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Considerations for CO_2 metering and allocation systems

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1 INTRODUCTION

With decarbonisation ambitions moving forward, the transport of CO_2 is becoming increasingly important to facilitate carbon capture, utilization, and storage (CCUS). As for natural gas systems, accurate measurement and subsequent billing for CCUS is required to show compliance with national and international emissions-reduction regulations, like the EU Emission Trading System (ETS) [5], [6]. The ETS commission implementation regulation 2018/2066 states that all CO_2 reported amounts above 500 kilotons/year should be within an uncertainty of 2.5% (k=2) independent of the thermodynamic state of the CO_2, i.e. gas, liquid, dense or supercritical phase. Each of these thermodynamic phases impose new challenges for flow metering technology, or more generically, flow metering and allocation systems. Next to that, regulation is often just a starting point and standards and guidelines will require adjustment to accommodate CO_2 measurements. The experience gained in upcoming pilot projects may set new limits for uncertainty. Current project contracts like Porthos are already demanding lower metering uncertainty than the ETS.

At NSFMW 2021, a paper was presented by DNV and Gasunie concerning flow performance testing of metering technologies and the challenges experienced under CO_2-rich gas streams [21]. The current work focuses on how these measurements will be used in CO_2 transport/allocation systems. As will be shown, the choice of where to install the metering equipment (i.e. under which conditions the meters will be operating) will have an impact on the total uncertainty of the measurement system. One example is the dependence of volume-based metering systems on the equation of state calculations for density. In recent years, much research has been dedicated to the development and verification of equations of states for CO_2-rich streams [8]. These improved equations of states indicate that, from a metering perspective, certain regions of the phase diagram should be avoided to prevent large sensitivity to pressure and temperature measurement.

Next to that, large CCS transport networks (and systems containing liquid CO_2 storage) have large buffer volumes/line pack in between measurement systems. Depending on the operational conditions, these large volumes may cause an uncertainty that is much larger than the typical measurement uncertainty in a CO_2 allocation system. This in turn will dictate the minimum required allocation period, which may become of the order of days.

An increased uncertainty in measurement systems and the exact layout of the CCS network may influence the approach used for allocation. DNV has attempted to capture these effects in a generalized framework for CCS transport systems to help the industry to quantify these effects and make decisions on the used allocation method.

2 REGULATION

Generally, CCUS policies find their way through acts, directives and regulations towards standards and guidelines, as visualized in Figure 1. These regulations often cover the full scope of CCUS projects, from capture to storage, and often do not cover specific conditions for metering and allocation systems. Most regulations state a maximum uncertainty on measured/transported/stored CO_2.

The implementation of these regulations towards metering standard and guidelines is an ongoing process that is expected to progress fast in the next couple of years. Section 2.1 and 2.2 provide an overview of relevant regulation for flow metering and allocation for CCUS systems. A brief overview of existing metering guidelines for both gas and liquid metering systems is provided in section 2.3, and the applicability of these standards is further elaborated.

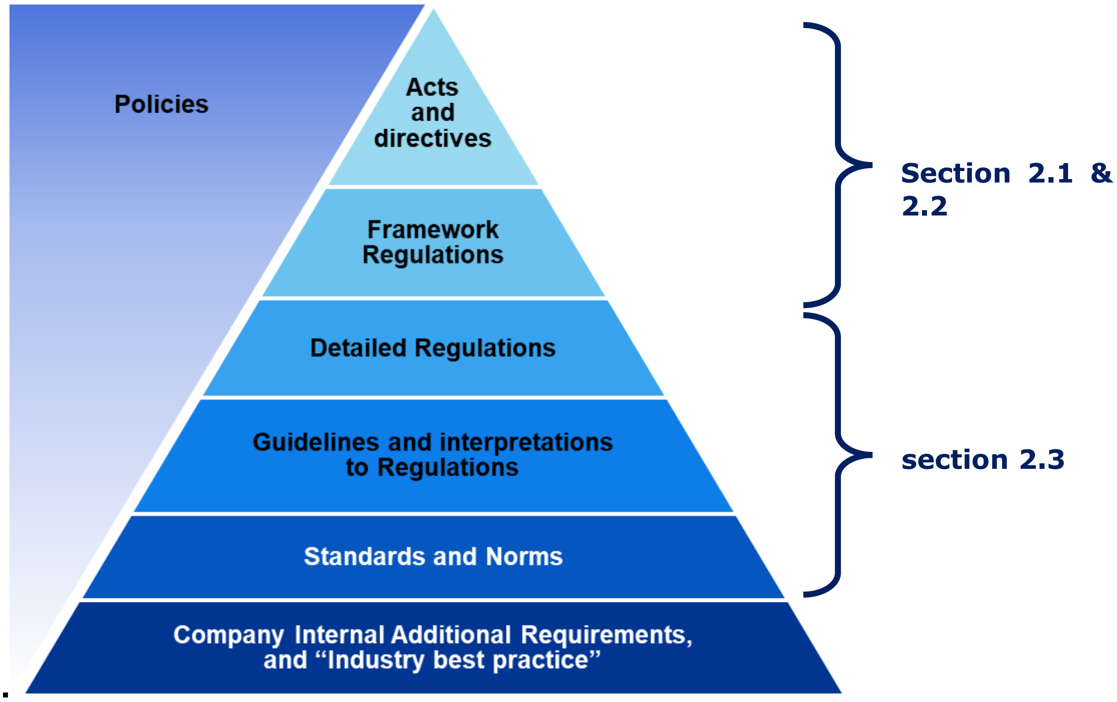

Figure 1 : Graphical representation of the implementation of policies towards regulations, guidelines and standards.

2.1 Global legal and regulatory framework for CCS

The EU ETS [5], [6] deploys a tier system for measurement-based methodologies and states that for each major source, the operator should apply the highest tier for category B and C emitters. Moreover, when the CO_2 is transferred out of the installation monitoring boundary to a capture installation, transport network or a storage site (all with the purpose of long-term geological storage), the highest tier should be applied regardless of the installation category. This means that for the measurement system a 2.5 % uncertainty limit on mass quantity applies. The measurement system includes the flow metering device and all associated equipment (e.g. compositional analyser, pressure and temperature, see section 3.2) and calculations required to provide the mass quantity of CO_2 transferred out of the installation monitoring boundary.

It should be noted that the EU ETS tiers for measurement-based methodologies were developed for Continuous Emission Monitoring System (CEMS) applications, 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. Oil & Gas typical metering skid will be used instead in this case meaning that the ±2.5 % requirement do not capture appropriately the performance of the technology used in the field. Similarly, when the CO_2 is transferred to a geological storage, measurement technologies other than CEMS will be used and the ±2.5 % requirement can be found inappropriate.

The US EPA Part 98 document states general emission monitoring accuracies in Subpart A [23]. For flow measurement systems used in transportation of CO_2 an uncertainty within 5% is demanded without specific mention on volume or mass. Flow meters based on differential pressure are excepted from flow calibration and require only sensor calibration with 2% of the full range. The specific Subpart RR for Geological Sequestration of Carbon Dioxide [24] states that any measurement device should comply with the accuracy requirement as set out in Subpart A and that the devices should be calibrated at facilities that are traceable to The National Institute of Standards and Technology (NIST). For the calibration procedure, an appropriate industry standard/guideline as published by a consensus-based standards organization, like the API or AGA may be used.

2.2 Allocation systems

The scope of an allocation/transport system is defined in the EU ETS 2018/2066 [**5**]. 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 of a transport network may quantify the emissions either by mass balancing of the allocation system (Method A) or by monitoring the emissions source individually (Method B). 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 %. Also, this method should be verified by the first mass balancing method (Method A) annually. It follows that 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.

It is noted that the EU ETS does not explicitly mention transportation by ship [9]. 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 [18].

2.3 Flow metering standards and guidelines

2.3.1 Liquid metering

The metrological and technical requirements applicable to dynamic measuring systems for liquids other than water are specified in the OIML R 117-1 [19]. Based on the field of application, the 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 uncertainty of the complete measuring systems of 1.5 %. Also, R117-1 specifies that the maximum permissible errors for a flow meter under rated operating conditions is 1 % for the measuring system of Accuracy Class 1.5.

NIST is the US National Institute for Standards and Technology. NIST Handbook 44 [17]. 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 %.

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 [14]: 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 [10]: Turbine meters for liquid hydrocarbon measurements. The standard is applicable to the metering of any appropriate liquid with 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 [11]: 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 [15]: 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 irrespective of the fluid and primarily a function of the Reynolds number. 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"*.

2.3.2 Gas metering

The principal recommendation of interest to CCS is OIML R 137 Gas meters [20]. Based on the field of application, the measuring systems are classified into three accuracy classes. The standard does not explicitly mention CO_2 however makes a general statement of the use of gas meters under different gases: *"The types of gas meters which are intended to be used for different gases shall comply with the metrological requirements as mentioned in 5.3 over the whole range of gases for which they are specified by the manufacturer"*.

The NIST Handbook 44 [17] only considers hydrocarbon gases and does not mention gaseous CO_2. It only states that a vapor equalization line shall not be used during a liquid CO_2 offloading unless the quantity of vapor displaced from the buyer's tank to the seller's tank is deducted from the metered quantity.

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 [14]: Coriolis meter standard for the measurement of liquid and gas applications.
- EN 12261:2018 [4]: Turbine meters for gas flows. The standard is applicable to the metering of general gas flows however does not mention CO_2 gas.
- ISO 17089 [12] and [13]: Ultrasonic meters 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 [15]: Measurement of fluid flow by means of pressure differential devices.

3 ALLOCATION AND FLOW METERING

Gas flow measurement systems can serve various purposes in a transport system, i.e. operational metering, allocation metering or custody transfer/fiscal metering. Depending on the purpose of the meter these measurements will be subject to allocation. Multiple methods were devised for oil and gas, but due to the differences between oil and gas transport systems and CCS transport systems, these methods may not be appropriate for CO_2 allocation.

A typical CO_2 transport system is schematically represented in Figure 2. In this figure an attempt is made to include all possible configurations for a given transport network. The CCS transport chain starts at the emitters where the CO_2 is captured and either transferred to a joint transport line or directly connected to a liquification plant. Following the top (black) transport line, the gas is typically transported via an onshore transport line towards a compressor station and brought to dense phase. The dense phase is then further transported either onshore or offshore to the injection location. Both the onshore gas and on/offshore transport pipelines may have a large buffer volume, and this may lead to long allocation periods to prevent a dominant uncertainty contribution due to change in buffer volume, this will be further explained in section 3.1.3. The lower part of the allocation schematic shows the process in which the CO_2 is liquified for shipping. After the liquification the CO_2 is temporarily stored before ship loading. After ship transport the inverse process takes place where the offloaded CO_2 is temporarily stored and pumped to high-pressure dense phase for further transportation and injection.

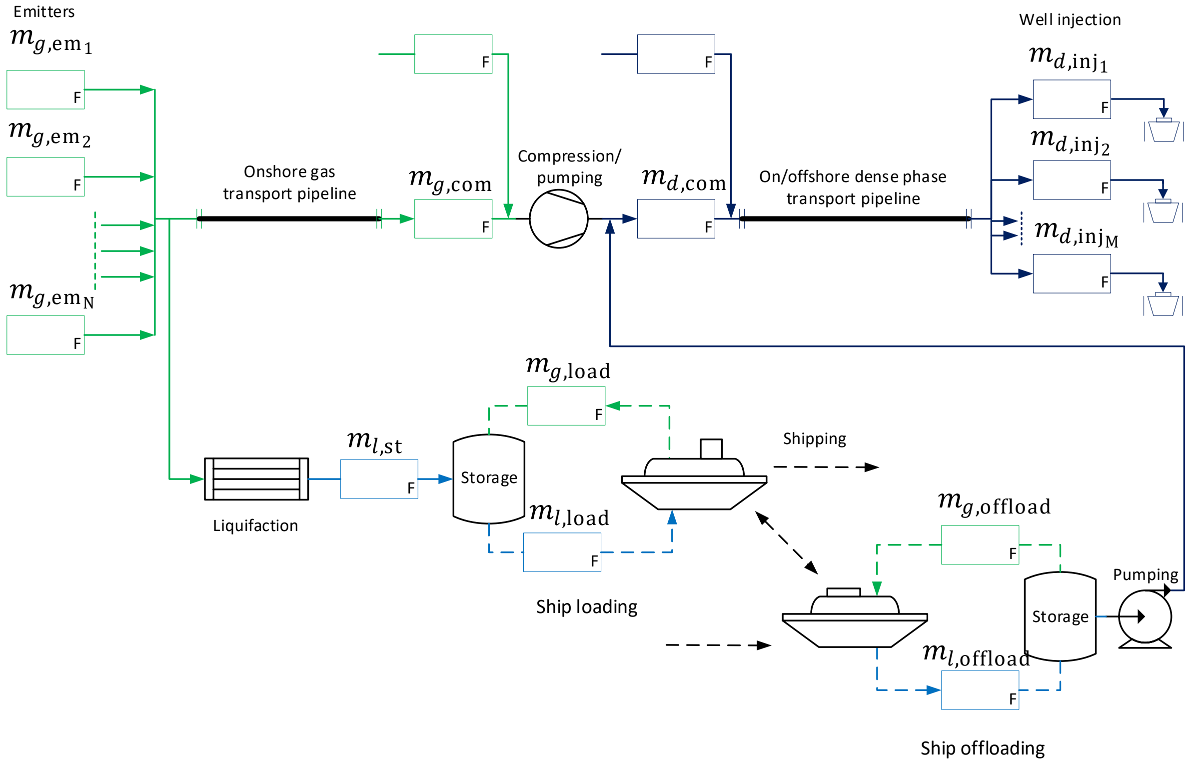

Figure 2 : Schematic representation of CCS transport/allocation system: gas streams indicated in green, liquid streams in light blue and dense phase in dark blue; continuous streams indicated by solid lines and intermittent streams by dashes lines.

In Figure 2, the measurements are indicated and provided with a variable which will be used for explaining different allocation methods in the remaining part of this section. The gas streams are indicated in green, liquid streams in light blue and dense phase in dark blue. The continuous streams are indicated by solid lines and intermittent streams by dashes lines. At each of the stages in the transport systems, i.e. compressor station, pipeline transport, storage and during shipping, emissions may occur. Emissions can be fugitive (unintentional, irregular, small and distributed) or vented (intentional, planned and a defined location of emission) typically for operational/maintenance reasons. Emission can be quantified based on theoretical quantification models or based on mass balancing.

3.1 Allocation

Allocation systems are necessary in shared transport networks to determine the amount of substance each user is entitled to once the input flows of the users have been commingled. The design of allocation systems typically involves selecting measurement equipment, measurement points in the network, allocation methodology and allocation period.

In an allocation system often the total mass, denoted by m_g, and the CO_2 mass require reconciliation, denoted by $m_{g,\mathrm{CO_2}}$. This means that for system balancing, the rest components are of importance and need to be accounted for. The CO_2 mass is obtained by multiplying the total mass by the CO_2 mass fraction $x_{\mathrm{CO_2}}$ which is obtained from composition measurement:

$$m_{g,\mathrm{CO_2}} = m_g \cdot x_{\mathrm{CO_2}}. \quad \textbf{(1)}$$

Due to uncertainties in the composition determination, the CO_2 mass balance requires an allocation procedure as well. So, the allocation systems described in this section apply to both the total mass and CO_2 mass. In the remainder of this section the equations will be presented in terms of m_g while it should be understood that these methods are also applicable to $m_{g,\mathrm{CO_2}}$.

In contrast to traditional upstream oil and gas networks, less complex measurement conditions are expected at the upstream side for CCS projects. In oil and gas systems, the upstream measurements are often performed in multiphase conditions which inherently results in higher measurement uncertainty. For CCS system the measurements along the value chain are expected to be of the same level of uncertainty. In fact, the measurement uncertainties at the capture site may be even lower compared to the measurement of the commingled flows which are typically at higher pressures and in the more complex domain of the CO_2 phase envelop. Consequently, alternative allocation methods that are not based on a hierarchical measurement uncertainty chain may prove to be more applicable for CCS networks.

3.1.1 Allocation method: EU ETS

The EU ETS directive suggests a method that considers both individual measurements of emitters and the measurement of the commingled flows, rather than solely relying on the commingled measurement to determine the amount of CO_2 transported. The suggested method in the ETS is to use the arithmetic average of the in- and output of the allocation system under the condition that the imbalance can be explained by uncertainty of the measurement systems [6].

For the onshore gas transport system as depicted in Figure 2, this becomes:

$$m_g = \frac{\sum_{j=1}^{N} m_{g,\mathrm{em}_j} + m_{g,\mathrm{com}}}{2}. \quad \textbf{(2)}$$

It depends on the specific project which measurement is used for allocation purposes, i.e. in equation (2) also the measurement downstream of the compressor station (or the injection measurements) could be used instead of $\boldsymbol{m_{g,\mathrm{com}}}$. The choice depends on the availability and the expected uncertainty of the flow measurement system, this is further elaborated for gas metering systems in section 5.2.

The subsequent back allocation for each of the emitter quantities can be performed by pro-rata allocation and the value upstream the compressor station is set equal to the arithmetic average of equation (2).

3.1.2 Allocation method: Inverse variance weighting

Equation (2) implicitly assumes equal uncertainty of the input and output flow measurements, which is typically not the case. It is possible that the uncertainty of the sum of individually measured input flows is lower than the commingled flow measurement. High measurement accuracy can be achieved at the capture site and the combined uncertainty of multiple measurements is lower than that of a single measurement. Consequently, more accurate allocation results can be achieved by using a weighted average of the input and output measurements. Inverse variance weighting is a method to minimize the variance of the average [16]. By doing so, the quantity with the lowest uncertainty will be given a higher weight factor in determining the total transported quantity and the weighted average will shift towards the most accurate measurement. Scaling the input and output by their inverse absolute variance ($\sigma_{\mathrm{em}}^{-2}$ and $\sigma_{\mathrm{com}}^{-2}$,respectively) and normalizing the weights results in:

$$m_g = \frac{\sigma_{\mathrm{com}}^2}{\sigma_{\mathrm{em}}^2 + \sigma_{\mathrm{com}}^2} \sum_{j=1}^{N} m_{g,\mathrm{em}_j} + \frac{\sigma_{\mathrm{em}}^2}{\sigma_{\mathrm{em}}^2 + \sigma_{\mathrm{com}}^2} m_{g,\mathrm{com}}. \tag{3}$$

For completeness, the absolute variance of the sum of the emitters is determined by:

$$\sigma_{\mathrm{em}}^2 = \sum_{j=1}^{N} \sigma_{\mathrm{em}_j}^2. \tag{4}$$

The subsequent back allocation for each of the emitter quantities can be performed by uncertainty-based allocation:

$$\widehat{m}_{g,\mathrm{em}_j} = m_{g,\mathrm{em}_j} + \frac{\sigma_{\mathrm{em}_j}^2}{\sigma_{\mathrm{em}}^2} \left(m_g - \sum_{j=1}^{N} m_{g,\mathrm{em}_j} \right), \tag{5}$$

where the hat indicates the allocated value and the value between the brackets is the measurement imbalance. This method requires uncertainty (variance) input from the measurement systems which may be subject for discussion among partners, especially when different measurement technologies and equations of state are used. It should be well-defined within the allocation concept how these variances are to be quantified.

3.1.3 Allocation method period

In CCS transport systems, the transport lines can become long and therefore large mass inventory may be present in the allocation system. For compressible fluids, these mass inventories can change due to changes in pressure and temperature. This so-called line pack needs to be compensated for in the allocation procedure, e.g. for the onshore gas transport part in Figure 2 this becomes:

$$m_{g,\mathrm{com}} = \sum_{j=1}^{N} m_{g,\mathrm{em}_j} - \Delta\rho_g \cdot V. \tag{6}$$

The difference in gas density over the allocation period is denoted by $\Delta\rho_g$ and the inventory volume by V. Due to uncertainties in pressure and temperature (and as second order effect the composition), the density calculation inhibits uncertainty and therefore the mass inventory also has uncertainty. Depending on the mass flow rates and the inventory volume of the pipeline, the allocated quantities may be influenced by the uncertainty in the inventory calculation. To prevent this effect to become dominant in the allocation procedure, the allocation period should be sufficiently long.

A way to quantify the minimum allocation time interval is to impose that the contribution of the inventory uncertainty is a factor f smaller than the uncertainty of the mass flow measurement system. For the onshore gas transport example in equation (6) the minimum allocation period is calculated as:

$$\Delta t > f\,\frac{U(\Delta\rho_g)V}{U(\dot{m}_{g,\mathrm{com}})}, \tag{7}$$

where $U(\dot{m}_{g,\mathrm{com}})$ is the absolute uncertainty in the mass flow rate and $U(\Delta\rho_g)$ is the absolute uncertainty in the density difference. As an example, consider a 16″ gas pipeline of 20 km length operating at 30 bar with a total mass flow rate of 200 t/h, and assume a relative uncertainty of 0.5% on the mass flow and density calculation, then the allocation period should be at minimum 12 hours for $f = 3$.

3.1.4 Allocation of utilities and emissions

In CCS allocation systems processing steps, like compression or liquefaction, may be required to transport the fluids further downstream, see Figure 2. These processing units consume power, and the costs and emissions need to be back allocated to the different emitters. In most contracts this is performed on a pro-rata basis. This approach can be disputed since the power consumption is not linearly proportional to the transported volume. This can be resolved by using more complex allocation methods based on Game Theory as explained by Stockton in [22]. The application of Game Theory to, for example, a compressor station requires an in-depth analysis of the operation of the station and should be developed for each specific application.

At each of the stages in the transport systems, i.e. compressor station, pipeline transport, storage and during shipping, fugitive and vented emissions may be expected. These emissions should be treated within the allocation process and depend on the contract between the partners. These emissions may be pro-rata allocated to all emitters (often done for fugitive emissions) or allocated based on a case-by-case when the emission is traceable to a single emitter or the pipeline operator (often done for vented emissions). The handling of fugitive and vented emission is part of the allocation agreement based on what is considered equitable for the partners and is not pre-specified in any standards.

As explained in section 2.2, the emissions may also be quantified by balancing in and output streams (Method A). For most emissions, however, the quantities are much smaller than the measurement uncertainty of the in and output flows, making emission quantification a difficult task.

3.2 Metering system uncertainty

A gas flow metering station will generally consist of a set of flow meters in a predefined configuration, pressure and temperature sensors (per meter) and an online or offline composition analysis system.

In a previous paper [21] we have demonstrated the effect of CO_2 on metering equipment with an experimental facility at DNV. This facility is currently being upgraded under the DNV JIP CO_2MET Gas to enable calibration of gas meters under CO_2-rich gas streams.

For volume-based meters, the composition directly feeds into the mass flow determination by using pressure and temperature and an equation of state (eos). For mass-based meters, the composition measurement is only used to determine the CO_2 content of the stream. The eos by itself has an uncertainty/bias, however, a lot of research has been dedicated to achieving low uncertainties on these models [8]. Next to that, the eos will propagate the uncertainty of pressure and temperature to density and as will be shown in the following section, this may have a large impact on the total uncertainty of the measurement.

3.2.1 Uncertainty of equation of state

The eos is important for the calculation of the physical properties. For the gas metering systems based on volume flow meters as described above, the density calculation is of main importance. Also, differential pressure-based measurements depend on the calculation of the density, however, the uncertainty propagates with half the factor as compared to volume-based meters (due to the square-root dependence on density).

In this section we will concentrate on the density calculation and determine the relative sensitivity of the density to the uncertainty in pressure and temperature. The eos depends on pressure, temperature and composition and the propagation of uncertainties on these independent input parameters can be written as:

$$U^*(\rho_g) = \sqrt{\left[S_p^* U^*(p)\right]^2 + \left[S_T^* U^*(T)\right]^2 + \sum_i \left[S_i^* U^*(x_i)\right]^2}, \quad \text{with } S_y^* \equiv \frac{y}{\rho}\frac{\partial \rho}{\partial y}, \qquad \textbf{(8)}$$

where the sum runs over all components in the gas mixture. In the current analysis, the focus will be on the relative sensitivity parameters for pressure and temperature due to their interesting behaviour. These sensitivities are presented as function of pressure and temperature in Figure 3 for pure CO_2 and based on the EOS-CG [8].

The figure shows that in the gas phase far below the critical point the sensitivities for pressure are in the range between 1 and 2. These relative large number are caused by the (non-ideal) compressibility of CO_2 in the gas phase. Near the critical point S_p^* can increase up to 3, whereas in the supercritical domain values of 8 can be obtained. This means that small relative uncertainties of pressure of e.g. 0.1% will result in 0.8% uncertainty for density. The near zero values for liquid CO_2 demonstrate the incompressibility of liquid CO_2 and hence the insensitivity of the density calculation to uncertainty in pressure.

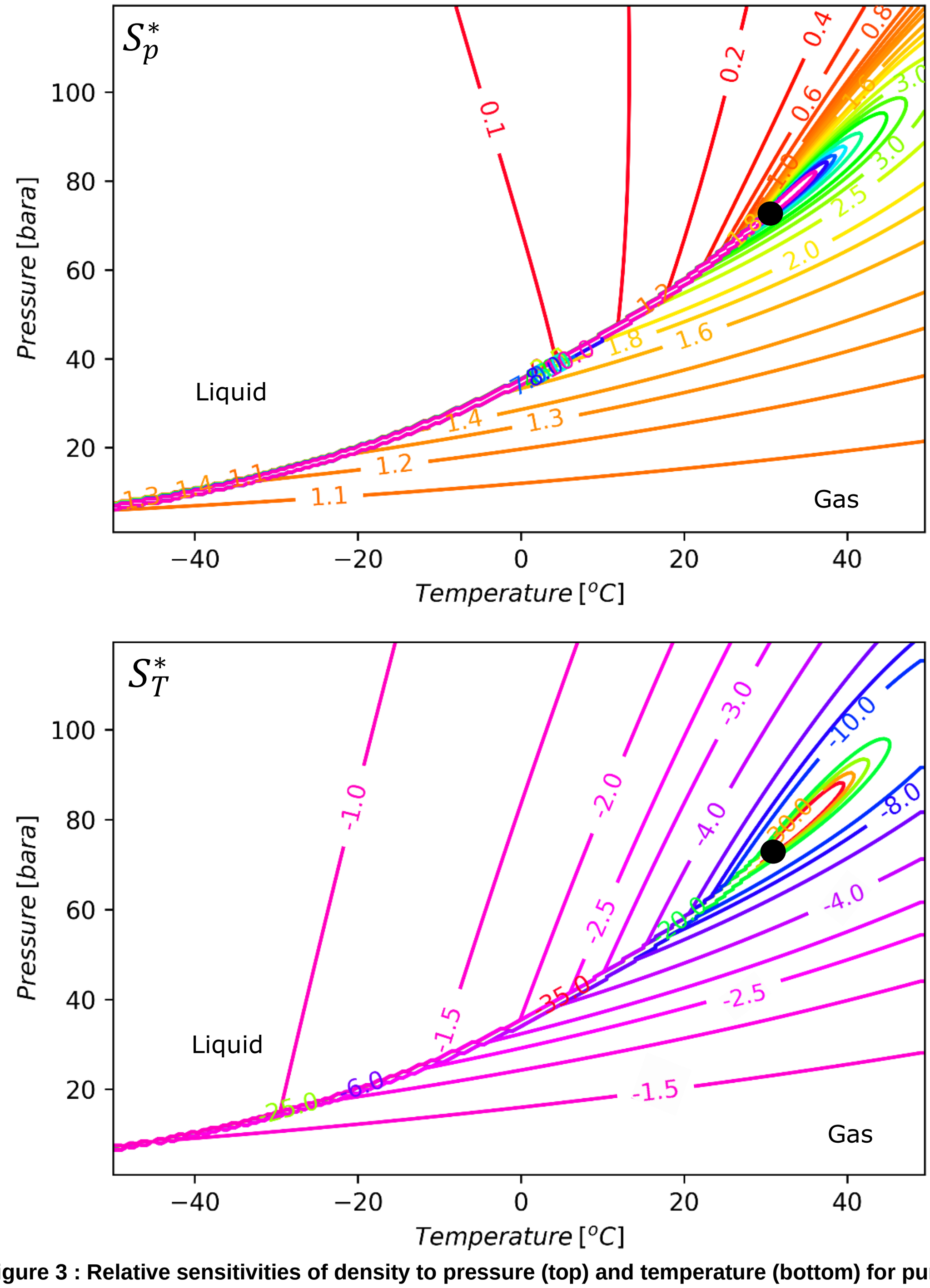

Figure 3 : Relative sensitivities of density to pressure (top) and temperature (bottom) for pure CO_2 based on EOS-CG; critical point indicated by black dot.

For the sensitivity to temperature similar behaviour is observed, however, with larger values for S_T^* that can increase up to -35 around the critical point (the values are negative since the density decreases with increasing temperature). This is mainly due to the definition of the relative sensitivity where the temperature is taken in units of Kelvin. It is noted that for typical gas applications, the relative uncertainty of the temperature measurement (also in units of Kelvin) is lower than the relative uncertainty of pressure. Therefore, the higher values for S_T^* between a factor of 1.5 and 3 larger than for pressure do not influence the density uncertainty as much as may be expected from the figure.

4 CONCLUSIONS

The CCS industry is moving at a rapid pace. Regulations are being developed around the world to facilitate the uptake of CCS. At the same time measurement specific standards and guidelines will need to be extended to the applications as found in CCS transport systems. This development is expected to accelerate in the upcoming years.

In this work, we have attempted to highlight certain peculiarities of CCS measurement and allocation systems that need to be considered and are different from our standard practice in oil and gas. Several (pilot) projects will start in the near future that will provide the community with valuable experiences and data from which the standards and guidelines will be developed further. In the meantime, activities have started to further develop the metrological structure for CO_2 gas calibrations [3], JIPs have been launched [1] and new test facilities are being built to suit the need of the industry [2].

5 NOTATION

f	Required reduction factor in uncertainty for line-pack effect
m_g	Total mass (in gas phase)
m_{g,CO_2}	CO_2 mass (in gas phase)
$\hat{m}_g$	Allocated mass (in gas phase)
S_y^*	Relative sensitivity of density to y
$U^*(y)$	Relative uncertainty of y
V	Pipeline inventory volume
x_{CO_2}	Mass fraction CO_2
Δt	Allocation period
σ_m^2	Variance of measurement m

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