21GRD06 MetCCUS

D2 - Good practice guide for CCS fiscal metering, including recommendations to advance the application of CCS fiscal metering solutions, which will contribute to traceable and accurate flow measurement (uncertainties below 2.5 %)

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Due date of the deliverable: September 2025

Actual submission date of the deliverable: September 2025

Confidentiality Status: PU - Public, fully open (remember to deposit public deliverables in a trusted repository)

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European Partnership Co-funded by the European Union

METROLOGY PARTNERSHIP EURAMET

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

Glossary

BPV_p	Base prover volume
c	Speed of sound in the fluid
$CO_{2(e)}$	CO_2 equivalent
CTL_m	Temperature correction factors at the meter under test
CPL_m	Pressure correction factors at the meter under test
CTL_p	Correction factor for liquid temperature at the prover
CPL_p	Correction factor for liquid pressure at the prover
CPS_p	Correction factor for steel pressure at the prover
CTS_p	Correction factor for steel temperature at the prover
E_m	Velocity of sound (VoS) effect
f_0	Natural frequency of Coriolis tube vibration
p	Pressure
r	Tube radius
SF	Scale factor determined based on meter construction
S_p^*	Relative sensitivities of density to pressure
S_T^*	Relative sensitivities of density to temperature
S_y^*	Sensitivity of density to variable *y*
T	Temperature
U^*	Relative uncertainty
$V_{F,ref}$	Calibrated reference volume at the reference meter
x_i	Mole content of substance *i* in the mixture
ρ	Density

TABLE OF CONTENTS

Executive summary 4
Scope and Introduction 4
1. Concepts, terms and definitions 4
  1.1 Measurement 4
  1.2 Flow rate measurement 5
  1.3 Fiscal metering 5
  1.4 Uncertainty 5
  1.5 Measuring system 5
  1.6 Accuracy 5
  1.7 Repeatability 5
  1.8 CO_2 phase 5
  1.9 CO_2 dense phase 5
  1.10 Nominal Flow rate 5
  1.11 Turndown ratio 6
2. Introduction to flow measurement principles 6
  2.1 Mass flow meters 6
2.1.1 Coriolis 6
  2.2 Volumetric flow meters 6
2.2.1 Ultrasonic 6
2.2.2 Turbine 6
  2.3 Differential pressure meters 6
3. Selection of a Fiscal Meter 6
  3.1 Note on instrument data sheet interpretation 7
  3.2 Standards and regulations 8
3.2.1 Relevant regulation for flow metering and allocation for CCUS systems as per EU ETS (Norway/UK) 8
3.2.2 Flow metering standards and guidelines for CCUS systems 10
3.2.3 Other relevant standards 12
3.2.4 Flow calibration 13
3.2.5 Advances in Standardisation Bodies 14
4. Performance and calibration 14
  4.1 Calibration and traceability 14
  4.2 Flow reference principles 15
4.2.1 Gravimetric Primary Reference 15
4.2.2 Volumetric Provers 16
4.2.3 Other reference meters 17
  4.3 Calibration uncertainty 18
4.3.1 Primary reference (volume prover) 18
4.3.2 Bootstrapping 19
  4.4 Calibration with proxy fluids 19
  5. Recommended Practices in CO_2 Fiscal Metering 20
  5.1 General recommendations 20
  5.2 Thermophysical properties and Equations of States (EOS) 20
  5.3 Fluid phase 21
  5.4 Temperature and Pressure conditions 22
  5.5 Sampling 23
  5.6 Practical recommendations for specific types of meters 23
5.6.1 Coriolis 23
5.6.2 Turbine 25
5.6.3 Differential Pressure (DP) 25

5.6.4 Ultrasonic 26
Summary of recommendations 27
References 29
Appendix - Phase envelope diagrams 34

Executive summary

This report, developed under the MetCCUS project, provides a comprehensive good practice guide for fiscal metering in Carbon Capture, Utilisation, and Storage (CCUS) systems. Accurate and traceable CO_2 flow measurement is essential for regulatory compliance, emissions accounting, and commercial transactions across the CCUS value chain.

The document addresses the selection, implementation, and calibration of fiscal metering systems, focusing on both technical and regulatory aspects. It evaluates key metering technologies—Coriolis, ultrasonic, differential pressure, and turbine meters—highlighting their performance under various CO_2 conditions. The guide also explores the influence of thermophysical properties, fluid composition, and phase behaviour on measurement accuracy.

Key contributions include:

- Guidance on managing measurement uncertainty, calibration traceability, and system design.
- An overview of relevant international standards and regulatory frameworks (EU ETS, MID, OIML, ISO, API).
- Recommendations for calibration methods, including the use of primary standards and proxy fluids.
- Practical advice for ensuring single-phase flow, impurity monitoring, and inline phase detection.

The report integrates lessons learned from recent research and standardisation efforts, offering actionable insights for stakeholders involved in the deployment of fiscal metering systems in CCUS projects.

Scope and Introduction

This document serves as a good practice guide for the selection and use of fiscal meters in CCUS applications, drawing on both established knowledge and the authors' direct experience. It is designed to facilitate the commercial deployment of fiscal metering technologies by providing insights into the technical, legal, and regulatory frameworks governing CCUS metering.

The guide outlines operational provisions for CCUS fiscal metering and incorporates lessons from the development of new flow standards and calibration facilities. It aims to support stakeholders in making informed decisions about metering technologies, ensuring compliance with regulatory requirements, and achieving accurate and traceable CO_2 flow measurements across the CCUS value chain.

1. Concepts, terms and definitions

1.1 Measurement

The Guide to the expression of uncertainty in measurement (JCGM 100:2008) [1] defines a measurement as the value of the particular quantity to be measured. A measurement encompasses an appropriate specification of the measurand, the method of measurement, and the measurement procedure.

1.2 Flow rate measurement

Flow rate measurement is the quantification of the rate of flow of materials. Flow can be measured in terms of its gravimetric or volumetric quantities. A flow rate measurement in terms of the mass flow rate is preferred for CCUS applications, given that CO_2 is traded in mass [2]. This means that if volumetric flow is measured, volume-to-mass flow conversion is needed.

1.3 Fiscal metering

Fiscal metering is the quantative measurement of a material when the material is subjected to a fiscal transaction, i.e., custody transfers, cross-border transport, buying and selling, and for calculation of taxes, credits, and liability.

1.4 Uncertainty

The result of a measurement is only an approximation or estimate of the value of the measurand and thus is complete only when accompanied by a statement of the uncertainty of that estimate [3]. The expression of uncertainty characterises the dispersion of the values that could reasonably be attributed to the measurand, which may be, for example, a standard deviation, or the half-width of an interval having a stated level of confidence.

1.5 Measuring system

Set of one or more measuring instruments assembled and adapted to give information used to generate measured quantity values within specified intervals for quantities of specified kinds [3].

1.6 Accuracy

The definition of accuracy from [3] defines accuracy as a qualitative term. Thus, unlike uncertainty, it cannot be quantified with a number. Accuracy can be expressed as high or low.

1.7 Repeatability

VIM [3] defines measurement repeatability as the precision under a set of repeatable measurements. Such precision is expressed numerically by means of imprecision, such as standard deviation, variance, or coefficient of variation, under specified measurement conditions. There are various definitions on how repeatability can be calculated, thus when repeatability is declared, the method should be stated (see section 5.1 – interpretation of uncertainty).

1.8 CO_2 phase

The CO_2 has four thermodynamic phases: solid, gas, liquid, and supercritical (see Annex).

1.9 CO_2 dense phase

The term dense phase is an engineering term widely used in the CCUS community. It is relevant to highlight that there is little agreement on the limits of the dense phase. As such, different standards classify dense phase differently; ISO 27913:2024 define dense phase as “the single-phase fluid state above a density of 500 kg/m^3”, thus encompassing the thermodynamic liquid phase and a portion of the thermodynamic supercritical phase. The API RP11CO2 draft document defines dense phase as “a fluid being transported by pipeline including either liquid or supercritical CO_2”.

1.10 Nominal Flow rate

In metrology, the nominal flow rate of a flow meter refers to the flow rate range at which the meter is designed to operate with optimal accuracy and repeatability under normal conditions.

1.11 Turndown ratio

The turndown ratio of a flow meter refers to the ratio between the maximum and minimum measurable or controllable flow rate range within which the meter can maintain its specified accuracy. In this sense, a higher turndown ratio means a wider range of measurable values with consistent accuracy.

2. Introduction to flow measurement principles

2.1 Mass flow meters

2.1.1 Coriolis

Coriolis meters provide direct mass measurement via resonating measuring tubes. The forces exerted by the tubes on the flowing fluid are proportional to the inertia and to the mass flow. Coriolis flow meters also provide a direct measurement of the density via the relationship between the resonant frequency of the measuring tube and the mass of the fluid inside. The ISO 10790:2015 [4] provides a concise summary of this relationship. ISO 10790:2015 also provides guidance regarding the selection, installation, and use of Coriolis flowmeters.

2.2 Volumetric flow meters

2.2.1 Ultrasonic

Transit-time ultrasonic meters measure the flow velocity from the difference in time for a signal to travel through the fluid in the upstream and downstream directions. Transit-time ultrasonic flow meters usually have multiple paths, where a variety of multipath configurations are available in the market. Ultrasonic flow meters for the measurement of gas flows are covered by ISO 17089–1:2019 [5] and for the measurement of liquid flows by ISO 12242:2012 [6].

2.2.2 Turbine

Turbine meters convert the mechanical work of a turbine rotating inside the flow stream into a volumetric flow rate, where the rotation speed is proportional to the fluid velocity. The ISO 2715:2017 covers their application for liquid hydrocarbons, and the ISO 9951:1993 covers gas flow measurement. EN 12261:2024 is a more updated standard for gas turbines [7].

2.3 Differential pressure meters

Differential pressure-based meters do not directly measure mass flow or volumetric flow and require the density as input. These encompass orifice, V-cone, and Venturi meters. In differential pressure meters, the difference in pressure is related to the flow rate across a constricted geometry, i.e., orifice or throat. The accuracy of these meters depends on the accuracy of the differential pressure measurements and the accuracy of fluid properties. Orifice meters, Venturi tubes, and V-cones are covered by the ISO 5167:2022 [8].

3. Selection of a Fiscal Meter

Factors relevant to consider when selecting a fiscal measurement system include:

Mass or volumetric – When selecting a measurement method, it is best to select one that directly quantifies the parameter of interest. For CCUS, using volumetric flow meters requires converting volume to mass, which introduces additional uncertainties. These uncertainties arise from (i) density calculations, which depend on accurate measurements of composition, temperature, and pressure, as well as a reliable equation of state across the full range of operating conditions, or (ii) density measurement uncertainties, including sampling errors if density is not measured in-line. Importantly, composition uncertainties affect both direct mass measurements and volume-to-mass conversions. Since composition analysis often involves sampling followed by either on-line or off-line analytical methods, these steps can be significant contributors to overall measurement uncertainty.

Range – Different types of measurement technologies typically have different turndown ratios. It is best to avoid using a meter at the upper or lower extreme of its range of measurement. Variations in process and ambient conditions, particularly pressure and temperature, should also be considered. Insulation and temperature compensation can be critical to achieving accurate measurements, especially in low-temperature applications such as those encountered in carbon dioxide shipping.

Phase—The composition and thermodynamic phase of the working fluid are critical factors in CCUS applications. Unlike natural gas, which is transported and metered in the gas phase well above its pseudocritical temperature, CO_2-rich mixtures in the CCUS value chain often operate near the critical point and along the saturation curve. These conditions introduce complexities in phase behaviour and fluid properties, which directly impact measurement accuracy. Importantly, different metering principles perform optimally in specific applications – some are better suited for gas-phase applications, while others are more effective in the liquid phase, as discussed later in this report.

Ancillary equipment – In field operations, fiscal flow meters measure the bulk CO_2-rich stream. However, the reported and/or traded quantity is either the pure CO_2 mass or the CO_2-rich stream mass, provided the latter meets the agreed-upon purity level [9]. Consequently, stream composition analysis is often required to either compute the pure CO_2 mass fraction or to verify compliance with purity specifications. When volumetric flow meters are used, additional measurements are required. These include in-situ density measurement or pressure and temperature measurements (when using an equation of state to compute density). Therefore, a fiscal metering system generally comprises: (i) at least one mass flow meter, and one or more composition analysers, as analysis methods depend on the species present; or (ii) one volumetric meter, one density meter, pressure and temperature sensors, and one or more analysers. It should be noted that even mass flow meters typically require temperature and pressure input to compensate for variations in operating conditions, including occasionally compressibility effects.

Material – CO_2 is non-corrosive and non-toxic, but impurities present in the stream can yield the formation of acids. Thus, chemical compatibility is required, with the CO_2-rich stream and the operational environment.

Performance – The accuracy requirements for the metering system are key in selecting the metering method. Besides uncertainty (repeatability or reproducibility – more on this in Section 5.1), it is relevant to set the criteria for stability.

Costs – Different metering technologies have higher CAPEX and OPEX than others. CAPEX variations may reflect the provision of special features or an indication of performance.

3.1 Note on instrument data sheet interpretation

Instrument data sheets typically provide performance specifications. The study in [10] reviewed the data sheets specifications for three measurement technologies - ultrasonic (both gas and liquid), Coriolis, and turbine - and compared them with various international definitions, several discrepancies and inconsistencies were identified.

With regard to the repeatability definition, various standards were compared by [10]:

(1) Repeatability in API MPMS is defined from the total spread of the quantity in question, i.e. (maximum value - minimum value)/(minimum value). Further, the reference uncertainty

required for a given number of repeats is computed so that the uncertainty contribution from the spread of repeated results shall be at most $U^* = 0.027\%$.

(2) Repeatability in ISO 17089-1, which addresses ultrasonic meters for gas, defines repeatability as the uncertainty contribution from repeatability to a single measurement in a measurement series. Repeatability during calibration is, in turn, defined as the expanded uncertainty contribution at a 95% confidence level from repeatability for the average number of measurements. ISO defines repeatability during calibration according to different accuracy classes; for class 0.5, the repeatability during calibration is at most $r_{cal} = 0.17\%$ for the highest flow rates.

(3) The definition of repeatability also varies according to other consulted standards. That is, it is considered quantified based on max-min in the OIML R117, and probably on max-min in the AGA7 and AGA9. In ISO 17089, repeatability is based on standard deviation, whereas in ISO 10790 and OIML R137, it is not quantified, and no specific method is given. In many of these standards, the number of runs/repeats is not indicated. This is not the case of the OIML R137, where the repeatability of errors of three consecutive measurements at the specific flow rate shall be less than or equal to one-third of the maximum permissible error.

The above examples shows that repeatability specification should be properly referenced, and the number of runs provided. In general, the terms accuracy and repeatability, which are widely used in flow meters specifications, are not well defined in instrument data sheets. In the data sheets consulted in [10], accuracy is often specified as a fraction of a “percentage of the measured value, after flow calibration and linearization”. However, proper interpretation requires knowledge of the uncertainty of the reference measurement.

Thereafter, to assess the uncertainty of a flow rate measured by a flow meter, the following are needed: calibration reference, linearity, and repeatability (together with reference definitions and number of runs). Additional contributions to uncertainty are installation effects, time since last calibration (ageing, wear, and tear), and contributions from other instruments in the system.

3.2 Standards and regulations

The report [11] outlines the Global Regulatory Framework for CCUS systems. A summary of the regulation relevant to CCUS fiscal metering from this report, complemented by updates in standardisation is provided below.

3.2.1 Relevant regulation for flow metering and allocation for CCUS systems as per EU ETS (Norway/UK)

3.2.1.1 Measurement systems

The EU ETS 2018/2066 [12] states that the operator shall classify each installation depending on the verified average annual emissions as follows:

a) category A installation, emissions equal to or less than 50 000 tonnes of $CO_{2(e)}$;
b) category B installation, emissions higher than 50 000 tonnes of $CO_{2(e)}$ and equal to or less than 500 000 tonnes of $CO_{2(e)}$;
c) category C installation, emissions higher than 500 000 tonnes of $CO_{2(e)}$.

All emissions are excluding CO_2 stemming from biomass. For typical CCUS systems emitters fall under category C.

The EU ETS deploys a tier system for measurement-based methodologies (see Table 1). For each major source, the operator should apply the highest tier for category B and C emitters. When the CO_2 is instead transferred out of the installation to (i) a capture installation for the purpose of long-term geological storage, (ii) a transport network with the purpose of long-term geological storage, or (iii) a storage site for the purpose of long-term geological storage; the highest tier should be applied (Article 49) regardless of the installation category.

This means that for the measurement system, a 2.5 % uncertainty limit on pure CO_2 mass quantity applies. However, subject to the approval of the regulator, the operator may apply the next lower tier provided that it establishes that applying the highest tier is technically not feasible or incurs unreasonable costs.

The authors in [11] highlight that the EU ETS tiers for measurement-based methodologies were developed for Continuous Emission Monitoring System applications (CEMS), i.e. for flue gas conditions. CEMS will be used only when the CO_2 is transferred out to a capture installation. When instead the CO_2 is transferred out to a transportation network, then CEMS will not be employed since the pressure is higher than atmospheric. When the CO_2 is transferred to a transport network or geological storage, measurement technologies other than CEMS will be used and the ±2.5 % requirement can be found inappropriate.

Table 1. Maximum permissible error of EU ETS tier classification for measurement-based methodologies

	Tier 1	Tier 2	Tier 3	Tier 4
CO_2 emission sources	±10%	±7,5%	±5%	±2,5%
CO_2 transfer	±10%	±7,5%	±5%	±2,5%

3.2.1.2 Allocation/transport systems

The scope of an allocation/transport system is defined in the EU ETS 2018/2066 Annex IV, section 22 [12], namely:

- The boundaries for monitoring and reporting emissions from CO_2 transport by pipeline shall be laid down in the transport network's greenhouse gas emissions permit, including all ancillary plant functionally connected to the transport network, including booster stations and heaters.
- Each transport network shall have a minimum of one start point and one end point, each connected to other installations carrying out one or more of the activities: capture, transport or geological storage of CO_2.
- Start and end points may include bifurcations of the transport network and cross-national borders.
- Start and end points, as well as the installations they are connecting to, shall be laid down in the greenhouse gas emissions permit.
- Each operator shall consider at least the following potential emission sources for CO_2 emissions: combustion and other processes at installations functionally connected to the transport network, including booster stations; fugitive emissions from the transport network; vented emissions from the transport network; and emissions from leakage incidents in the transport network.
- The operator may quantify the emissions either by mass balancing of the allocation system (Method A, Annex IV, Article 22, B.1) or by monitoring the emissions source individually (Method B, Annex IV, Article 22, B.2).
    - When method B is chosen, each operator shall demonstrate that the overall uncertainty for the annual level of greenhouse gas emissions for the operator's transport network does not exceed 7.5 %.
    - This method should be verified by the first mass balancing method (Method A) annually.

  - Although Method B can be employed, the operator is still required to install metering stations at the network inlet and outlet points for annual verification of Method B.
- In terms of content ownership, two models exist for pipeline operators: private and common operators:
  - Private operators (model often applied in the USA) the operator is responsible for the content and hence the emissions of the transport network.
  - Common operator models the content is not owned by the operator and emissions need to be distributed among the emitters. However, there is a transfer of ownership when the CO_2 is transferred out of an installation monitoring boundary to a capture installation, a transport network or a storage site, and the transferred CO_2 should be subtracted from the installation annual greenhouse gas emission (Article 49).

It is noted that the EU ETS does not explicitly mention transportation by ship [12]. In July 2020, the EU endorsed Norway's interpretation of the regulations, which entails that the capture facilities will be able to subtract CO_2 from their emissions accounting when CO_2 is transferred from the ship to the reception terminal [13]. The capture operator may not subtract allowances for CO_2 that leaks during transport and must thus surrender allowances for these emissions. The financial loss that results from such leakages during transport can be regulated in private legal contracts between the operators. Each capture facility must have detailed and adapted monitoring plans developed in consultation with the national authorities that regulate leakage and emissions of CO_2 during transport.

3.2.2 Flow metering standards and guidelines for CCUS systems

3.2.2.1 Liquid/dense phase dynamic measurement systems

(a) EU ETS

The current basis for custody transfer metering regarding the European ETS is provided by the EU ETS 2018/2066 [12]. From the text in Article 49, regulations for the transfer of CO_2, and Annex VIII, Section 1, Tier 4, it can be deduced that the required accuracy for measuring the transferred CO_2 mass is 2.5 % on an annual basis. This is a relaxation from the previous and often quoted limit of 1.5 % specified by the now superseded Commission Decision 2010/345.

(b) EU MID

The EU MID (Directive 2014/32) [14] was written to harmonise the laws of the EU and EEA member countries on measurement devices. Annex VII MI-005 provides regulations for continuous measurements of liquids other than water and has a dedicated accuracy specification of Class 1.5 on the measurement of liquified CO_2. Under the MID this means that the whole measurement system should have a maximum permissible error (MPE) of 1.5 %, but the meter must have an MPE of 1.0 %. It is noteworthy that neither the MID nor the OIML (below) makes reference to the stream composition, contrary to EU ETS which refers to pure CO_2 [11].

(c) OIML

OIML is the international organisation for legal metrology. The principal recommendation of interest to CCUS is OIML R 117 Dynamic measuring systems for liquids other than water. The metrological and technical requirements applicable to dynamic measuring systems for liquids other than water are specified in the OIML R 117-1 [15]. Depending on their field of application, measuring systems are classified into four accuracy classes. The measuring systems for liquefied CO_2 belong to Accuracy Class 1.5, which requires an overall MPE of the complete measuring systems of 1.5 %. This is in agreement with EU MID. Also, R117-1 specifies that the maximum permissible errors for a meter under rated operating conditions is 1 % for the measuring system of Accuracy Class 1.5.

(d) NIST

NIST is the US National Institute for Standards and Technology. NIST Handbook 44 [16]. Section 3.38 covers the code requirements applicable to liquid measuring devices used to measure liquid

CO_2, though not all of it applies to large-scale flow. The measurement of liquid CO_2 is classified as Accuracy Class 2.5 with an acceptable tolerance for the measuring devices of 1.5 %, and the test liquid shall be CO_2 in a compressed liquid state.

(e) ISO

For different metering technologies, ISO standards have been developed. Although many of these standards do not explicitly mention CO_2 as a medium, the basic guidelines may remain valid for CO_2 applications. A list of meter technology-specific ISO standards are:

- ISO 10790 [4]: Coriolis meter standard for the measurement of liquid and gas applications. The application to CO_2 liquid/dense phase is not explicitly mentioned; however, it is claimed that: "*Density and viscosity may have a minor effect on measurements of mass flow. Consequently, compensation is not normally necessary. However, for some designs and sizes of meters, density and/or viscosity changes can induce an offset in the flowmeter output at zero flow and/or a change in the flowmeter calibration factor*"
- ISO 2715 [17]: Turbine meters for liquid hydrocarbon measurements. The standard is applicable to the metering of any appropriate liquid with the exception of cryogenic liquids. Explicit mention of the sensitivity of the turbine meter to changes of viscosity, however also: "*for liquids of lower relative density such as gasoline whose viscosity remains essentially unchanged with changes in temperature, meter factor values likewise remain virtually unchanged".* At the same time, the application to so-called dry liquids (like CO_2) can lead to accelerated wear and increased bearing friction.
- ISO 12242 [6]: Ultrasonic meters for the measurement of single-phase homogeneous liquids. The standard does not mention any restrictions on the used fluid, although CO_2 applications are not explicitly mentioned.
- ISO 5167 [8]: Measurement of fluid flow by means of pressure differential devices. The standard includes liquid and gas applications. The response of differential pressure meters should be independent of the fluid and primarily a function of the Reynolds number. For some of the metering technologies, e.g. Venturi tubes, the standard discharge coefficients are limited in the Reynolds range. Furthermore, for dense phase and supercritical conditions: "*In the case of a compressible fluid, it is also necessary to know the isentropic exponent of the fluid at working conditions".*

3.2.2.2 Liquid phase static measurement systems

The use of automatic tank gauging on pressurised tanks is described in API MPMS Chapter 3.3 [18] and ISO 4266-3 [19]. Special considerations must be weighed when designing radar tank gauges for pressure applications, such as for liquid CO_2 shipping. The API and ISO standards do not explicitly mention liquified CO_2, however, they do mention the use of automatic tank level gauging for liquid hydrocarbons with vapour pressure above atmospheric pressure. The ISO explicitly mentions the use of non-refrigerated tanks; the impact of the low-temperature during liquid shipping is unclear for the applicability of the ISO standard.

3.2.2.3 Gas phase measurement systems

(a) EU ETS

The EU ETS 2018/2066 [12] specification as mentioned under section 2.1.1 also applies to gas measurement, meaning that the required uncertainty for measuring the net transferred gaseous CO_2 mass is 2.5 % on an annual basis.

(b) EU MID

The EU MID (Directive 2014/32) [14] does not explicitly mention CO_2 gas under Annex IV MI-002. This annex only considers fuel gas measurement. Under the MID-002, industrial gas measurements fall under accuracy class 1.5, if the Qmax/Qmin is ≥ 150, 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 ($Q_t \leq Q_{max}/10$).

(a) OIML

The principal recommendation of interest to CCUS are the OIML R 137 [20] and R 140 [21] for gas meters and measurement systems for gaseous fuels, respectively. The OIML R 137 classifies the MPE of gas meters in three accuracy classes, class 0.5; class 1.0 and class 1.5 with the lowest permissible error during initial verification given by accuracy class 0.5, yielding MPE ±1% between Q_{min} and Q_t and ±0.5% between Q_t and Q_{max}. The OIML R 140 specifies that for converted volume, converted mass or direct mass measurement systems, Classes A, B, and C allow for MPEs of ±0.9%, ±1.5%, and ±2.0%, respectively.

(c) NIST

The NIST Handbook 44 [16] only considers hydrocarbon gases and does not mention gaseous CO_2. It only states that a vapour equalisation line shall not be used during a liquid CO_2 offloading unless the quantity of vapour displaced from the buyer's tank to the seller's tank is deducted from the metered quantity.

(a) ISO

For different metering technologies, ISO standards have been developed. Although many of these standards do not explicitly mention CO_2 as a medium, the basic guidelines may remain valid for CO_2 applications. A list of meter technology-specific ISO standards comprises:

- ISO 10790 [4]: Coriolis meter standard for the measurement of liquid and gas applications.
- ISO 9951:1993 [22] and EN 12261:2024: Turbine meters for gas flows. Both the ISO and EN standard are applicable to the metering of general gas flows however does not mention CO_2 gas. The ISO standard has not been updated since 1993.
- ISO 17089 [23] Ultrasonic meters (USM) for gas. The standard does not mention any restrictions on the used fluid, and: can be applied to the measurement of almost any type of gas, such as air, natural gas, and ethane. The application to CO_2 is explicitly mentioned and: In particular, high levels of carbon dioxide and hydrogen in a gas mixture can influence and even inhibit the operation of a USM owing to their acoustic absorption properties.
- ISO 5167 [8]: Measurement of fluid flow by means of pressure differential devices.

Table 2 Summary of current uncertainty requirements in percentage of the reading (source [9])

	Measuring system uncertainty	**Flow meter uncertainty**	**Phase**
EU ETS[24] UK ETS[25]	2.5 %	Not specified	Any phase
NIST [26]	1.5 %	Not specified	Liquified carbon dioxide
EU MID (Directive 2014/32) [14]	1.5 %	1 %	Liquified carbon dioxide
OIML R 117 [15]			Liquified carbon dioxide
OIML R 137 [20]	N/A	0.5% - 3 % (depending on accuracy class and flow rate)	Gas
OIML R 140 [21]	0.9 % - 2% (depending on flow rate)	Not specified	Gas (>1000m^3/h)

3.2.3 Other relevant standards

For volume-to-mass conversions using density meters, the table 4 of Annex VII section 2.6 of the MID [14] is relevant. The MID specifies a density accuracy of ± 2 kg/m^3 for Class 1.5. The OIML R117-1 [15] 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 [27].

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. ISO27913:2016 outlines requirements and provides guidance for CO_2 pipeline transport. As per the analysis in [28] none of the above standards addresses the effect of impurities in flow meters, and methods to quantify impurities in the CO_2 stream are marginally defined.

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. For this, the use of Equations of State (EoS) that accurately describe the behaviour of CO_2-rich mixtures of interest is paramount.

3.2.4 Flow calibration

The EU ETS 2018/2066 [12] states under article 42 that the operator shall ensure that laboratories carrying out calibrations and relevant equipment assessments for continuous emission monitoring systems (CEMS) are accredited in accordance with EN ISO/IEC 17025 [29] for the relevant analytical methods or calibration activities. Laboratories not accredited in accordance with EN ISO/IEC 17025 may be used only where the operator can demonstrate to the satisfaction of the competent authority that access to laboratories is technically not feasible or would incur unreasonable costs, and that the non-accredited laboratory meets requirements equivalent to EN ISO/IEC 17025.

According to the US EPA Federal Register Vol. 74 [30], any facility owner, operator or supplier subject to the provisions of this regulation, must ensure that flow meters and other devices used to calculate GHG emissions meet the calibration accuracy requirements. These instruments shall be calibrated prior to April 1, 2010 using the procedures specified in this section and each relevant subpart of the regulation. All measurement devices must be calibrated according to the manufacturer’s recommended procedures, an appropriate industry consensus standard, or a method specified in a relevant subpart of this part. All measurement devices shall be calibrated to an accuracy of 5%. 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.

Also, most ISO standards on flow metering technology require calibration under ISO 17025. Generally, only orifice meters can be exempted from a calibration under flowing conditions if manufactured in compliance with ISO 5167.

In Europe, the calibration methodology and frequency are regulated by Article 60 in the ETS M&R Regulation 2018/2066 [12]. 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. If the meter performance is stable with time, calibration in a certified calibration facility may not be required more than every fifth year.

As mentioned above, regulatory provisions can grant reduced calibration frequencies under ETS M&R Article 18, Paragraph 3, provided the calibration costs (at the specified frequency) are unreasonable. Equation (1) 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.

$$Benefit = Improvement\ factor \times Reference\ price \qquad \textbf{(1)}$$

According to ISO 27913, “where the flow meter is calibrated with a fluid different from the operational fluid, transferability of the calibration shall be assessed for the employed metering technology and if acceptable the additional uncertainty from calibration from an alternative fluid shall be accounted for in the overall uncertainty budget. Where the flow meter is calibrated at line pressure and temperature different from the operational ones, the impact of this difference on the performance of the meter shall be assessed for the employed metering technology and corrected for where needed and if feasible. Any additional uncertainty from calibration of the meter at line pressure and temperature different from the operational ones shall be accounted for in the overall uncertainty assessment”

3.2.5 Advances in Standardisation Bodies

The CEN/TC 474 Technical Committee approved a work item proposal on carbon dioxide quantification and verification across the CCUS Value Chain and assigned it to Working Group 3 “CO_2 Accounting”. Under this Work Item, Working Group 3 aims to develop a standard that defines the methodologies and requirements for quantifying the mass of CO_2 and CO_2 stream, as well as for quality assurance and verification [31].

The API has established a working group to develop Chapter 6.XB “Metering Systems for Mass Measurement of Carbon Dioxide”, which focuses on carbon dioxide measurement in the liquid and supercritical phase.

4. Performance and calibration

4.1 Calibration and SI-traceability

Calibration provides a comparison of measurement values of a meter under test against a standard reference to identify bias and systematic measurement errors. Calibration certificates provide the limits within which the behaviour of the meter can be expected to operate at a specified uncertainty [9]. Traceability to international standards results in consistency of measurement among users at different times and locations. SI=-traceability is the foundation of fiscal metering; it is key to precisely trace the mass flow measurement of CO_2 back to a standard or references linked to the International System of Units (SI) for time and mass.

The primary standard serves as the foundational reference for calibrating other instruments, which in turn become transfer standards used to extend the calibration chain. This process, often referred to as bootstrapping calibration, involves calibrating secondary references against the primary standard. Chain calibration typically relies on the incremental capacity and precision of these secondary reference meters. The primary standard apparatus establishes traceability to national or international standards and defines the baseline calibration accuracy for the entire system. It acts as the critical link between national metrology institutes and the transfer flow standards employed in calibration laboratories, ultimately ensuring reliable calibration of meters deployed in the field.

4.2 Flow reference principles

There are two basic primary reference principles, namely, (i) gravimetric, in which flow is diverted to a closed container, thus more practical for liquids, although also used for gases, and (ii) volumetric, with or without stream diversion.

Gravimetric reference is the most used calibration method for liquid flows at low pressures, like water and oil. In gravimetric calibrations, the flow is diverted to a closed container where it is weighed. An overview of both primary flow reference systems for CCUS is provided in [9, 32]. The authors argue that using this method for large-scale CO_2 flows would require advanced pressure control at the inlet of the tank to maintain the pressure. A drawback of this method is that large pressure drops of liquid CO_2 can yield dry ice formation. As illustrated in [33] and Section 7.2, all isentropic expansions left of the saturated gas line will lead to the formation of solids close to atmospheric pressure. When expansion from the liquid and dense phase (including a large part of the supercritical region) occurs, a second phase (gas) will be formed. Depending on the initial state, the expansion will result in different gas fractions with density reducing isentropically until the solid-vapor boundary is reached. Thus, during operation, the pressure should be maintained above the boiling point to avoid fast boil-off and prevent the system from entering the solid-vapor region. Tight control of the fluid temperature warrants uniform stream composition through the system.

Alternatively, for liquid and gaseous CO_2, combined volumetric primary reference and mass calculation is possible. Volumetric proving has long been implemented in various industries. Small volume provers (SVP) use a travelling piston to measure volume flow where the position of the piston is correlated to a calibrated volume. This method requires accurate density, pressure, and temperature measurements for volume-to-mass flow conversions from the measured flow.

4.2.1 Gravimetric Primary Reference

As per available literature, there are limited CO_2 facilities with gravimetric traceability. The CO_2 loop at Tianjin University [34] 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 CO_2 and of their master meters of 0.16% (k=2) for CO_2 liquid flows, and 0.3% (k=2) for CO_2 gas flows.

Heriot-Watt University has also developed an apparatus and method for calibrating a mass flow meter, which accounts for mass verification. In the method, the totalised mass from the inbuilt mass totaliser inside the Coriolis meter recorded by the flow meter during the calibration is compared with the increase in weight of transported CO_2 inside a receiving cylinder monitored by a high-resolution weigh scale with certificated standard uncertainty of 0.1 g and overall uncertainty of the setup of ±0.017% [35].

As indicated above, the authors in [35] report challenges to maintain the CO_2 in liquid phase through the meter under calibration. A back-pressure controller was connected at the outlet of the meter, with the receiving cylinder initially under vacuum. Although this allowed maintaining CO_2 in liquid phase, the pressure in the receiving cylinder depends on the amount of CO_2 injected during a calibration. This pressure yielded a phase transition downstream of the outlet of the back-pressure controller.

The above raises concerns about the effects of transition in the meter under calibration with increased measurement error. Additional measures comprise comparison of density measurements with calculations from Equation of State, although care is advised, given the high dependency of density on in-situ temperature measurements [36] and discrepancies reported in the supercritical phase [37]. Additionally, Joule–Thomson effect produced dry ice on the receiving cylinder, requiring careful wiped dry during testing.

4.2.2 Volumetric Provers

Volumetric provers for calibrating CO_2 flow meters can be divided between liquid CO_2 volumetric provers and gaseous CO_2 volumetric provers.

4.2.2.1 Liquid Volumetric Provers

Volumetric provers for calibrating liquid meters are covered by the API standard chapter 4 [38], developed for the oil and gas industry. Therein, the overall minimum uncertainty is required to be less than ±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 liquid is in single-phase and that the density is determined by an accepted practice. Furthermore, since in certain parts of the dense and supercritical region the fluid becomes compressible, the proving procedure itself may induce pressure fluctuations which result in density fluctuations. This may deteriorate the repeatability of the proving runs and depends on the proving configuration, i.e. size of prover, buffer volume and internal construction of the prover, for details see [39].

API describes traditional ball provers and SVPs (Small Volume Provers). SVPs are recommended for calibrating liquid CO2 flow meters. They 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 ±0.04% (k=2) [40, 41]. Yet, the accuracy and repeatability of SVP with CO_2 require further investigation. For liquid and supercritical CO_2, primary standards are being independently developed by NEL and SINTEF.

4.2.2.2 Accuracies of Volumetric Provers for Gaseous CO_2

Ongoing research aims to build a traceability chain for CO_2 in the coming years. In this sense, the MetCCUS project developed primary standards for gaseous CO_2. INRIM, VSL, and FORCE have built volume provers for intermediate scale (<50 Sm^3/h) and large scale (<400 m^3/h) CO_2 flows.

VSL: Mercury-seal piston provers are also used for calibrating CO_2 gas flow meters at atmospheric pressure and temperature and flowrates up to 3.6 m^3/h, with a CMC of 0.2%.

VSL has also used a medium-pressure (<10 bar) mercury-seal piston prover for CO_2 gas, at flow rates between 0.006-0.6Sm^3/h. The piston prover has three discrete volumes, nominally 42 ml, 82 ml, and 163 ml [42]. The reference uncertainty of this proving equipment is ±0.31%.

At large scale, VSL has upgraded its Gas-Oil Piston Prover (GOPP) for use with CO_2 and has a CMC of 0.06% with natural gas up to 60 bar, operating up to 160 m^3/h with gaseous CO_2 [43]. The prover provides SI-traceable calibrations that are linked to the meter and the second. The traceability of the calibrations with the GOPP is through the determination of the prover's internal volume independent of the gas, making it a suitable standard for any gas. When operating the GOPP with

CO2, the system could achieve lower flowrate than with Natural Gas and nitrogen because of the higher density of CO2.

INRIM: For the MetCCUS Project, INRIM performed upgrades on its existing large piston prover (MeGAS); specifically, the works included the renovation of (i) the feed gas lines for increased available flow rate to 30 m^3/h and feeding of CO_2, (ii) addition of a discharge line for safety handling of large quantities of CO_2 (up to 1200 L) to be released from the piston after a measurement, (iii) addition of a CO_2 concentration sensor in the laboratory, and (iv) upgrades of the control software.
The piston prover is of the plunger type, with a total volume of about 1500 L and a usable volume of about 900 L; the movement is controlled by an electric motor through a lead screw. The maximum speed of the piston is self-limited to a velocity corresponding to a flow rate of 30 m^3/h.
For lower flow rates, INRIM uses the bell-prover facility, which did not further require modifications, as it shares the gas lines with the piston prover. This facility is essentially a standard bell prover, except for the position reading, which is obtained by a high-resolution encoder, and the buoyancy compensation, which is performed by a moving weight, allowing for a very high uniformity of the pressure within the bell throughout the bell run.
Regarding the uncertainty of measurement, since both test rigs operate at ambient pressure and temperature and are based on a volumetric principle, the standard uncertainty budget of the facilities hold also for the CO_2 measurements, provided that the correct estimates for the uncertainty components are used. Specifically for CO_2, the uncertainty contribution associated with the molar mass of the working gas was increased. Yet, since this is a minor contribution, the final uncertainty is essentially the same as for traditional working gases (e.g. N_2, air). The minimum possible uncertainty is estimated in 0.10% for the large piston and 0.12% for the bell. The final uncertainty also depends on the scatter of the data and is usually larger than the best-possible scenario. In the measurements performed in MetCCUS, no noticeable differences in scatter were observed between tests in N_2 and in CO_2.

FORCE: For the MetCCUS project, FORCE has upgraded its gas primary facility to also be used for CO_2. The primary facility is a piston prover designed for natural gas.
When testing on CO_2 the Piston prover can operate from 20 to 340 m^3/h and at a pressure up to 30 bar. The uncertainty depends on the meter type (volume or mass) but varies within 0.15% and 0.30%.

4.2.3 Other reference meters

DNV facility for gaseous CO_2 tests operates with three reference technologies, i.e., Sonic Nozzles, Coriolis, and Turbine meters. Each type of reference has its own traceability chain (refer to [44] [45] for details of the calibration chain). The nozzles are traceable to the PTB air flow facility. The Coriolis meters are traceable via Emerson's test facility in Ede (NL) to the kilogram, and the turbine gas meters are traceable via DNV and FORCE. For the latter, the calibration parameters of the bearing friction are traced to the atmospheric air PTB facility. The reported uncertainties are between ±0.13% and ±0.18% for the sonic nozzles, ±0.25% for the Coriolis, and ±0.22-0.26% for the turbine meters. However, the operation of the sonic nozzles has shown operational constraints, as highlighted below.

The use of Sonic nozzles is restricted by the lower speed of sound of CO_2 and therefore limits the flow rate capabilities. Condensation of the CO_2 at the throat conditions has been seen to yield large negative bias, of up to 2% [46]. Moreover, sonic conditions must be ensured at the throat. When the sonic nozzles are over-expanded (Mach>1), CO_2 droplets will be formed if the conditions downstream the throat enter the liquid region. The impact of these droplets on the total mass flow is difficult to quantify, however, it is known that a small fraction of droplets may decrease the speed of sound significantly [46].

The high-pressure gaseous CO_2 facility at NEL uses ultrasonic meters as reference. The calibration of the ultrasonic meters against a traceable turbine meter in gaseous phase is detailed in [42]. Turbine meters are recognised as a reliable means of transferring a natural gas calibration to gaseous carbon dioxide when the k-factor is determined as a function of the Reynolds number and the meter is subsequently used within the calibrated Reynolds range. The calibration factor of transfer turbine meter used at NEL was determined by fitting the PTB turbine meter model to the calibration results obtained with high-pressure natural gas at Pigsar and atmospheric air at PTB. The overall reported uncertainty of the reference turbine meter is ±0.185% in volume flow, while the overall NEL high-pressure facility uncertainty is ±0.35% (k=2) in volume flow. Refer to Section 5.6.1 for further notes on Turbine meters.

4.3 Calibration uncertainty

4.3.1 Primary reference (volume prover)

In [47] the calibration uncertainty of a CO_2 liquid calibration facility using an SVP is exemplified following the API Manuals of Petroleum Measurement Standards (MPMS) method and the GUM [48]. The calibrated reference volume $V_{F,ref}$ at the reference meter is expressed as:

$$V_{F,ref} = \frac{BPV_p \cdot CTS_p \cdot CPS_p \cdot CTL_p \cdot CPL_p}{CTL_m \cdot CPL_m} \qquad \textbf{\textit{(2)}}$$

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 under 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 ≤ 0.03 % according to [47], although no experience operating SVP with CO_2 has been documented yet.

Additional uncertainty contributors listed in [47] 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 [47] estimate that the overall accuracy of the temperature measurement of the liquid at the SVP and the reference flow meter must be at ±0.2 °C or smaller.

For high-pressure applications, an added uncertainty source is the density calculations. If an equation of state is used, the density depends on the local temperature, pressure, and composition (and their respective measurement uncertainties). More on this is discussed in Section 6.5.

4.3.2 Bootstrapping

The bootstrap method is a stepwise calibration technique used when the primary flow standard cannot cover the required high flow rates. Multiple meters, first calibrated at the lower flow rates achievable by the primary standard, are arranged in parallel so their combined flow rate serves as a higher capacity transfer standard for calibrating larger meter. The process can be repeated, providing a flexible way to scale flow rate. However, the calibration uncertainty increases with each step and depends on the configuration.

A preliminary uncertainty analysis was performed in [32] for a bootstrapping array where all secondary references of the same capacity are placed in parallel to measure the maximum flow. Direct reference calibration of all the secondary reference meters decreases the overall calibration uncertainty; compared to increased calibration stages. The authors in [9] assessed the added uncertainty by increasing the calibration stages and reducing the number of secondary meters by a factor of up to 2. However, such a configuration calls for chain calibration, thus increasing measurement uncertainty by a factor of 1.5 to 3.5, for the case studied, depending on the correlation between meters and stages. The maximum relative uncertainty contribution of the calibration stages was found to occur when the fluctuations of the meters in the arms of the stage have a correlation of 1. The minimum value occurs when the fluctuations of the stage meters are independent of each other. The optimum configuration is a trade-off between CAPEX, OPEX, and targeted uncertainty.

4.4 Calibration with proxy fluids

Calibrating CO_2 at close-to-operation conditions is typically preferable and, in some locations, required by regulatory authorities. Such a strategy reduces the effects that fluid properties and process conditions have on measurement accuracy. However, matching process and stream compositions with precision and performing calibrations at all relevant process conditions can be time-consuming and expensive.

Various works outline the performance of flow meters for CO_2 services; from them and the references therein, a summary of the transferability was provided in [9]. Overall, documented test outcomes for gaseous phase suggest that turbine meters and Coriolis meters have high chances for being calibrated using alternative fluids – provided influential factors, such as temperature, pressure and compressibility effects, 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. Depiction of transferability considerations for the specific technologies are provided in section 5.6.1. A summary of relevant experiences is summarised below.

Table 3. Relevant fiscal metering technologies for CCUS and considerations for CO_2 service ([9], [7])

Technology	Relevant experience
Coriolis	Tests with gaseous and liquid/dense CO_2 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 [46, 49]. The Coriolis meter should be corrected for pressure and temperature effects, and might require correction for compressibility effects. Performance shifts above critical temperature have been reported [7]. Comparison tests with an orifice meter showed 0.35 % agreement for the liquid and dense phases [37]

Differential Pressure	No uncertainty analysis and comparisons of water calibrations to liquid CO_2 calibrations for DP meters have been reported. Still, in [37] the authors use an orifice flow meter calibrated on water and nitrogen as a reference in a relative error assessment of meters for liquid CO_2. 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 CO_2.
Ultrasonic	No extensive data exists to compare water calibrations to liquid CO_2. 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 CO_2 reached 3 % with 1 MHz transducers. No reading was feasible in the supercritical phase [37]. 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 [50].
Turbine	Uncertainty analyses and comparisons of water-to-CO_2 calibrations for turbine meters are lean in the literature. Turbine meters calibrated in natural gas have been used with gaseous CO_2 with reported uncertainties of less than 0.25% (k=2) [46, 51]. 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 CO_2 [37]. 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 CO_2, and thus.

5. Recommended Practices in CO_2 Fiscal Metering

5.1 General recommendations

- Use the appropriate measurement method. Before ordering, detail the measurement requirements to ensure the right technology selection and calibration range. Open a dialogue with the technology provider to ensure the uncertainty and repeatability requirements, as well as references, are aligned.
- Select the correct type of flow meter for the application. Take into account the measurement uncertainty, fluid phase, meter sizing, effect of impurities, and whether mass or volume flow is required.
- When available, seek SI-traceable calibrations through accredited laboratories or equivalent schemes.
- Calibrate the flow meters and temperature and pressure sensors at a regular interval to ensure accurate, reliable, and consistent measurements of the CO_2 flow.
- Wherever possible, ensure that meters are calibrated under the conditions of use.
- Check the health of instruments, if possible, at intervals between calibrations and monitor long-term drifts.

5.2 Thermophysical properties and Equations of States (EOS)

Flow measurements, and calibration methods are closely related to accurate prediction of the thermophysical properties of the CO_2 stream measured. The most relevant single-phase thermodynamic properties are density, speed of sound, and the Joule-Thompson coefficient. The thermodynamic properties of the CO_2-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. 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.

No single equation of state is appropriate for all modelling purposes [52]. Generally, multiparameter equations of state are the most accurate and are applicable across all fluid phases [53]. Their accuracy results from a correlation procedure that demands extensive experimental data on thermodynamic properties. For CCUS mixtures, the EOS-CG-2021 multiparameter model [54] extends previous works [55-57] and is valid for systems containing most of the abundant impurities expected in CCUS systems.

Density is an important input to build thermodynamic equations of state and correlations for other properties such as viscosity and thermal conductivity. As for other thermophysical properties, small impurity concentrations can have a significant impact on density. To illustrate the accuracy of the EOS-CG-2021 model, the authors in [9] consider the CO_2-N_2 system. This binary model 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.

Multiparameter equations benefit from accurate and abundant data. An overview of density measurements for CCUS shows that some of the major components are relatively well covered. However, gaps in property data of CO_2-rich mixtures have been reported [58-61], in particular corresponding to viscosity and density datasets. Such scenario can compromise the accuracy in models and derived measurements.

In a similar fashion, the default multiparameter EOS for pure CO_2, Span-Wagner EOS, was derived based on existing datasets, of which, speed of sound measurements at conditions relevant for CCUS transport processes are covered solely by Novikov and Trenlin data gathered at 288-373 K 3-10 MPa. Such dataset provided no reasonable uncertainty estimation. The overall uncertainty of the Span-Wagner model for speed of sound calculations in the region of interest for CCUS is expectedly <±0.5% for gas, between 0.5 and ±1.0% for liquid and supercritical, and above 1% in the vicinity of the critical point. Further, the work in [62] reported a deviation between measured speed of sound of CO_2-C_3H_8 mixtures and GERG-2008 computed values of up to 1.5% at pressures around 80 bar.

In the literature, high variations in flow measurements are reported in the supercritical phase, due to the high sensitivity of Density-calculated from EOS to the pressure and temperature measurements, as discussed above, especially in the supercritical region. 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 [9]. In these regions, equations of state will inevitably be less accurate.

5.3 Fluid phase

Fiscal metering technologies require that the CO_2 stream exists in a single phase. Thus, to ensure high measurement accuracy, the formation of a second phase shall be avoided by predictive models and or monitored by phase-sensitive sensor systems.

The appearance of an unwanted vapour phase in the CO_2 stream can be a problem for metering technologies. The major impurities in CO_2 streams are typically non-condensable, i.e., nitrogen, oxygen, argon, methane, carbon monoxide, hydrogen, and helium. If the total concentration of these impurities becomes too high, a gas phase will appear. The phase envelope of different systems can greatly vary depending on the concentration and the system itself. Fortunately, the thermodynamics of CO_2 streams containing only these impurities are now well understood, and equations of state such as EOS-CG-2021 [54] 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 CO_2-rich phase is usually small [9]. However, for condensed phases, the phase boundaries are generally harder to predict compared to vapour phases. A typical unwanted condensed phase is an aqueous phase. For the binary system CO_2-water, the phase boundaries are well-known, but in generic CO_2 streams, this is complicated by the presence of other impurities that may form stable acids even at low humidity levels [63]. While these phases are usually present in very small quantities, if they accumulate over time, significant inaccuracies may ensue.

Concentrations of minor species are commonly measured offline by sampling-based technologies. Yet, analysing equipment can be expensive and require regular calibration and skilled personnel. For certain operations, inline solutions are preferred; this is to avoid sampling, which is prone to non-representative consideration of different phases, particularly for very small volume fractions (see Section 5.6.5). Inline detection of a second phase can trigger corrective operative actions to avoid erroneous measurement quantities. Inline phase detection has long been used in numerous industries. The applicability of some of these technologies for CO_2 transport has been theoretically assessed, with reportedly limited operational experience for CCUS [64, 65]. Dielectric measurements can measure volumetric fractions of contrasting permittivity phases, which could be leveraged for high-contrast species like CO_2 and O_2, N_2, Ar, H_2, CH_4, and/or H_2O [64]. Two electrical permittivity technologies were recently tested for identification and measuring contaminants in liquid CO_2; for this, two independent low-frequency electrical permittivity electrodes and microwave sensors were installed in a CO_2-N_2 mixture stream. The early results showed a good correlation between measured and theoretical permittivity values for every given condition and composition [66]. However, 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 CO_2. Although results suggest that the tested technologies are highly sensitive to impurities having a high contrast in permittivity compared to CO_2, the concentration of such impurities in the stream has a direct impact on the measurement accuracy [67-73]. Two-phase pure CO_2 has also been detected by means of gamma-densitometry at saturation conditions [74].

5.4 Temperature and Pressure conditions

All thermophysical properties are defined by pressure and temperature conditions. The relative sensitivity of density to changes in pressure and temperature for CO_2 was studied in [75]; where the sensitivity to pressure and temperature based on EOS-CG is defined by Equation (3)

$$U^*(\rho) = \sqrt{[S_p^* U^*(p)]^2 + [S_T^* U^*(T)]^2 + \sum_i [S_i^* U^*(x_i)]^2}, \text{ with } S_y^* \equiv \frac{y}{\rho}\frac{\partial \rho}{\partial y'} \qquad \textbf{\textit{(3)}}$$

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.

Disregarding the term $\sum_i [S_i^* U^*(x_i)]^2$ for pure CO_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 [76].

5.5 Sampling

In addition to model uncertainty and uncertainty contributions from pressure and temperature measurement, the uncertainty of density from Equation of State will depend on the representativity of the sample used for the calculation.

The uncertainty contribution from sampling representativity can be challenging to establish, and will depend on the following: temporal and spatial variation of impurities, sampling point design, sampling handling (subsampling, transport, mixing etc.), sampling frequency, and laboratory procedures and accuracy.

Additionally, reactions can take place with the vessel material, where samples are transported for offline analysis. Reactions within the sampling vessel can lead to inaccurate and unreliable analysis results. Special care is required for reactive gases such as sulphur compounds or ammonia, which could be adsorbed onto, or react with the vessel surface. A good practice guide for the sampling of CO_2 in CCUS process is provided in [77]. In general, aluminium gas cylinders with internal passivation treatment show better long-term stability for reactive gases in low concentrations in different matrix gases [78]. However, it is recommended to determine suitable sampling vessels, stability studies under identical conditions and possible interactions between species present potentially simultaneously in the CO_2.

5.6 Practical recommendations for specific types of meters

5.6.1 Coriolis

Regardless of the application, the general factors to consider when using Coriolis flow meter technology include: (i) temperature effect, (ii) pressure effect, (iii) Zero effect, (iv) viscosity effect, and (v) compressibility effect, also known as Velocity of Sound (Vos) effect [79].

The temperature and pressure effects are not fluid-dependent. Thus, CO_2 service is, in thisregards, not uniquely different from other common applications. The temperature effect is a function of materials and is well-known and commonly compensated automatically in Coriolis meters based on the measurement input of an internal temperature measurement element. Similarly, pressure corrections have their origin in the change in shape of the tubes and are well-known.

The viscosity effect is only applicable for high viscous fluids; CO_2, in any state, has a low viscosity (under 20 ·10-6 Pa.s).

The minimum flowrate of a Coriolis flow meter is determined by its behaviour under no flow conditions, i.e., zero effect. The zero effect is a standalone quality which determines the low end of the mass flow range based on the application rangeability requirements.

That leaves the compressibility or VoS effect. The phenomenon relates the drive frequency f_0 of the Coriolis tube vibration, the speed of sound in the fluid c, the inner radius of the measuring tubes r, and a scale factor SF determined for each type of meter depending on its construction [79], as follows:

$$E_m = SF\,\frac{1}{2}\left(\frac{2\pi f_0}{c}r\right)^2 \qquad \textbf{\textit{(4)}}$$

Thus, the compressibility effect is more significant for larger Coriolis meters with a high drive frequency, at applications where fluids have a low speed of sound. The work from [79] shows that Coriolis meters smaller than 2 inch and with operating frequency below 200 Hz, have negligible VoS effect. For larger meters with low natural frequencies or small meters with high natural frequency, the assessment of VoS effect should be done separately.

If large throughput is not required and space or pressure drop are not limiting factors, one approach to avoid or mitigate influences of VoS effect in CO_2 measurement would be to design measurement systems with multiple, parallel runs made of smaller-size meters. If that is not the case, and larger sizes are desired, the best option would be to select Coriolis flow meters with the lowest possible natural frequency. This will become more relevant when impurities are present.

The Mach number dependence was investigated in [80]. The term becomes dominant at tube Mach numbers of $Ma>0.2$. This means that for a gas service with a speed of sound of 250 m/s, at flow velocities in the tubes of 50 m/s, the effect must be considered.

(a) Presence of impurities

The presence of impurities in CO_2 alters its speed of sound. Therefore, the use of equation (4) without consideration of the impact of impurities on the speed of sound, could lead to incorrect estimation of the mass error shift. The work in [79] shows that potential variation in the speed of sound in supercritical CO_2 due to the presence of non-condensable impurities can be much more significant than for gaseous CO_2. Again, Coriolis flow meters with low drive frequencies have lower sensitivity to impurities in both the gas and dense phases.

The pressure and the speed of sound correction depend on the meter vendor and meter size and need to be quantified to enable the correction under CO_2-rich gases [46].

(b) Transferability

The calibration of Coriolis meters requires matching flow rates. Density output should typically be corrected for pressure, temperature and compressibility 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 CO_2 [7].

Note that the Reynolds number for gaseous CO_2 is two to three times higher than for nitrogen or methane for a given volumetric flow rate. The compressibility difference between CO_2 and the proxy fluid must be considered and corrected for [42]. For liquid CO_2 at conditions relevant to CCUS, the Reynolds number is between 4 and 18 times that of water at the same flow rate [7]. Such a difference should be reflected in the maximum calibration volumetric flow rate with the proxy fluid.

(c) Ambient Temperature

The work in [81] sheds light on how the density measurements from a Coriolis meter are affected by the temperature of the fluid within the meter internal and the ambient air surrounding the meter. A density drift of up to 2 kg/m^3 was detected due to increased fluid-ambient air temperature difference of 1.5°C.

5.6.2 Turbine

It is known that the bearing friction can yield higher measurement errors at lower pressures. Tests where turbine meters have been used, show high measurement errors at low flow rates and low pressure, where the bearing friction correction for turbine meters becomes dominant.

Changes in temperature affect the lubrication properties of the bearings, thus a temperature dependent dynamic bearing friction coefficient needs to be implemented. The correction depends on the viscosity of the lubricant. The model selected also plays a relevant role. Compensation based on the extended Lee model has not been verified for low-viscosity fluids like liquid CO_2. The authors in [80], found that the viscosity model selected overpredicted the temperature correction for the dynamic bearing friction coefficient, leading to a measurement offset.

(a) Thermophysical properties

Other than mechanical integrity concerns due to fluid compatibilities and uncertainties in density calculation, the effect of impurities on the performance of turbine meters is inconsequential.

(b) Transferability

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 [47], 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. To the authors' knowledge, uncertainty analysis and comparisons of water calibrations to liquid CO_2 calibrations for turbine meters have not been performed previously. Work on water and LNG of a turbine flow meter [82] shows 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 LNG. No investigation has been undertaken to understand if the same case occurs with liquid CO_2.

Significant differences in error magnitude and slope from the water calibration were observed in [37]. However, it is argued that calibration with CO_2 by fitting a variable K-factor could potentially decrease measurement errors.

(c) Ambient temperature

Other concerns relate to the effect of CO_2 on the bearings and the thermal expansion of the meter body [47], which is further elaborated in the section for ultrasonic meters.

5.6.3 Differential Pressure (DP)

DP meters with promise for CO_2 service encompass orifice plates, venturi meters and cone meters. In DP meters, a difference in pressure related to the flow rate across a restriction of known geometry is used to compute the mass flow rate.

Unlike smoothly contoured venturi tubes, the sharp-edge orifice causes significant eddying and frictional effects upstream of the plate. If the vena contracta diameter could be determined, then the element of the discharge coefficient that compensates for the diameter of the orifice in place of that of the vena contracta could be eliminated, and the discharge coefficient, compensating for losses alone, would be much closer to one, similar to the Venturi. The work in [83] proposes the introduction of third pressure tapping, which provides additional measurements that can be used to calculate the vena contracta diameter and generate a new flow rate equation for the orifice meter.

The measurement uncertainty of a DP meters, should thus account for the reference uncertainty of the calibration facility, the discharge coefficient fitting residuals, the uncertainty of the density in input to the orifice, measurement uncertainty of the instrumentation used like pressure and temperature, and the uncertainty of the composition.

(a) Thermophysical properties

The accuracy of DP meters depends on the accuracy of the differential pressure measurements and of the accuracy of fluid properties, like the density. However, DP meters, have lower sensitivity to density than ultrasonic technology because density occurs under square root sign in mass calculation [84].

Variation measurements have been observed in the dense-phase and supercritical region with different density inputs, i.e. density measurements and calculations from Equations of State [37]. Further, higher variations were reported in the supercritical phase, due to the high sensitivity of the EOS to the pressure and temperature measurements in the region. A recommendation to employ direct density measurements from [37], suggests caution in exclusively relying on density values calculated from the EOS until a more comprehensive understanding is achieved on their performance for CO_2-rich mixtures.

(b) Transferability

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 [47].

Calibration with alternative fluids should be suitable for CO_2, 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 CO_2, yet experimental proof is required [7].

5.6.4 Ultrasonic

The attenuation of ultrasound waves through CO_2, is dominated by the fluid’s molecular thermal relaxation properties [85]. Although molecular thermal relaxation is not unique for CO_2, the predominant deterrent is that the acoustic attenuation peak for gaseous CO_2 is in the frequency range typically used in ultrasonic flowmeters, reaching attenuation coefficients up to 6 times that of natural gas at 80 kHz [86]. This effect is, however, less prominent for liquid CO_2, as the relaxation frequency is approximately proportional to the density, up to 900 kg/m^3 [62, 87, 88].

The operating pressure in ultrasonic meters has two effects. Firstly, the reduction of the impedance, which is a general effect for all fluids, and the increase of acoustic attenuation, specific relevant for CO_2 at operational conditions relevant for CCUS.

Special care needs to be taken for low-pressure gaseous CO_2 tests since the speed of sound becomes frequency-dependent [80]. To minimise this effect, a lower operating frequency is recommended.

Experimental campaigns show a large deviation among different ultrasonic technologies. Authors in [80] argue that transferability of calibration results between different gases is not straight-forward and depends on the ultrasonic meter design.

(a) Thermophysical properties

The presence of impurities that have faster relaxation times could dramatically reduce the thermal relaxation frequency, thus aiding acoustic measurements. Even in very small concentrations, significantly different results for the ultrasonic transmission have been documented [46, 89].

(b) Transferability

Transferability is more challenging than for other technologies scalable with Reynolds numbers. Acoustic attenuation is fluid-dependent; it peaks for gaseous CO_2 in the frequency range typically used in ultrasonic flowmeters [90]. The speed of sound of liquid CO_2 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. For subcooled liquid CO_2, the thermal effect resulting from temperature differences of approximately 50 K between calibration and operation must be accounted for. To illustrate this, the thermal expansion on a pipeline cross-section is given by $\Delta D = \alpha D_i \Delta T$, where α is the material linear expansion coefficient, D_i is the initial inner diameter, and ΔT is the temperature difference. For stainless steel, a change in path length of over 0.10 % is likely to occur [47].

(c) Ambient temperature

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 [50]. For liquid CO_2, water calibration and temperature corrections are only viable so long as actual traceable data is available.

Summary of recommendations

Meter Selection

- When capacity allows and uncertainty requirements are met, prefer mass flow meters for direct CO_2 mass measurement to minimise conversion uncertainties.
- Ensure the selected meter is suitable for the phase (gas, liquid, or supercritical) and composition of the CO_2 stream.
- Consider operational range, pressure/temperature limits, and impurity tolerance when selecting metering technology.

Calibration and SI-traceability

- Use SI-traceable calibration methods under realistic operating conditions whenever possible.
- Employ primary standards (e.g., gravimetric or volumetric provers) and maintain traceability to SI units.
- When using Small Volume Provers (SVPs) for calibration, ensure temperature measurement accuracy of the liquid at both the prover and reference meter is within ±0.2 °C. This is critical for achieving a high flow measurement uncertainty, especially under low-temperature and high-pressure CO_2 conditions.
- Consider additional uncertainty contributors, which include repeatability, pulse interpolation, and time measurement errors.
- Ensure that repeatability and accuracy specifications in meter data sheets are clearly defined and referenced. Assess the number of runs, reference definitions, and calibration conditions.
- Uncertainty assessments should also account for installation effects, instrument ageing, and inter-device contributions.
- Calibrate the flow meters and temperature and pressure sensors at a regular interval to ensure accurate, reliable, and consistent measurements of the CO_2 flow.
- Monitor metering health and long-term drift.

Uncertainty Management

- Quantify all sources of uncertainty, including repeatability, linearity, installation effects, and instrument drift.

- Avoid operating near the critical point or Widom line due to the high sensitivity of thermophysical properties.
- Use validated equations of state, suitable for the components of the CCUS streams, for density and phase behaviour predictions.
- Use calibrated meters to ensure the a total uncertainty of 1.5 – 2.5 %

System Design & Operation

- Ensure compliance with relevant regulations and standards for both gas and liquid CO_2 measurement.
- Design systems to maintain single-phase flow and avoid condensation or solid formation.
- Include composition analysers, temperature/pressure sensors, and density meters where needed.
- When single phase cannot be ensured, consider the use of inline phase detection and impurity monitoring to ensure measurement integrity.
- For sampling-based composition analysis, select suitable vessels based on stability studies under identical conditions to those in operation.
- Consider potential interactions between CO_2 and co-present species, especially reactive impurities, to avoid degradation or misrepresentation of sample integrity.
- In general, calibrate metering units across expected pressure/temperature range.
- The influence of meter size and impurities on compressibility correction factors should be further studied.
- When Coriolis meters are used:
    - Check the impact of compressibility effects for the specific process conditions. This check equally applies to liquid and gaseous phase.
    - Correct for compressibility effects, if necessary, to meet uncertainty requirements.
    - If compressibility effects cannot be corrected reliably (i.e. correction equation have not been established):
        - Favour low drive frequency models for reduced compressibility effects.
        - If large throughput is not required and space or pressure drop are not limiting factors, consider designing measurement systems with multiple, parallel runs of smaller-size Coriolis meters.
        - If larger meters are necessary, select models with the lowest possible drive frequency to reduce sensitivity to compressibility effects.
    - Ensure compensation for ambient-process temperature difference
- For ultrasonic meters, use lower frequencies for gaseous CO_2; ensure proper insulation and account for acoustic attenuation.
- During the operation of turbine meters, monitor bearing friction and temperature effects.
- Prior to installing DP meter, validate discharge coefficients experimentally.

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Appendix - Phase envelope diagrams

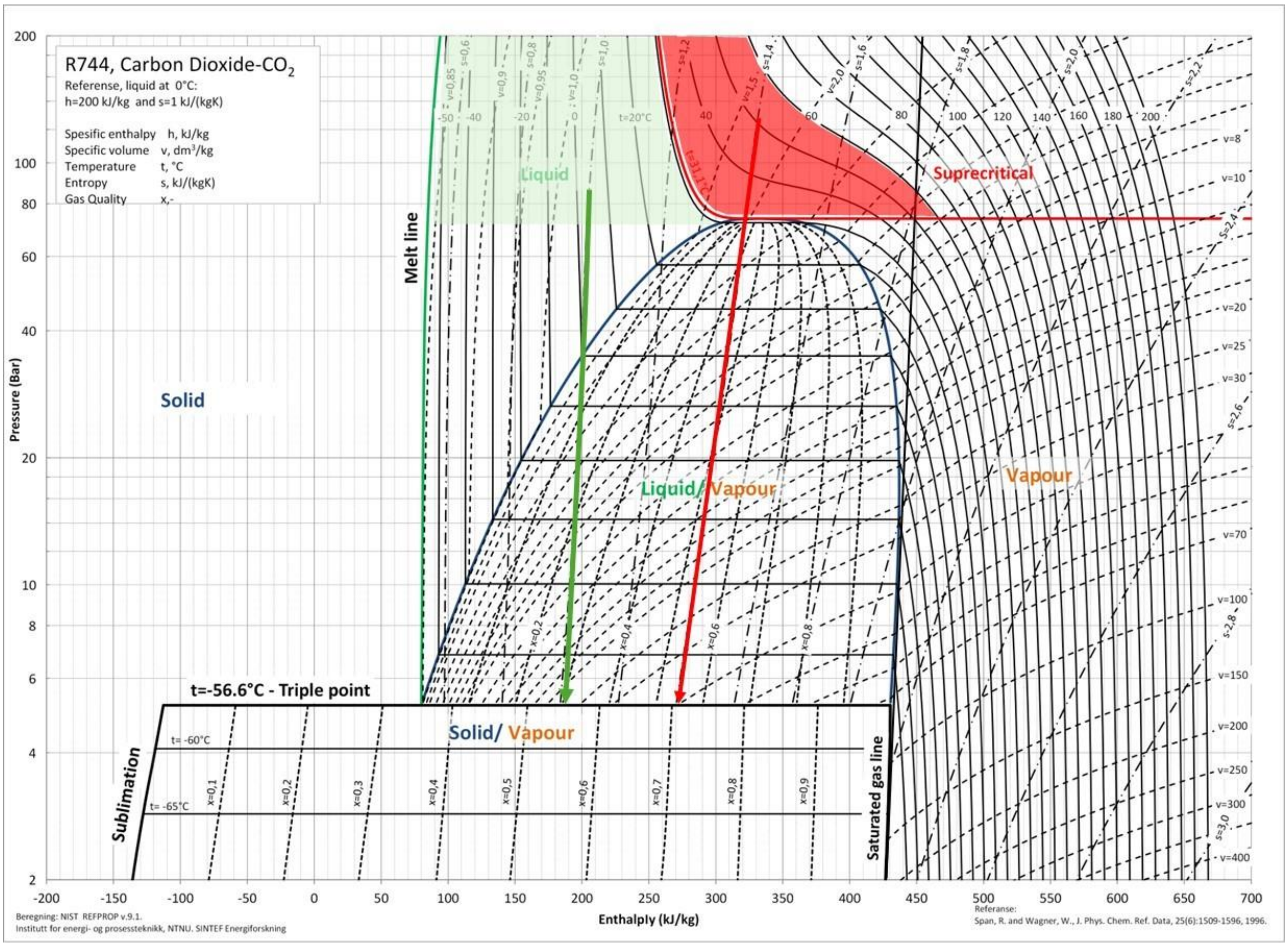
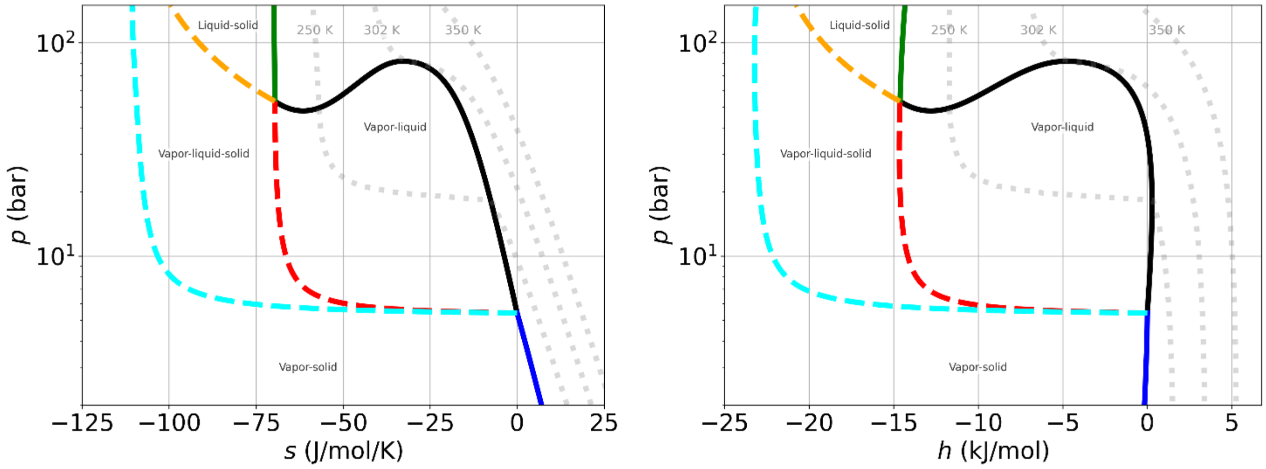


Figure 1 Pressure-Enthalpy diagram for pure CO2, indicating all the phases.



(a) (b)

Figure 2 Diagrams of (a) Pressure-Enthalpy and (b) Pressure-entropy for a CO_2 mixture containing N2=2.25%, CH4=1%, and H2=0.75%.