Custody transfer of hydrogen: Design of fiscal flow metering stations

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1. INTRODUCTION

The global demand for hydrogen is foreseen to grow significantly in the next decades [1]. Large scale transport of gaseous hydrogen through pipelines is considered the most cost-efficient distribution method for distances up to at least 2-3000 km, compared to the alternatives such as transportation in tube trailers or as liquified hydrogen or ammonia. Several European initiatives, including the Hynetwork (https://www.hynetwork.nl/en) in the Netherlands and the European Hydrogen Backbone initiative (https://ehb.eu/), aim to repurpose existing natural gas infrastructure and build new hydrogen pipelines to enable a future hydrogen economy.

For natural gas, custody transfer practices are well established, supported by international standards (e.g., OIML R140 [2], ISO 15112 [3]) and decades of operational experience. While some foundational principles can be transferred, the transition to hydrogen introduces new technical and operational complexities that must be addressed. Thus, there are several challenges in transferring competence and practice to hydrogen:

1. The physical properties of hydrogen differ significantly from natural gas, which will affect the behavior of flow meters.
2. The variation in flow rates in the hydrogen transmission network will be higher than for natural gas due to variable renewable production, which sets requirements for the turn down ratio and dynamic response of the flow meters to handle the rapid change in flow rates.
3. More cost-efficient metering and allocation methods are needed as the economic margin for hydrogen will likely be lower than for natural gas.

Additionally, safety and integrity issues are significantly more severe for hydrogen than for natural gas and set strict requirements on the mechanical solutions.

While several studies and vendor reports discuss hydrogen metering technologies, there is limited published work that systematically compares technology options for custody transfer under realistic operating conditions and links this to metering station design. In particular, while metering station design methodologies are well-established for natural gas, there is limited published guidance on how to systematically adapt these approaches to hydrogen applications, where significantly different physical properties, higher flow dynamics, and tighter economic constraints require careful reconsideration of technology selection, sizing criteria, and uncertainty propagation.

This paper contributes to the development of hydrogen custody transfer practices by:

1. Systematically evaluating the applicability of common flow metering technologies (ultrasonic and Coriolis meters) for hydrogen custody transfer, based on vendor input, literature, and operator experience from natural gas.
2. Presenting a structured framework for configuring and comparing metering station designs, including uncertainty considerations.
3. Applying this framework to a case study of an electrolyser-based hydrogen producer delivering to the Hynetwork pipeline, illustrating practical design trade-offs and uncertainty results.

The analysis includes detailed uncertainty propagation studies comparing mass-based and volume-based energy determination methods, revealing important differences in their sensitivity to gas composition uncertainty - insights that are particularly relevant for high-purity hydrogen applications.

This work has been performed as a part of the HyMe research project, a competence-building initiative (2023–2026) focused on developing knowledge and methodologies for reliable and cost-efficient hydrogen metering. The project addresses key challenges related to large-scale transport of pressurized hydrogen through pipelines, including metering technology performance, metering station concepts, calibration and traceability, and detection of supply chain losses and quality changes. HyMe is coordinated by NORCE in collaboration with Equinor, Gassco, Shell, TotalEnergies, Justervesenet, and the University of Bergen, and is partly funded by the Research Council of Norway (project 336565).

2. BACKGROUND

2.1. Hydrogen vs Natural gas: Property implications

Compared to natural gas, the physical properties of hydrogen at similar pressure and temperature conditions differ significantly. Figure 1 shows a comparison between a natural gas (Ekofisk) and hydrogen for density and speed of sound (SOS) as a function of pressure. The properties were calculated using GERG-2008 [4] (ISO 20765-2 [5]) Equation of State with the REFPROP software from NIST [6]. Hydrogen density is approximately an order of magnitude lower than that of natural gas, while the speed of sound (SOS) is about three times higher for hydrogen than natural gas.

The volumetric energy density (kWh/m^3) of natural gas is more than 3 times higher than that of hydrogen. Consequently, to transfer the same amount of energy using hydrogen instead of natural gas, the gas velocity, pipe diameter and/or pressure must be increased. However, several tradeoffs must be considered, particularly issues related to pipeline integrity and process constraints. Higher gas velocities increase the risk of erosion and vibration, which can compromise pipeline integrity and reduce component lifetime. Frictional losses, compressor power demand and operating costs also rise with increased velocity. In addition, flow meters often have maximum velocity limits that cannot be exceeded. Increasing pipe diameter comes at the expense of higher material and installation costs, a larger footprint, and challenges in repurposing existing infrastructure. Similarly, operating at higher pressures requires thicker and/or more costly materials and may have implications for compressor design and energy consumption.

These property differences have direct implications for flow meter selection and configuration. The lower density affects the sensitivity of mass flow meters, while the higher speed of sound influences the signal processing requirements for ultrasonic meters. The need for higher velocities to achieve comparable energy throughput also affects the operating range and turndown ratio requirements for metering stations.

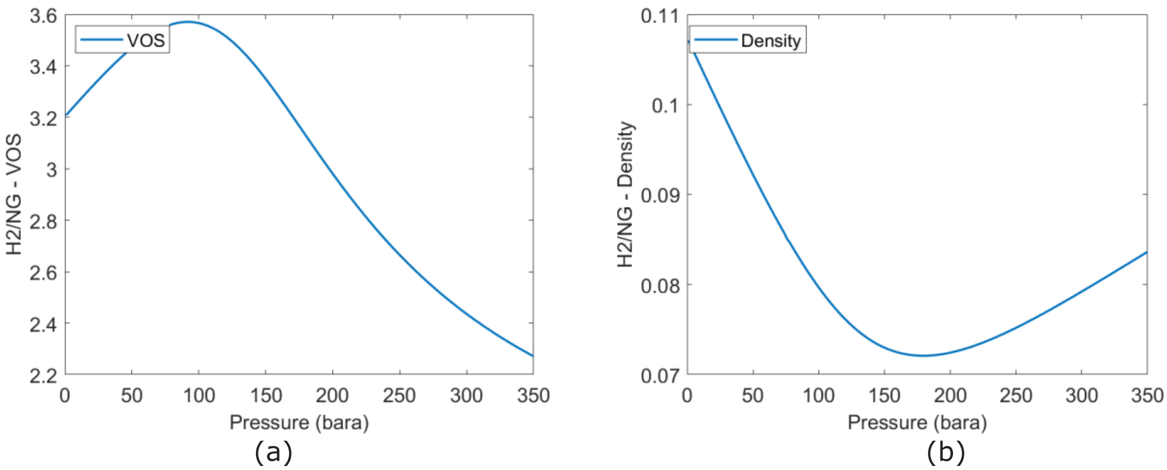

Figure 1 Hydrogen-to-Natural Gas Property Ratio (H2/NG) for (a) Speed of sound and (b) Density. Calculations are for a temperature of 20 $°C$.

2.2. Energy determination

The European Association for the Streamlining of Energy Exchange – gas (EASEE-gas) recommends that custody transfer of hydrogen is based on the energy-content of hydrogen molecules [7]. By following the approach in ISO 15112 [3], the energy content of the gas is calculated by combining flow rate measurement and calorific value.

Two fundamentally different metering approaches can be used:

- Mass-based measurement (e.g., Coriolis meters): directly measures mass flow rate
- Volume-based measurement (e.g., ultrasonic meters): measures volumetric flow rate at operating conditions

The choice between these approaches has significant implications for instrumentation requirements, uncertainty propagation, and sensitivity to gas composition—issues that become particularly important for hydrogen due to its low density and the potential for impurities. The mathematical framework below shows how energy is calculated for each approach and sets the foundation for the uncertainty analysis in section 5.6.

The calorific value is typically calculated from measured gas composition using ISO 6976 [8]. For hydrogen with low amounts of impurities, the calorific value can also be determined using correlative methods (e.g. sound velocity) or a fixed value can be used if the impurity level is guaranteed to be stable [9]. The energy over a time interval Δt is calculated from the accumulated energy flow rates over the interval

$$E(t_j) = \Delta t \sum_{i=0}^{j} \dot{E}_i. \qquad (2\text{-}1)$$

For mass-based meters, the energy flow rate is calculated from measured mass flow rates ($\dot{m}_i$), while for volume-based meters it is calculated from volume flow rates at reference conditions ($\dot{V}_{0,i}$),

$$\dot{E}_{m,i} = \dot{m}_i H_{m,i}, \tag{2-2}$$

$$\dot{E}_{V,i} = \dot{V}_{0,i} H_{V,i}. \tag{2-3}$$

Here $H_{m,i}$ is the gross calorific value (GCV) on mass basis and $H_{V,i}$ is the GCV on volume basis. In practice, the summation in (2-1) corresponds to the totalization of small increments of measured volume or mass multiplied by the corresponding GCV, as specified in EN 12405-2 [10], ensuring that variations in flow and composition are accurately captured. The volume rate at reference conditions is found from the measured volume rate at actual conditions ($\dot{V}$) by the following relationship

$$\dot{V}_0 = \frac{T_0 p Z_0}{T p_0 Z} \dot{V}, \tag{2-4}$$

where T, p, and Z refer to temperature, pressure and compressibility factor at operating conditions, and T_0 p_0 and Z_0 refer to the same properties at reference conditions.

The mass-based and volume-based GCV are both functions of the GCV on molar basis (H_c), which is given in ISO 6976 [8]

$$H_m = \frac{H_c}{M}, \tag{2-5}$$

$$H_V = \frac{p_0}{R T_0 Z_0} H_c, \tag{2-6}$$

where M is the molar mass of the gas, and R is the universal gas constant.

Thus, the energy flow rates can be reformulated as

$$E_{m,i} = \dot{m}_i \frac{H_{c,i}}{M}, \tag{2-7}$$

$$E_{V,i} = \dot{V}_i \frac{p}{TZR} H_{c,i}. \tag{2-8}$$

This shows that mass-based energy determination relies on accurate determination of molar mass in addition to the GCV on molar basis and mass rate measurements. Similarly, volume-based energy determination relies on measurement of compressibility factor, temperature, and pressure, as well as volume rate and GCV on molar basis. These relations will be applied later when comparing how uncertainty propagates differently through mass-based and volume-based energy calculations, with particular attention to the role of gas composition uncertainty.

3. TECHNOLOGY MAPPING

Several metering technologies have been reported for hydrogen applications, including ultrasonic (USM), Turbine, Coriolis, venturi, and rotary flow meters. Based on the industry partners' experience from natural gas, we carried out a detailed mapping of some selected technologies. This mapping was based on the basic operating principles, literature review, discussions with vendors, and input from operators and other stakeholders. In particular, we evaluated how the hydrogen physical properties may influence the meters' performances and operating ranges. The evaluation is limited to meters intended for high-capacity transmission networks, and does not consider meters designed for distribution systems or domestic applications.

This study focuses on USM and Coriolis meters, which represent technologies that are particularly promising for hydrogen custody transfer in large and small pipeline applications, respectively, due to their high accuracy potential. This assessment aligns with recent industry evaluations, including the H2GAR Working Group 4 report [9]. In the following we give a summary of the findings for these two technologies, with focus on the following evaluation criteria:

- Influence of hydrogen on basic operating principles
- Technology strengths and limitations
- Operating flow range restrictions

Calibration capabilities are not evaluated separately in this study, as accredited hydrogen-specific calibration facilities for custody transfer at high flow rates are currently not available. This represents a known limitation in studies of this type, as the performance characteristics presented below are based on vendor specifications, laboratory tests at limited conditions, and extrapolation from natural gas experience rather than verified field performance data for hydrogen service.

3.1. Ultrasonic flow meters

The lower density and higher speed of sound in hydrogen compared to natural gas reduce the signal-to-noise ratio due to weaker acoustic coupling at low pressure, increase the risk of cross-talk between transducers because of a wider acoustic beam, and shorten the time-of-flight, which demands higher timing resolution to maintain measurement accuracy. Vendors address these challenges through optimizing the transducer design, electronics and signal processing of the USM.

Ultrasonic flow meters (USMs) offer several advantages for custody transfer applications in hydrogen and natural gas systems. Their non-intrusive design, with no moving parts, ensures low maintenance requirements and long-term reliability. USMs can accommodate high flow velocities and provide a large turndown ratio, making them suitable for dynamic operating conditions. When flow conditioners are avoided, the associated pressure drop is minimal, which is beneficial for energy efficiency. Furthermore, USMs incorporate advanced diagnostic capabilities and can deliver gas quality information through speed-of-sound measurements, adding value for process monitoring. However, limitations exist: USMs are generally not available for small pipe diameters, and their performance at very low flow rates or velocities may introduce increased uncertainty. Additionally, the need for flow conditioning in some configurations can introduce system pressure loss.

The operating flow rate range of a USM is typically restricted by the gas velocity. For natural gas, most vendors provide meters capable of handling at least the range from 0.5 – 25 m/s. Depending on meter size, lower limits down to 0.1-0.3 m/s are claimed by some vendors. Due to the higher sound velocity in hydrogen, the applicable operating range will move to higher velocities. Some vendors report that they have successfully reached 80 m/s in flow loop tests [11]. However, even though the meter technology itself may be applicable, excessively high gas velocities may not be advisable due to pipeline integrity and process constraints.

Figure 2 shows a summary of restrictions regarding operating range and operating conditions based on our assessment of collected information and vendor interviews. In the initial implementation phase, USMs are generally targeted for pipeline sizes from 4″ to 16″ (with some vendors claiming effective operation down to 2″), and there are no fundamental obstacles to scaling up to diameters as large as 64″. Similarly, the pressure range for early deployments is expected to be 5–20 bar, while future designs could accommodate pressures up to 100 bar. The typical operating temperature range spans from −40 °C to 100 °C, although the exact limits depend on transducer design and material selection. The wide flow velocity range from 0.5 m/s to 80 m/s translates into large turndown ratios, with reported capabilities from 1:10 up to 1:160, making USMs particularly suitable for applications with highly variable flow rates. These characteristics indicate that USMs can provide both flexibility and scalability for hydrogen custody transfer, provided that material compatibility and calibration requirements are addressed for the extended operating envelope.

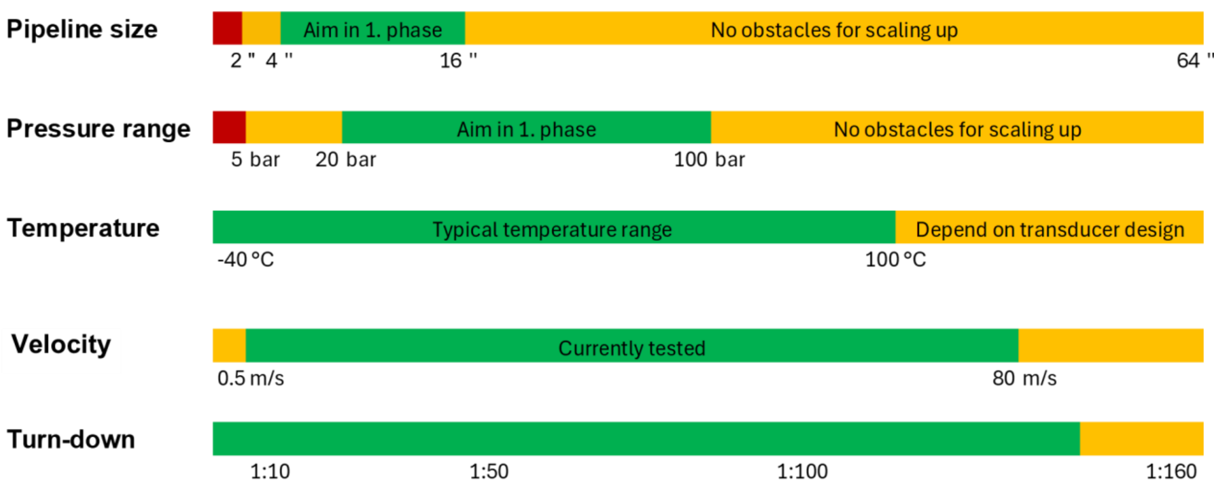

Figure 2 Operating range and condition restrictions for USM based on our interpretation of vendor interviews. The evaluation is limited to meters intended for high-capacity transmission networks, and does not consider meters designed for distribution systems or domestic applications.

3.2. Coriolis flow meters

Coriolis meters measure the mass flow rate directly. The low density of hydrogen results in low mass flow rates even at high volumetric flows. This results in very low mass flow rates that challenge the meter's sensitivity at the lower end of its measurement range, particularly under low pressure conditions. The higher hydrogen flow velocity needed to give the same maximum mass rate as for natural gas would result in a higher pressure loss. To reduce the pressure loss, the maximum flow rate therefore has to be reduced compared to that of natural gas. Thus, the mass flow range is reduced in hydrogen compared to natural gas at comparable pressure and pipe size. To mitigate this, some vendors have developed meters with improved zero-point stability (i.e., lower zero-point drift) to widen the operating range downwards.

Coriolis flow meters are widely recognized for their robustness and accuracy in custody transfer applications, offering several operational advantages. Their design, which lacks moving mechanical parts, ensures low maintenance requirements and high reliability. Coriolis meters are particularly suitable for small pipeline sizes, require no flow-conditioning, and allow straightforward installation with calibration transferability, often from liquid to gas applications [12]. However, these benefits are offset by certain limitations. The meters become physically large and heavy, and therefore costly for pipeline diameters typically above 10–14 inches. Achieving large turndown ratios can be also be challenging, particularly under low-pressure or low-pressure-drop conditions. Additional considerations include potential issues in applications operating above 100 bar, environments with significant vibration, and scenarios demanding both wide turndown and minimal pressure loss.

Figure 3 shows a summary of our interpretation of restrictions regarding operating range and operating conditions. The technology is generally suitable for smaller diameters, but becomes bulky beyond approximately 12" and is not available for very large sizes, which limits its application in high-capacity transportation lines. The pressure range is acceptable up to about 20 bar, but vendor feedback indicates potential material embrittlement issues at higher pressures, requiring careful material selection and design verification for hydrogen service. Temperature capability is broad, spanning from −40 °C to +100 °C, with no significant issues reported, making the technology robust for typical operating environments. Turndown ratio, however, poses a challenge: while ratios up to 1:10 or 1:20 are feasible, achieving very large turndown ratios may require multiple meters in parallel and case-specific solutions.

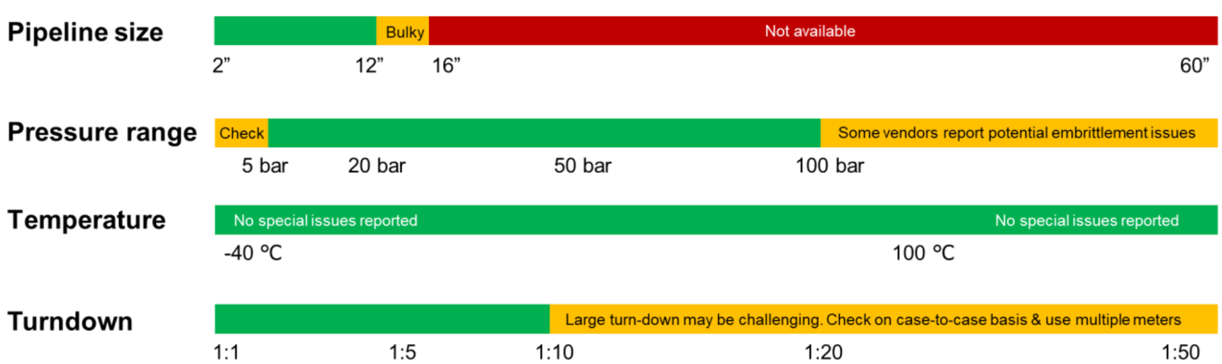

Figure 3 Operating range and condition restrictions for Coriolis based on our interpretation of vendor interviews. The evaluation is limited to meters intended for high-capacity transmission networks, and does not consider meters designed for distribution systems or domestic applications.

4. METERING STATION CONFIGURATION FRAMEWORK

Based on our experience from analysing natural gas systems, we have developed a framework for configuring and comparing flow metering stations, using expected production rates and requirements from the pipeline operator on hydrogen quality and operating conditions as key inputs. This systematic approach enables evaluation of multiple design alternatives and selection of configurations that balance accuracy, cost, and operational performance.

The approach can be summarised in 5 steps:

1. *Define design basis*
   This step establishes the operating envelope, functional requirements and technology constraints. This includes specifying the minimum and maximum flow rates, pressure, and temperature, as well as requirements for measurement accuracy,

redundancy, and compliance with relevant standards.

2. *Calculate process parameters*
   This step involves determining volumetric flow rates at both operating and standard conditions, mass rates, energy rates, and calculating gas properties such as density, compressibility factor, viscosity, and speed of sound across the full operating range. Properties that depend on metering size and arrangement, such as gas velocity and Reynolds number, will also be calculated. These calculations establish the technical boundary conditions that constrain meter selection and sizing decisions.

3. *Technology assessment of metering station configurations*
   This step involves a systematic mapping of metering technologies, meter sizes and metering arrangements (e.g. number of meters in parallel) that fulfills the operating envelope and functional requirements. In addition, installation requirements such as straight pipe lengths, flow conditioning, and bypass arrangements should be considered.

4. *Uncertainty analysis*
   For the most promising configurations, an uncertainty budget is developed. This step quantifies how measurement uncertainties from flow rate, pressure, temperature, and gas composition propagate into the overall energy calculation using Monte Carlo simulation.

5. *Trade-off analysis, selection, and operability check*
   A comprehensive trade-off analysis is performed to compare the configurations. This analysis considers uncertainty, pressure loss, cost, footprint, and maintainability, as well as operability under dynamic conditions such as rapid load changes. The configuration that best balances accuracy, cost, and operational flexibility is then selected.

Parts of the framework have been implemented in a software package (*HyMeTool)*, enabling streamlined execution of steps 1-4 and providing a structured decision basis for the trade-off analysis in step 5. The software tool automates many of the calculations and comparisons, reducing the potential for errors and enabling rapid evaluation of alternative configurations.

Inputs to the software include the functional requirements, expected flow profile, process conditions (temperature and pressure), gas composition, and associated uncertainties (i.e. step 1). Based on these inputs, the *HyMeTool* calculates relevant gas properties and flow/process properties for selected meter technologies, meter sizes, and metering arrangement (step 2). These results can be visually compared against the functional requirements to assess compliance and performance (step 3). Finally, an uncertainty and sensitivity analysis of the selected configurations are performed using the Monte-Carlo Method (step 4). A decision basis in the form of tables and graphs for the trade-off analysis (step 5) can be obtained directly from the software-package. The figures shown later in this paper are derived from the *HyMeTool*.

The framework and software-package are broadly applicable and can be adapted for flow metering stations for other applications such as natural gas, biogas and CO_2. This would, however, require revisiting technology performance assumptions and carrying out dedicated evaluations similar to the hydrogen-specific mapping presented in this work.

5. CASE STUDY: CONFIGURATION OF AN ELECTROLYSER PRODUCER METERING STATION

The approach outlined in previous chapter will now be exemplified for an illustrative case. Focus will be on the step 1-4 in the framework, as the trade-off analysis in step 5 typically involves operator-specific proprietary procedures and considerations.

The example considers configuration of a metering station for an entry point to the Hynetwork hydrogen transportation network in the Netherlands. The Hynetwork has defined clear requirements for the metering stations [13]. The hydrogen is produced by electrolysis from wind power. The hydrogen production rate will vary strongly as a function of the available wind power. Thus, the flow dynamics is expected to be high.

5.3. Step 1: Define design basis

A summary of the requirements for hydrogen producers connected to the Hynetwork pipeline infrastructure is given in Table 1. Since the hydrogen is produced by electrolysis, no hydrocarbons are expected to be present in the gas. The focus in the analysis is on energy measurements rather than pipeline integrity and end-user quality requirements, and impurities in the ppm-range are neglected in the calculations. For the purpose of the example, inert gas impurities are assumed to consist only of nitrogen.

Table 1 Hynetwork specifications [13].

Parameter	Requirement
Pressure (barg)	40 - 66.2
Temperature (°C)	5 - 30
Hydrogen content (mol%)	>99.5
Hydrocarbon content (mol%)	<0.5
Inert gas content (mol%)	<0.5
Other impurities	ppm range
Wobbe index (MJ/m^3)	45.99 -48.35
Hydrogen energy uncertainty (%)	<1.0

The hydrogen transport rates are expected to be as shown in Table 2. Since the production is based on wind energy, the dynamic range of the flow will be very high. Also, the flow rates are expected to change rapidly due to fast changing wind conditions. This sets strict requirements for the configuration for the metering station, in particular with regard to turn-down ratio and rapid response to flow variations.

A design constraint of Δp < 250 mbar was applied to limit the pressure loss across the metering section. This constraint ensures that the metering station does not significantly impact the overall system pressure profile or increase compression requirements.

Table 2 Expected transportation rates from the hydrogen producer to the hydrogen transportation network

Flow rates	Min	Nom	Max
Mass rate (ton/d)	3	60	70
Mass rate (kg/h)	125	2500	3000

5.4. Step 2: Calculate process parameters

The gas properties, volume rates, and energy rates depend on the operating conditions and the actual hydrogen production rate. Using the data in Table 1 and Table 2, minimum and maximum values for relevant properties can be calculated using Equation of State (EoS) methods. Here, the properties are calculated using REFPROP [6] with the GERG-2008 EoS [4]. Table 3 shows the resulting ranges for gas and flow properties.

Table 3 Range of gas properties, volume flow rates and energy flow rates calculated from specifications in Table 1 and the expected mass rates in Table 2. The hydrocarbon content is assumed to be negligible, and inert gas impurities are assumed to consist only of nitrogen.

Calculated property ranges	Min	Max
Molar mass (kg/mol)	2.02	2.15
Density, actual conditions (kg/m^3)	3.13	5.9
Density, standard conditions (kg/m^3)	0.09	0.09
Z, actual	1.023	1.041
Z0, standard	1.0006	1.0006
SOS (m/s)	1265	1381
Dynamic viscosity (Pa·s)	8.52	9.33
Volume rate, actual (m^3/h)	21.2	957.6
Volume rate, std.cond. (m^3/h)	1,378	35,209
Mass flow rate (kg/h)	125	3,000
Energy flow rate (MJ/h)	16,585	425,844

In the following, the property ranges given in Table 3 are used as design requirements when assessing configurations for USM and Coriolis-based metering stations.

5.5. Step 3: Technology assessment of metering station configurations

5.5.1. USM

As discussed in chapter 3, the operating range of a USM is primarily limited by gas velocity. Based on overall USM vendor feedback and considering typical pipeline design criteria, a practical constraint in gas velocities for hydrogen is here considered to be between 1 and 40 m/s. This range will be assumed in the case study discussed later. While broader velocity ranges may be feasible, this should be evaluated on a case-to-case basis with the vendor.

A metering station can be configured with either a single flow meter or multiple meters in parallel to increase capacity. Other configurations may also be considered, such as using meters in series to reduce uncertainty or as a check-meter, or arranging meters in a Z-configuration for enhanced flexibility. In this discussion, focus is on assessing the number of meters in parallel required to cover the expected flow range.

Consider N meters of diameter D arranged in parallel. The flow velocity through each meter is

$$v = \frac{\dot{V}}{\pi\left(\frac{D^2}{4}\right)N}. \quad (5\text{-}1)$$

At maximum flow rate, the flow is routed through all meters, and the constraint is that $v \leq v_{max}$ with v calculated using equation (5-1). At minimum flow rate, the flow may be routed through a single meter, and the constraint becomes that $v \geq v_{min}$, again with v calculated using equation (5-1), but now with N=1. If meters of different diameters are used in parallel, similar calculations can be applied for each operating mode.

Table 4 shows potential configurations using parallel meters of the same diameter. All configurations that satisfy the constraint $v \leq v_{max}$ are included, and those that also fulfill $v \geq v_{min}$ are highlighted in green in the respective column. Figure 4 shows the mass flow rates that can be covered by various flow meter configurations, including combinations of meters with different diameters.

As discussed in chapter 3, it is challenging to apply USM in small pipelines. This is primarily because USM with small diameters only allow a limited number of acoustic paths, making them highly sensitive to flow profile distortions. Therefore, USMs smaller than 4″ are generally not recommended. The table shows that the minimum flow velocity through a 4″ meter is approximately 0.7 m/s, which is below the design constraint of 1 m/s. While a 4″ meter may still operate with sufficient accuracy at this velocity, a more thorough evaluation is recommended before selecting this option. Specifically, vendor consultation should confirm whether signal quality and measurement uncertainty remain acceptable at this lower velocity, particularly given hydrogen's lower density compared to natural gas.

Table 4 Gas flow velocity ranges though flow meters in various metering station configurations

Pipe size (inch)	No. of meters	v_{min} (m/s)	v_{max} (m/s)	USM applicable
1	14	11.61	37.57	X
2	4	2.90	32.88	X
3	2	1.29	29.22	X
4	1	0.73	32.88	OK
6	1	0.32	14.61	OK
8	1	0.18	8.22	OK

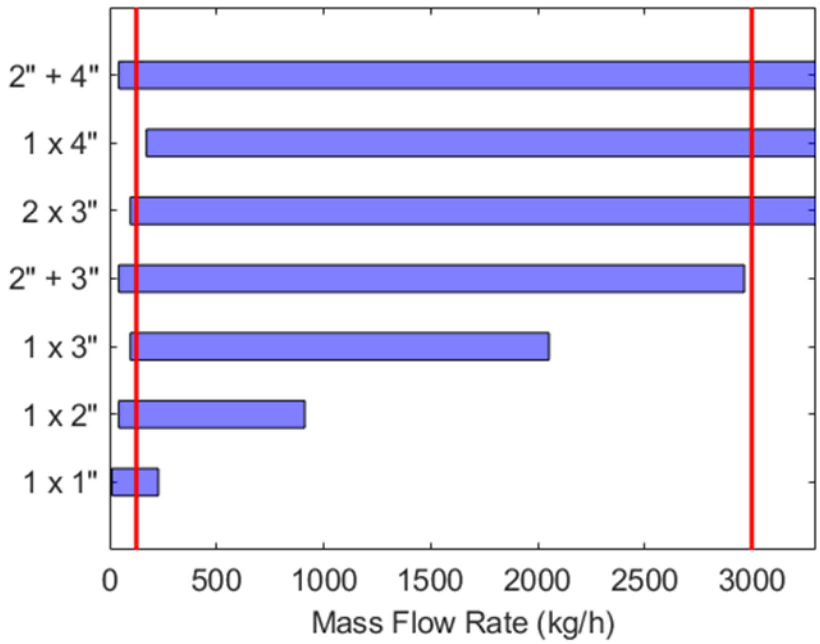

Figure 4 Mass flow rates covered by various USM meter configurations (based on acceptable velocity range 1-40 m/s and the complete range of properties given in Table 3).

5.5.2. Coriolis technology assessment

The operating range of a Coriolis meter is constrained by the base uncertainty and zero-point stability at low flow rates and the pressure loss at high flow rates. The minimum flow rate is calculated as

$$\dot{m}_{min} = \frac{\dot{m}_{zero-point}}{100 \cdot u_{base}[\%]}. \quad (5\text{-}2)$$

The base uncertainty (u_{base}) is typically 0.25 %, while the zero-point stability will depend on vendor and meter dimensions. The pressure loss though a Coriolis is

$$\Delta p = K \frac{1}{2} \rho v^2, \quad (5\text{-}3)$$

where K is a loss coefficient that depends on tube design, ρ is the fluid density, and v is the gas velocity. Equation (5-3) shows that the pressure loss increases rapidly at high gas velocities. The quadratic dependence on velocity means that doubling the flow rate quadruples the pressure loss, making this a critical constraint for high-capacity applications.

The zero-point stability and loss coefficient can be obtained from online tools provided by the meter vendors. The following calculations are based on the Endress+Hauser Promass Q300. Similar calculations may also be done using meters from other vendors. Table 5 shows the minimum and maximum mass rates for some example configurations. The minimum mass rate is calculated using equation (5-2) with $u_{base} = 0.25\%$, and the maximum mass rate is determined using equation (5-3) with $\Delta p = 250\,\text{mbar}$. The corresponding uncertainty and pressure loss values for the design ranges given in Table 2 are also included. These results are further visualized in Figure 5, which clearly shows that a combination of meters with different pipe sizes is required to cover the complete design range. The most suitable configuration appears to be a parallel arrangement of one 1” meter and two 2” meters, although the base uncertainty at the lowest flow range may exceed 0.25 % somewhat. Note that this combination of meters provides overlapping operating regions, which is important to avoid strict switching points between operating modes. This reduces the operational complexity and potential uncertainty. Alternatively, a 3” meter may be preferred for the highest flow rates as this will give an even lower pressure loss, but at the cost of smaller overlapping operating ranges.

The considerations above reflect the minimum configuration required to cover the design range. In practice, additional meters may be included to provide redundancy, enable check-metering, and enhance the reliability.

Table 5 Coriolis configuration considerations. Minimum mass rate calculated from 0.25 % base accuracy, Maximum mass rate calculated from 250 mbar pressure loss

Pipe size (inch)	No. of meters	Min rate (kg/h) @ u<0.25%	Max rate (kg/h) @ PL<0.25bar	Unc. @ qmin (%)	Unc. @ qmax (%)	PL @ qmin (mbar)	PL @ qmax (mbar
3	1	1760	6020	3.52	0.25	0.1	62
2	2	1040	3982	2.08	0.25	0.1	142
2	1	520	1991	1.04	N/A	1	N/A
1	1	144	656	0.29	N/A	9	N/A
1	2	288	1313	0.58	N/A	3	N/A

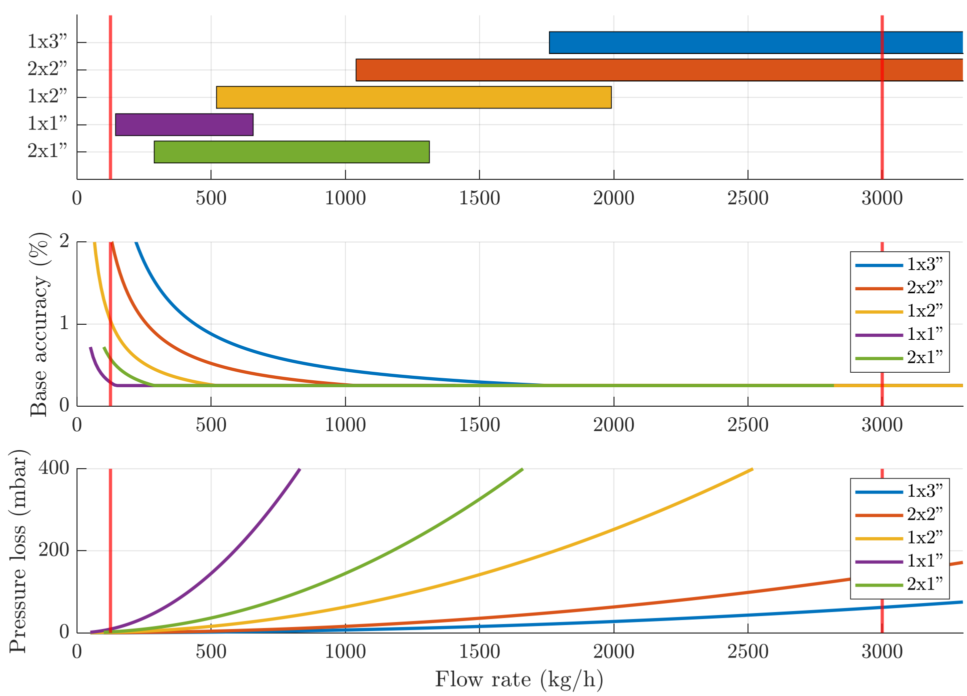

Figure 5 Pressure loss, base accuracy, and mass flow ranges for example configurations.

5.6. Step 4: Uncertainty analysis

5.6.1. USM

An uncertainty budget for the energy flow rate measured by the USM has been derived based on the energy calculation method in equation (2-8). The calculations were done using the Monte Carlo Method (MCM) based on the synthetic input uncertainties in Table 6.

The input uncertainties are preliminary estimates on what may be achievable with instrumentation for hydrogen applications. Due to the lack of accredited calibration facilities for high flow rates, reliable data on achievable uncertainties is still lacking. Consequently, the actual uncertainties and operating ranges for hydrogen systems remain uncertain and may differ from the assumptions made here.

The input parameters to the Monte Carlo calculations are volume flow rate, temperature, pressure, and gas composition (i.e. impurity fraction). The hydrogen content is determined as the remainder after subtracting the impurity fraction. Both the compressibility factor and the gross calorific value are treated as input quantities in the Monte Carlo analysis. Correlations between these parameters are inherently accounted for by the MCM, as they are derived from the same underlying gas composition.

Figure 6 shows the resulting uncertainty contribution at the high (66.2 barg) and low (40 barg) pressure. This shows that the total energy uncertainty requirement of 1.0 % is satisfied with a comfortable margin. However, as noted earlier, the analysis relies on preliminary estimates, and the uncertainty may be higher in practice due to factors not fully captured here. The volume flow rate measurement is the primary source of uncertainty in both regions, followed by pressure measurements as the second-largest contributor. The uncertainty in gas composition, which influences on the compressibility factor (Z) and the calorific value (H_c), has only a negligible effect compared to the contributions from flow rate and pressure.

Table 6 Input uncertainties (k=2) applied in USM uncertainty analysis

Parameter	**Uncertainty**
Volume Flow rate, actual cond.	0.5 %
Inert gas content (N_2)	0.01 mol%
Hydrogen content	By-diff
Temperature	0.3 °C
Pressure	0.2 barg

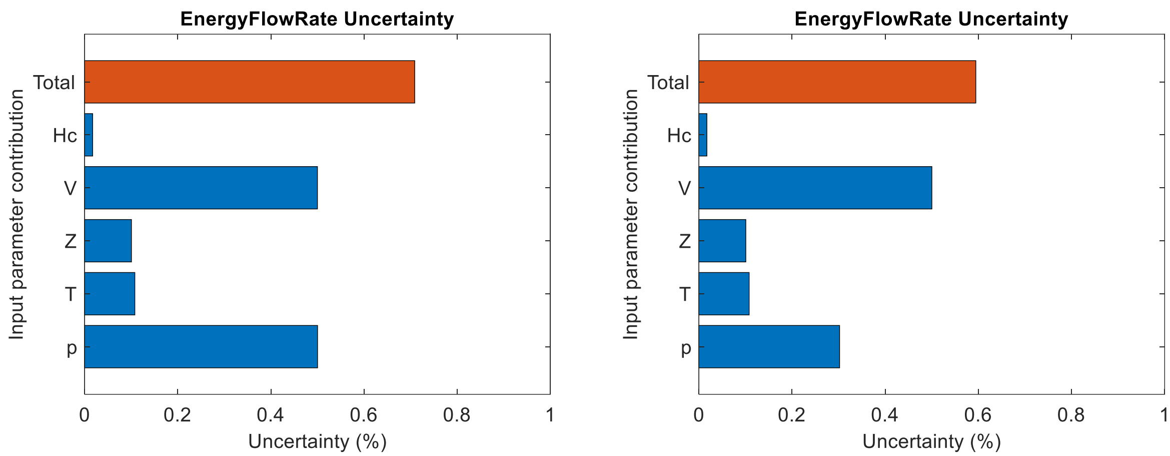

Figure 6 Energy uncertainty contributions for USM measurements calculated from input uncertainties in Table 6. (a) low pressure, (b) high pressure

5.6.2. Coriolis

An uncertainty budget for the energy flow rate measured by the Coriolis is calculated using the energy calculation method in equation (2-7). The resulting uncertainty contribution to the energy flow rate uncertainty for the highest mass flow rate range is shown in Figure 7, assuming a configuration with a 3” meter in this operating range. The input uncertainties applied in the example are shown in Table 7. As discussed for the USM case, the input uncertainties are preliminary estimates on what may be achievable with instrumentation for hydrogen applications.

The analysis shows that the 1.0% energy uncertainty requirement is met also for the Coriolis meter. The mass flow rate is the dominating uncertainty contributor, whereas the molar mass uncertainty has a minor influence.

Note that the assumed flow rate uncertainty of 0.5 % applied to both USM and Coriolis is not based on verified performance data for hydrogen service. This generic assumption was introduced to enable the uncertainty propagation analysis, but it does not reflect technology-specific characteristics or calibration capabilities. Consequently, the resulting uncertainty budgets should be interpreted with caution, and the analyses cannot be used for a direct comparison between the two technologies.

Table 7 Input uncertainties applied in Coriolis uncertainty analysis

Parameter	**Uncertainty**
Mass Flow rate	0.5 %
Inert gas content (N_2)	0.01 mol%
Hydrogen	By-diff

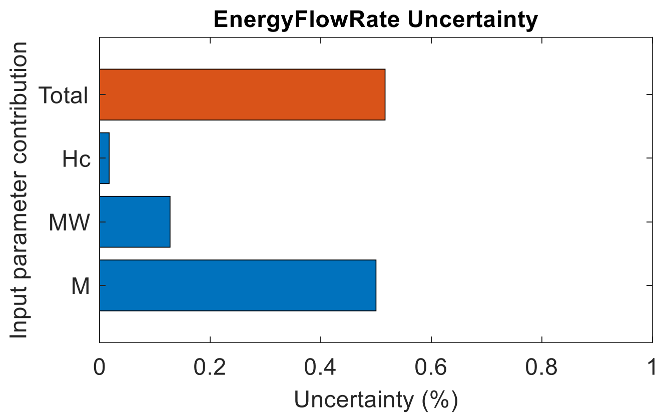

Figure 7 Energy uncertainty contributions for measurements with a 3" Coriolis calculated from input uncertainties in Table 7.

5.6.3. Gas composition uncertainty

The uncertainty propagation analysis for the USM and Coriolis meters indicated that the gas composition uncertainty has a much smaller impact than flow rate uncertainty on the energy uncertainty. However, if the uncertainty is systematic, even small uncertainties may accumulate to large values over time. A closer examination on how gas composition uncertainty affects the mass-based and volume-based energy measurement is therefore provided below. The discussion is based on the work presented at MathMet 2025 [15].

As shown in equations (2-7) and (2-8) in chapter 2.2. the propagation of uncertainty differs between mass-based (e.g. Coriolis) and volume-based (e.g USM) approaches. Following the law of propagation of uncertainty from GUM [16], the uncertainties (when neglecting correlations) are

$$\left[\frac{u(\dot{E}_v)}{\dot{E}_v}\right]^2 = \left[\frac{u(\dot{V})}{\dot{V}}\right]^2 + \left[\frac{u(p)}{p}\right]^2 + \left[\frac{u(T)}{T}\right]^2 + \left[\frac{u(Z)}{Z}\right]^2 + \left[\frac{u(H_c)}{H_c}\right]^2, \tag{5-4}$$

$$\left[\frac{u(\dot{E}_m)}{\dot{E}_m}\right]^2 = \left[\frac{u(\dot{m})}{\dot{m}}\right]^2 + \left[\frac{u(M)}{M}\right]^2 + \left[\frac{u(H_c)}{H_c}\right]^2. \tag{5-5}$$

Gas composition uncertainty affects three of these parameters: Z, M, and H_c. Since uncertainty in H_c contributes equally to both energy calculation approaches, the focus is on the composition influence on Z and M.

Volume-based approach: The uncertainty in Z arises from both the composition uncertainty (i.e. nitrogen content) and model uncertainty for the EoS mode, i.e. GERG-2008. The GERG-2008 model uncertainty is below 0.1 % within its validated operating range [14], dominating the combined uncertainty for hydrogen mixtures purer than 99.95 mol%.

Mass-based approach: For molar mass M, model uncertainty using ISO 6976 [8] is negligible compared to composition uncertainty. Thus, the composition uncertainty typically dominates the combined uncertainty in M.

Overall, composition uncertainty has a stronger influence on M than on Z for hydrogen gases. However, when the composition is accurately known, the uncertainty contribution from Z becomes greater than that from M due to the 0.1 % model uncertainty.

Figure 8 illustrates this by showing the relative change in energy caused by a small nitrogen impurity (calculated as H_c/M and H_c/Z for mass-based and volume-based, respectively; see equations (2-7) and (2-8)). Consequently, accurate composition measurement is critical for the mass-based approach, whereas its impact on the volume-based approach is minor.

According to the H2GAR 6th Activity Report [9], using a fixed GCV is acceptable when the hydrogen quality is both high and stable, as the variability in energy content becomes negligible in this case. However, Figure 8 shows that an erroneous purity value of e.g. 99.99 mol% instead of 99.98 mol% (i.e. an error of 0.01 mol%) can give a systematic error of 0.14 % for mass-based calculation, while the systematic error for volume-based calculations is only 0.01 %. This suggests that a fixed GCV should not be applied for mass-based measurement unless the impurity level is well known and very stable.

It should be noted that this analysis only considers composition effects and excludes uncertainties in temperature, pressure, or flow rate, which also contribute significantly to the overall uncertainty. Furthermore, while composition may have limited influence on energy determination for high-purity hydrogen using volume-based methods, it remains essential for other requirements—such as pipeline integrity and end-user quality requirements—which may necessitate precise and continuous composition monitoring.

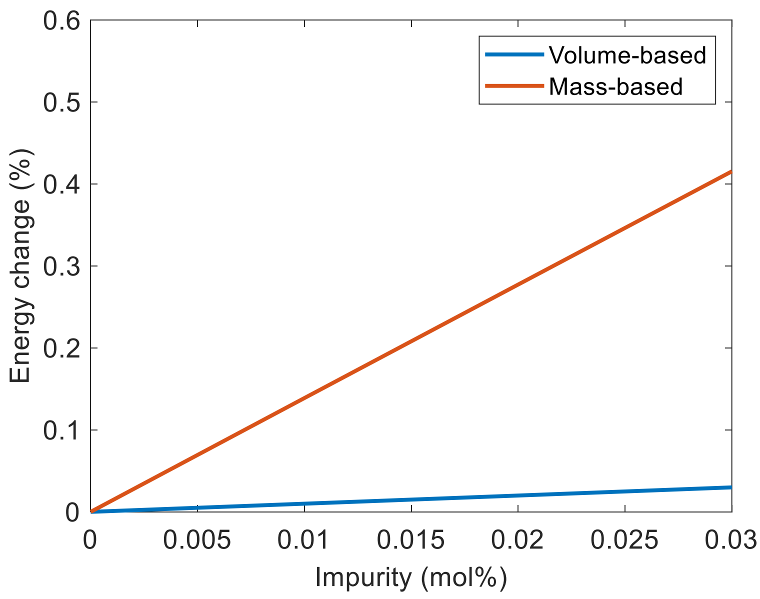

Figure 8 Relative change in energy caused by a small nitrogen impurity in hydrogen. Calculations done at 80 bara and 20 $°C$.

6. CONCLUSION

This study has explored key considerations for designing hydrogen custody transfer metering stations, with a focus on adapting existing technologies and methodologies to the specific challenges posed by hydrogen's physical properties and dynamic production profiles. A structured framework was proposed to guide the configuration and evaluation of metering stations, including uncertainty analysis and technology assessment.

Ultrasonic and Coriolis flow meters were examined in detail, highlighting their respective strengths and limitations in hydrogen applications. The case study demonstrated how the framework can be applied to a realistic scenario, providing insights into meter sizing, operating range, and uncertainty propagation.

The analysis suggests that volume-based energy determination may be less sensitive to gas composition uncertainties than mass-based approaches, which could be relevant in high-purity hydrogen contexts. However, it is important to note that volume-based methods are also influenced by uncertainties in temperature and pressure, while this is not the case for mass-based methods. A comprehensive evaluation should therefore consider the full range of contributing factors, as both approaches involve distinct measurement dependencies and trade-offs that must be addressed in system design.

To support practical implementation, parts of the framework have been incorporated into the HyMeTool software package. This tool facilitates streamlined analysis and visualization of metering configurations and uncertainty budgets. While still under development, it shows potential for broader application across other gas types such as natural gas, biogas, and CO_2. However, applying the full methodology to these gases would require additional technology-specific assessments similar to those performed for hydrogen.

Calibration capabilities were not included as a separate evaluation criterion in this study, due to the current lack of accredited hydrogen calibration facilities. As such infrastructure becomes available, calibration should be considered an integral part of future metering system assessments.

7. REFERENCES

[1] IEA (2023) – Global Hydrogen Review 2023. International Energy Agency. https://www.iea.org/reports/global-hydrogen-review-2023

[2] OIML, "Measuring systems for gaseous fuel," OIML R 140:2007, 2007.

[3] ISO, "Natural gas — Energy determination," ISO 15112:2018, 2018

[4] O. Kunz, R. Klimeck, W. Wagner, and M. Jaeschke, "GERG-2008 equation of state for natural gases and other mixtures," GERG TM15 2008, 2007.

[5] ISO, "Natural gas — Calculation of thermodynamic properties — Part 2: Single-phase properties (gas, liquid, and dense fluid) for extended ranges of application," ISO 20765-2:2015, 2015

[6] E. W. Lemmon, M. L. Huber, and M. O. McLinden, "NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP), Version 10.0," NIST, 2018. [Online]. Available: https://doi.org/10.18434/T4/1502528

[7] EASEE-gas, "Common Business Practice 2023-001/01 – Hydrogen units," European Association for the Streamlining of Energy Exchange – gas, Nov. 23, 2023.

[8] ISO, "Natural gas — Calculation of calorific values, density, relative density and Wobbe indices from composition," ISO 6976:2016, 2016

[9] H2GAR Working Group 4, 6th Activity Report: Common Proposal of Minimum Requirement for a H_2 Metering Station, Jul. 2, 2025.

[10] EN 12405-2:2012, "Gas meters – Conversion devices – Part 2: Energy conversion"

[11] A. Andreev, E. Starke, T. Dietz, M. Oberländer, and M. Siegfried, "Practical Experience, Challenges and Solutions at Testing and Calibrating of Hydrogen Ultrasonic Flow Meters," Proc. Global Flow Measurement Workshop (GFMW), Oct. 2024
[12] A. Druzhkov, Y. Alghanmi, M. Brugman, S. Pitti, and R. Blankestijn, "Coriolis Flow Technology in H_2 and CO_2 Measurement: Key Questions and Answers to Make Reliable Measurement Happen in Industrial Applications," Proc. Global Flow Measurement Workshop (GFMW), 2024
[13] Hynetwork specifications, https://www.hynetwork.nl/en/business/become-a-customer/specifications
[14] DVGW, "Modification of GERG-88 for hydrogen applications (SGERG88-Mod-H2)," Research Report, 2023.
[15] K. Folgerø, J. Kocbach "Evaluating uncertainty propagation in mass- and volume-based methods for custody transfer of hydrogen", MathMet 2025, Gothenburg, Oct. 7-9, 2025
[16] ISO/IEC Guide 98-3:2008. "Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement " Joint Committee for Guides in Metrology (JCGM 100:2008).

Tekna

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