theta + (1 - \lambda) \mathbb{E}(\dot{m}_{\text{EMA}}[N - 1]), & N > 1 \end{cases}$$

where the constant flow rate allowed us to write also that $\mathbb{E}(\dot{m}[n]) = \theta$. Such an equation is a *linear first-order difference equation with constant coefficients* with shape $x[n] = a x[n - 1] + b$ and initial condition $x[1] = c$, which has the following solution $x[n] = a^{n-1} \left(c - \frac{b}{1-a} \right) + \frac{b}{1-a}$ [187]. When applying this to our case, we obtain:

$$\mathbb{E}(\dot{m}_{\text{EMA}}[N]) = (1 - \lambda)^{N-1} \left(\theta - \frac{\lambda \theta}{1 - (1 - \lambda)} \right) + \frac{\lambda \theta}{1 - (1 - \lambda)} = \theta$$

The variance of the filter's estimate can be easily obtained by following a procedure similar to the expected value by exploiting the solution of linear first-order difference equations. Moreover, we can drop the assumption of constant flow rate. This leads to the following variance at the N th instant:

$$\begin{aligned} \text{Var}(\dot{m}_{\text{EMA}}[N]) &= \begin{cases} \text{Var}(\dot{m}[1]), & N = 1 \\ \text{Var}(\lambda \dot{m}[N] + (1 - \lambda) \dot{m}_{\text{EMA}}[N - 1]), & N > 1 \end{cases} \\ &= \begin{cases} u^2, & N = 1 \\ \lambda^2 u^2 + (1 - \lambda)^2 \text{Var}(\dot{m}[N - 1]), & N > 1 \end{cases} \\ &= (1 - \lambda)^{2(n-1)} \left(u^2 - \frac{\lambda^2 u^2}{1 - (1 - \lambda)^2} \right) + \frac{\lambda^2 u^2}{1 - (1 - \lambda)^2} \\ &= u^2 \left(\frac{2(1 - \lambda)^{2(N-1)}}{2 - \lambda} + \frac{\lambda}{2 - \lambda} \right) \end{aligned}$$

where we exploited $\text{Cov}(\dot{m}_{\text{EMA}}[n], \dot{m}_{\text{EMA}}[m]) = 0$, for all n and m , with $n \neq m$.

Two main observations accompany this result. First, the result highlights that the filter's variance is conveniently independent of the value of $\theta[N]$, which allows us to claim the same result even when the flow is not in steady-state conditions. Lastly, one can notice that as N increases, the variance of the filter tends to converge toward a fixed value:

$$\lim_{N \rightarrow \infty} \text{Var}(\dot{m}_{\text{EMA}}[N]) = \lim_{N \rightarrow \infty} \left[u^2 \left(\frac{2(1 - \lambda)^{2(N-1)}}{2 - \lambda} + \frac{\lambda}{2 - \lambda} \right) \right] = u^2 \frac{\lambda}{2 - \lambda}$$

where the first inequality turns into an equation for $N = 1$.

The following is the suggested procedure for selecting λ for a specific flowmeter. This method requires a computer simulation:

- 1) Simulate a flow rate $\theta[n]$, with $n = 1, \dots, N$, with samples generated with the same frequency as the flowmeter's sampling frequency.
- 2) Simulate the flowmeter's reading by adding noise $\dot{m}[n] = \theta[n] + w[n]$, with $\mathbb{E}(w[N]) = 0$ and $\text{Var}(w[N]) = u^2$ (other distributions than the normal distribution can be used if necessary), for all $n = 1, \dots, N$.
- 3) Select a sufficiently high number of values of $\lambda \in (0, 1)$ to be tested and indicate them with λ_k , with $k = 1, \dots, K$.
- 4) Let $k = 1$.
- 5) Run the EMA filter with λ_k on the synthetic measurements $\dot{m}[n]$'s.
- 6) Estimate the MSE:

$$\text{MSE}_k \approx \frac{1}{N} \sum_{n=1}^N (\dot{m}_{\text{EMA}}[n] - \theta[n])^2$$

- 7) Let $k \leftarrow k + 1$.
- 8) If $k \leq K$, return to point 5; otherwise, proceed to point 9.
- 9) Select the value λ that minimizes the MSE.

Online filter for multiple flowmeters

First Method

For multiple flowmeters the reading of the mass flow rate θ_t , for any continuous-time t , can be reformulated as the measurement of the generic i th flowmeter, with $i = 1, \dots, I$:

$$\dot{m}^{(i)} [N_t^{(i)}] = \theta_t + w^{(i)} [N_t^{(i)}]$$

where $N_t^{(i)}$ is the number of measurements done by the i th flowmeter as of time t , with uncorrelated noise samples $w^{(i)} [N_t^{(i)}]$'s between the flowmeters. Here, we introduce the benefits of averaging the flowmeter's measurements followed by the filtering process. The weighted average of the measurements at the generic continuous time t can be defined as:

$$\begin{aligned} \dot{m}_t^{(\text{mean})} &= \sum_{i=1}^I \left(\frac{\dot{m}^{(i)} [N_t^{(i)}]}{\text{Var}(\dot{m}^{(i)} [N_t^{(i)}])} \right) / \sum_{i=1}^I \left(\frac{1}{\text{Var}(\dot{m}_{\text{EMA}}^{(i)} [N_t^{(i)}])} \right) \\ &= \sum_{i=1}^I \frac{\dot{m}^{(i)} [N_t^{(i)}]}{u_i^2} / \sum_{i=1}^I \frac{1}{u_i^2} \end{aligned}$$

In other words, $\dot{m}_t^{(\text{mean})}$ is defined as the weighted average of the flowmeter's last available reading at time t using the inverse of the flowmeter's variances as weights. This allows us to handle flowmeters with different sampling frequencies. Of course, forcing $\dot{m}_t^{(\text{mean})}$ to be the average of readings taken at various times adds an unknown bias contribution to the estimator. This is not the case for steady-state conditions or perfectly synchronized flowmeters, and it becomes negligible at sufficiently high sampling frequencies. Because of this reason, we can only see this estimate as a weighted LSE estimator, with no further claims on optimality.

Let us discretize the values of $\dot{m}_t^{(\text{mean})}$ and θ_t :

$$\begin{cases} \dot{m}^{(\text{mean})} [N_t^{(\text{mean})}] \triangleq \dot{m}_t^{(\text{mean})} \\ \theta [N_t^{(\text{mean})}] \triangleq \theta_t \end{cases}$$

where $N_t^{(\text{mean})}$ is the number of times that $\dot{m}_t^{(\text{mean})}$ updated its value as of time t . This is helpful

to define the consequent filtering procedure applied to $\dot{m}^{(\text{mean})}$ and whose result is indicated with $\dot{m}_{\text{EMA},t}^{(\text{mean})}$:

$$\dot{m}_{\text{EMA},t}^{(\text{mean})} = \begin{cases} \dot{m}^{(\text{mean})}[1], & N_t^{(\text{mean})} = 1 \\ \lambda_{\text{mean}} \dot{m}^{(\text{mean})} [N_t^{(\text{mean})}] + (1 - \lambda_{\text{mean}}) \dot{m}^{(\text{mean})} [N_t^{(\text{mean})} - 1], & N_t^{(\text{mean})} > 1 \end{cases}$$

where λ_{mean} is the EMA's coefficient. As previously stated, in the case of non-steady-state conditions, the individual measurement $\dot{m}_{\text{EMA},t}^{(\text{mean})}$ has an unknown bias due to the biased nature of the EMA filter as well as to the previously mentioned bias contribution given by $\dot{m}_t^{(\text{mean})}$.

We can now assess the variance of the resulting $\dot{m}_{\text{EMA},t}^{(\text{mean})}$. For the sake of simplicity, let us assume that the meters are perfectly synchronized. First, we obtain the variance of the average measurement $\dot{m}_t^{(\text{mean})}$:

$$\mathbb{Var}(\dot{m}_t^{(\text{mean})}) = 1 / \sum_{i=1}^I \frac{1}{u_i^2}$$

which is conveniently independent of time. Then, we can find the variance of the filter:

$$\mathbb{Var}(\dot{m}_{\text{EMA},t}^{(\text{mean})}) = \left(1 / \sum_{i=1}^I \frac{1}{u_i^2} \right) \left(\frac{2(1 - \lambda_{\text{mean}})^{2(N_t^{(\text{mean})} - 1)}}{2 - \lambda_{\text{mean}}} + \frac{\lambda_{\text{mean}}}{2 - \lambda_{\text{mean}}} \right)$$

As $t \rightarrow \infty$, one can write the asymptotic variance:

$$\lim_{t \rightarrow \infty} \mathbb{Var}(\dot{m}_{\text{EMA},t}^{(\text{mean})}) = \left(1 / \sum_{i=1}^I \frac{1}{u_i^2} \right) \frac{\lambda_{\text{mean}}}{2 - \lambda_{\text{mean}}}$$

It is easy to notice the decrease in variance compared to a single EMA filter:

$$\mathbb{Var}(\dot{m}_{\text{EMA},t}^{(\text{mean}_2)}) < \mathbb{Var}(\dot{m}_{\text{EMA},t}^{(j)})$$

This is true because, if we set $\lambda_{\text{mean}} = \lambda_j$ (without loss of generality), the inequality becomes

$1/\sum_{i=1}^I \frac{1}{u_i^2} < u_j^2$, which is always true. If no significant additional bias is generated by ensuring sufficiently high sampling frequencies (or perfectly synchronized flowmeters), the decrease in variance is sufficient proof to state that averaging the filter's measurements and then adding an EMA filter is a viable way to reduce measurement errors.

As before, the choice of λ_{mean} is fundamental to ensure an optimal bias-variance trade-off. The following procedure is here outlined (based on the previously described procedure for single flowmeters):

- 1) Simulate a continuous flow rate θ_t .
- 2) For each i th meter, simulate the flowmeter's reading by adding noise $\dot{m}^{(i)}[N_t^{(i)}] = \theta_t + w[N_t^{(i)}]$, with $\mathbb{E}(w[N_t^{(i)}]) = 0$ and $\text{Var}(w[N_t^{(i)}]) = u_i^2$ (other distributions than the normal distribution can be used if necessary). The readings must be recorded at the flowmeter's sampling frequencies, and they must be paired with their corresponding acquisition time $(\dot{m}^{(i)}[N_t^{(i)}], t)$.
- 3) Compute the average readings $(\dot{m}^{(\text{mean})}[N_t^{(\text{mean})}], t)$.
- 4) Select a sufficiently high number of values of $\lambda_{\text{mean}} \in (0,1)$ to be tested and indicate them with λ_k , with $k = 1, \dots, K$.
- 5) Let $k = 1$.
- 6) Simulate the EMA filter with λ_k on the synthetic measurements $(\dot{m}^{(\text{mean})}[N_t^{(\text{mean})}], t)$'s with $N_t^{(\text{mean})} = 1, \dots, N$.
- 7) Estimate the MSE:
$$\text{MSE}_k \approx \frac{1}{N} \sum_{N_t^{(\text{mean})}=1}^N (\dot{m}^{(\text{mean})}[N_t^{(\text{mean})}] - \theta[N_t^{(\text{mean})}])^2$$
- 8) Let $k \leftarrow k + 1$.
- 9) If $k \leq K$, return to point 6; otherwise, proceed to point 10.
- 1) Select the value λ_{mean} that minimizes the MSE.

Second Method

Alternatively, one can benefit from averaging the EMA's filters associated with each flowmeter. The filtered measurement associated with the generic i th flowmeter at the generic continuous-time t can be defined as:

$$\dot{m}_{\text{EMA},t}^{(i)} \triangleq \dot{m}_{\text{EMA}}^{(i)}[N_t^{(i)}]$$

In other words, $\dot{m}_{\text{EMA},t}^{(i)}$ is defined as the i th flowmeter's last available EMA's value at time t . This allows us to handle flowmeters with different sampling frequencies. Forcing the value $\dot{m}_{\text{EMA},t}^{(i)}$ to be constant in the time interval that goes from the $(N_t^{(i)})$ th to the $(N_t^{(i)} + 1)$ th measurement adds an unknown bias contribution to the estimator. Analogously to the previously shown method, this is not the case for steady-state conditions or perfectly synchronized flowmeters, and it is negligible for sufficiently high sampling frequencies.

At any time t , we can define a weighted mean measurement $\dot{m}_{\text{EMA},t}^{(\text{mean}_2)}$ that accounts for each flowmeter's last EMA's value and the inverse of their variance as a weight, resulting in the

following weighted LSE estimator:

$$\begin{aligned}\dot{m}_{\text{EMA},t}^{(\text{mean}_2)} &= \sum_{i=1}^I \left(\frac{\dot{m}_{\text{EMA},t}^{(i)}}{\text{Var}(\dot{m}_{\text{EMA},t}^{(i)})} \right) / \sum_{i=1}^I \left(\frac{1}{\text{Var}(\dot{m}_{\text{EMA},t}^{(i)})} \right) \\ &= \sum_{i=1}^I \left(\frac{\dot{m}_{\text{EMA},t}^{(i)} (2 - \lambda_i)}{u_i^2 (2 (1 - \lambda_i)^{2(N_t^{(i)} - 1)} + \lambda_i)} \right) / \sum_{i=1}^I \left(\frac{2 - \lambda_i}{u_i^2 (2 (1 - \lambda_i)^{2(N_t^{(i)} - 1)} + \lambda_i)} \right)\end{aligned}$$

where u_i^2 and λ_i are the variance and the EMA's coefficient of the i th flowmeter, respectively.

As previously stated, in the case of steady-state conditions, the individual measurements $\dot{m}_{\text{EMA},t}^{(i)}$'s have an unknown bias due to the biased nature of the EMA filter as well as to the previously mentioned contribution. The variance of $\dot{m}_{\text{EMA},t}^{(\text{mean}_2)}$ is readily given:

$$\text{Var}(\dot{m}_{\text{EMA},t}^{(\text{mean}_2)}) = 1 / \sum_{i=1}^I \left(\frac{2 - \lambda_i}{u_i^2 (2 (1 - \lambda_i)^{2(N_t^{(i)} - 1)} + \lambda_i)} \right)$$

As $t \rightarrow \infty$, one can write the asymptotic variance:

$$\lim_{t \rightarrow \infty} \text{Var}(\dot{m}_{\text{EMA},t}^{(\text{mean}_2)}) = 1 / \sum_{i=1}^I \left(\frac{2 - \lambda_i}{u_i^2 \lambda_i} \right)$$

It is easy to notice the decrease in variance compared to a single EMA filter:

$$\text{Var}(\dot{m}_{\text{EMA},t}^{(\text{mean}_2)}) = \left(\frac{1}{\text{Var}(\dot{m}_{\text{EMA},t}^{(j)})} + \sum_{\substack{i=1 \\ i \neq j}}^I \left(\frac{1}{\text{Var}(\dot{m}_{\text{EMA},t}^{(i)})} \right) \right)^{-1} < \text{Var}(\dot{m}_{\text{EMA},t}^{(j)})$$

If no significant additional bias is generated by ensuring sufficiently high sampling frequencies (or perfectly synchronized flowmeters), the decrease in variance is sufficient proof to state that averaging the filter's results is a possible way to reduce measurement errors.

This alternative method has the advantage of being able to be implemented on the fly as it merely averages a number I of independent filters' outputs, making it a flexible option. However, it is expected to be less reliable than the first method.

Other real-time techniques

- **Holt Linear Method:** Also known as second exponential smoothing, this method is an evolution of the EMA. While the EMA does not perform well when in non-steady-state conditions, the Holt Method allows linear trends in the flow rate $\theta[n]$ to be captured [132].
- **Holt-Winters Method:** Also known as triple exponential smoothing, this is a further evolution of the EMA. The Holt-Winters Method allows low-frequency components in the flow rate $\theta[n]$ to be captured. The algorithm is not reported here but follows the same exponential smoothing philosophy seen in the previous two methods [132, 136].
- **Stochastic Time-Series Models:** Various ARIMA models and their evolutions are available, and their use can be evaluated. While EMA, the Holt Model, and the Holt-Winters Model are based on reasonable assumptions of volatility, linear trend, and

seasonality, more complex ARIMA models (and their evolutions) might account for assumptions that cannot easily be verified [137].

- **Recursive Least Squares Filter:** This filter recursively minimizes the LSE cost function. Especially in the version named *Generalized Forgetting Recursive Least Squares Filter*, it is possible to additionally model correlations both over time and between the flowmeters. However, the computational complexity of such a solution and the potential difference in sampling frequencies between the meters might hinder using this solution, which also requires extensive data to estimate the covariance matrixes [138].
- **Kalman Filter:** This filter is an algorithm that provides estimates of unknown variables by predicting and updating state information over time, optimal for linear systems with Gaussian noise. Its derivatives, like the *Extended Kalman Filter* (EKF) and *Unscented Kalman Filter* (UKF), handle nonlinear systems. These filters are particularly useful in filtering multivariate time series data, efficiently estimating the evolving state of dynamic systems, improving predictions in complex, noisy environments [130].

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