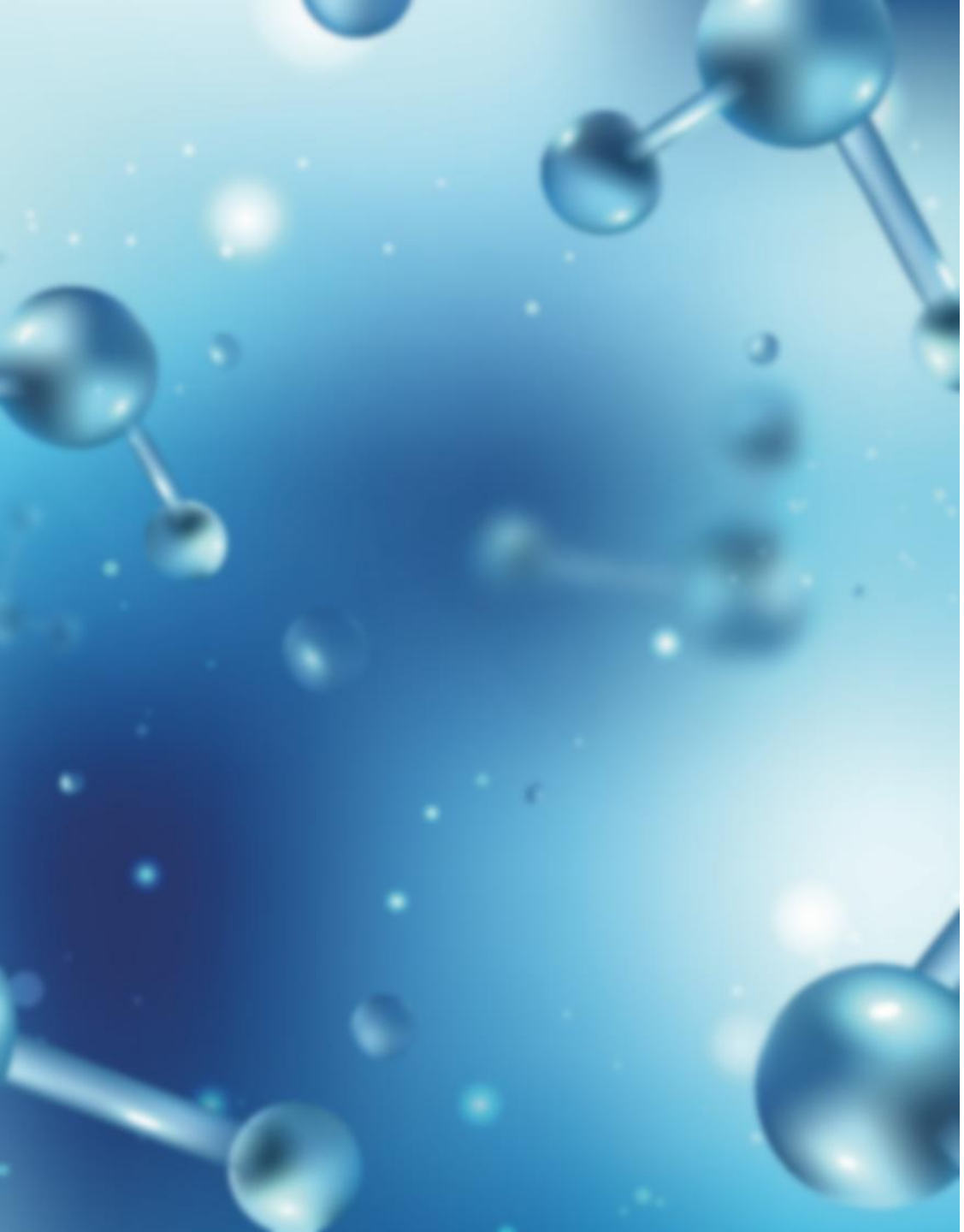


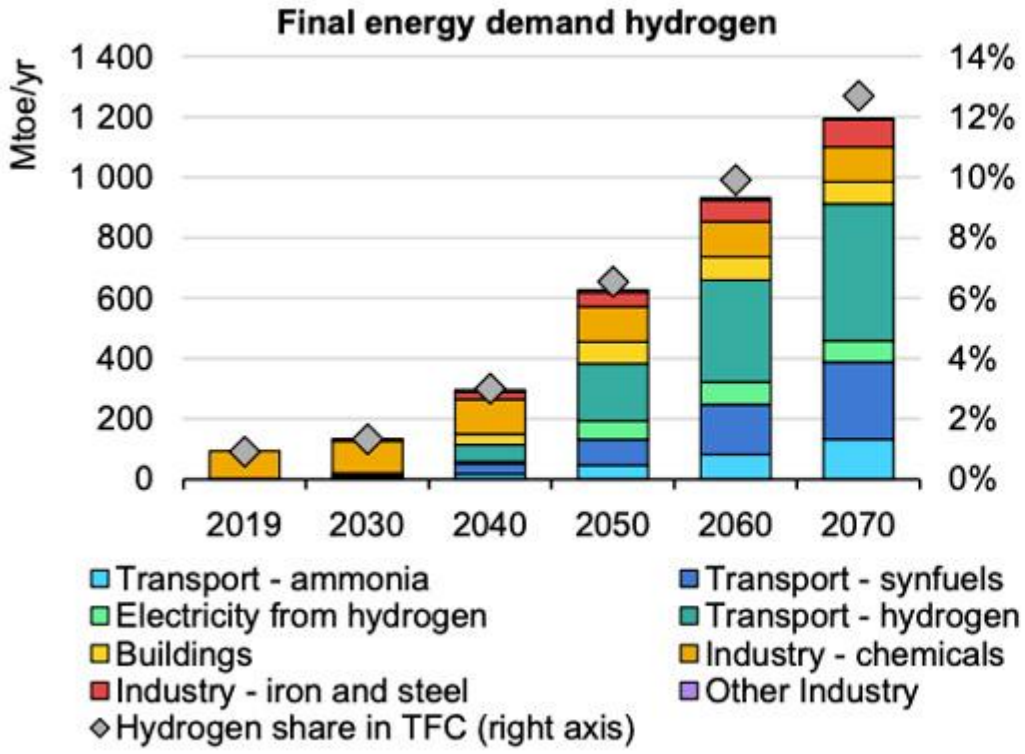
METROLOGY FOR THE HYDROGEN SUPPLY CHAIN – FINAL STAKEHOLDER WORKSHOP

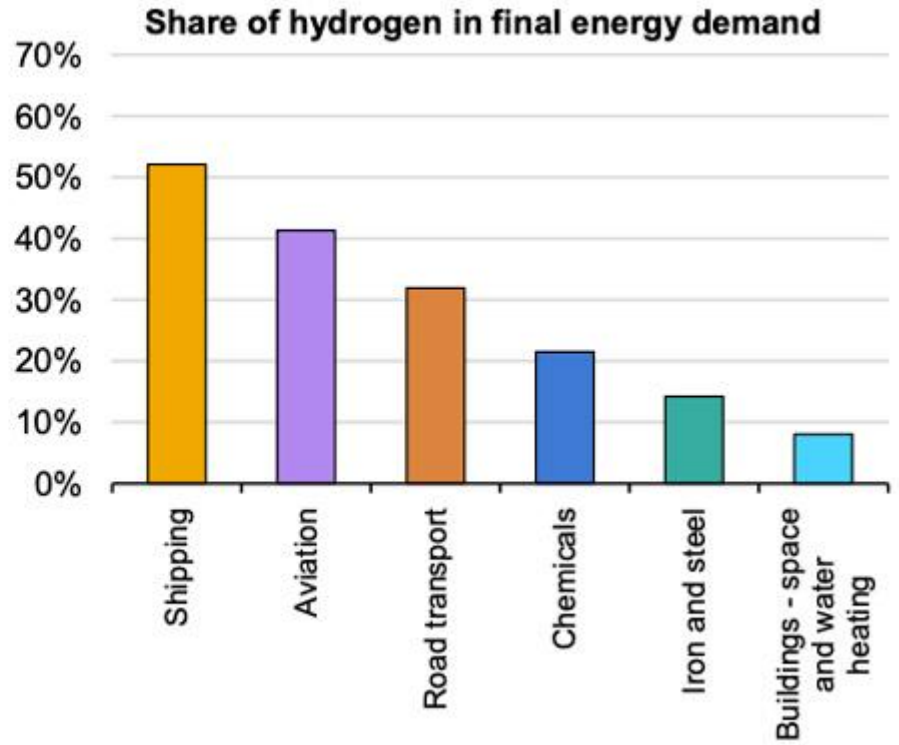
Adriaan M.H. van der Veen (VSL)
18 September 2025
21GRD05 Met4H2 M36 Workshop

INTRODUCTION AND RATIONALE

- "Unless there are rapid and large-scale reductions in greenhouse gas emissions, limiting warming [...] to 1.5 °C will be beyond reach" [IPCC, 2021]
- European Green Deal (EGD) is Europe's response to decarbonise energy use and to shift to renewable energy sources
- Hydrogen, produced from electricity from renewable sources, is at the centre of this energy transition
- Without access to gas grids, a substantial part of the EU agenda on greening the energy supply cannot be carried out
- Project addresses immediate needs: **safety**, **conformity** with specifications and regulations, and **billing**

WE NEED TO GET STARTED NOW!





Source: IEA, Energy Technology Perspectives, 2020

METROLOGY FOR THE HYDROGEN SUPPLY CHAIN (MET4H2)

- Response to needs when introducing hydrogen into (natural gas) grids
- 27 partners, project started 1 October 2022 and will last 3 years
- Objectives:
  1. To develop calibration and measurement methods in view of **safety, process efficiency and environmental issues**
  2. To develop measurement standards to enable calibration and validation of **flow metering** equipment
  3. To develop and improve measurement standards and methods for validation and performance evaluation of **gas quality measurement** methods for hydrogen, for impurities, e.g., oxygen, hydrogen sulfide, moisture content, and for reactive components such as hydrogen chloride and chlorine.
  4. To develop novel methods for the evaluation of **measurement uncertainty** along the supply chain regarding the measurement of **total quantity, and energy** and impurity content of hydrogen and hydrogen blends.

PARTNERS

MET4H2

VSL National Metrology Institute

BAM Bundesanstalt für Materialforschung und -prüfung

Bundesamt für Eich- und Vermessungswesen

CEM Centro Español de Metrología

CEAME exadébit SA

Český metrologický institut

le cnam Conservatoire national des arts et métiers

DTU Danmarks Tekniske Universitet

DFM

METAS

Environment Park Parco Scientifico Tecnologico per l'Ambiente

FORCE Technology

GERG The European Gas Research Group

INRiM Istituto Nazionale di Ricerca Metrologica

Justervesenet

Laboratoire national de métrologie et d'essais LNE

Nippon Gases

NORCE

NPL

Politecnico di Torino

PTB Physikalisch-Technische Bundesanstalt Nationales Metrologieinstitut

RISE Research Institutes of Sweden

Endress+Hauser

TÜV SÜD

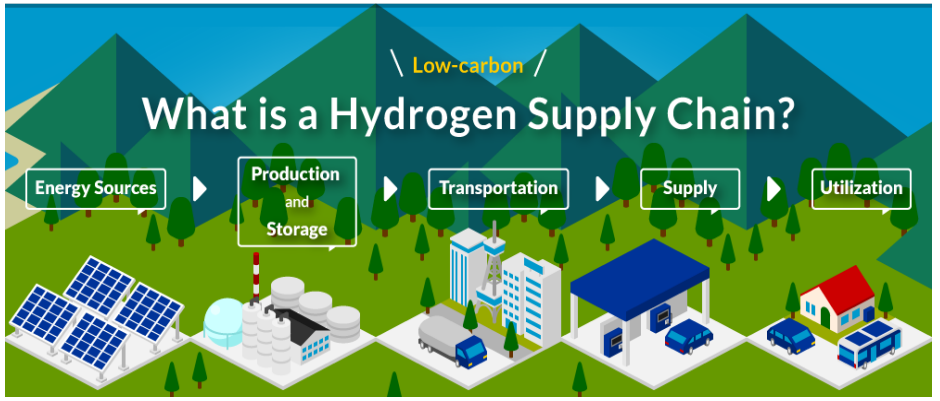
Univerza v Ljubljani University of Ljubljana

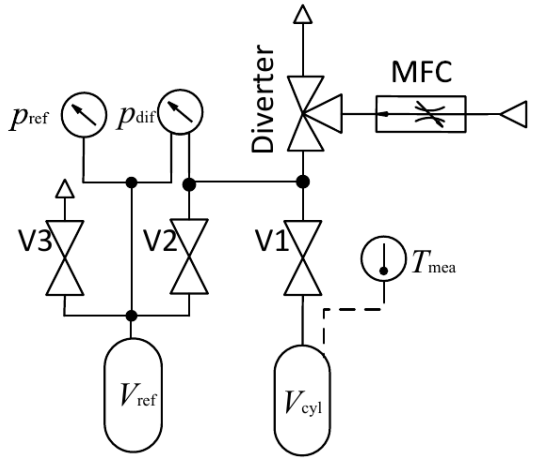
VTT

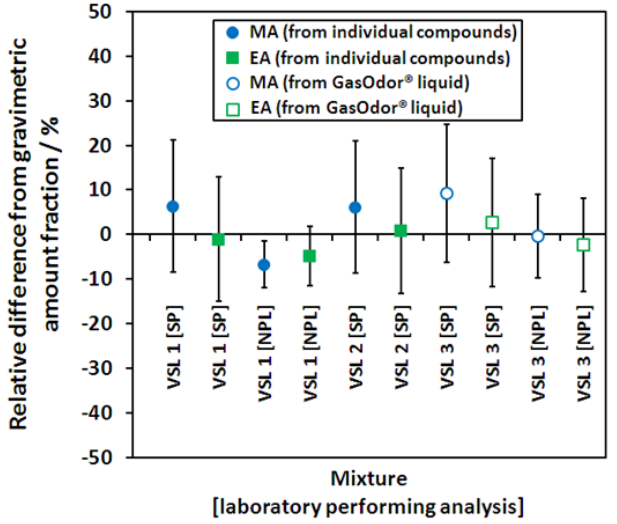
CAE zero carbon

HEALTH, SAFETY AND ENVIRONMENT

- Primary standards for leak flow rate measurements (10^{-6} to 10^{-9}) mol s^{-1}
- Characterisation methods for permeation analysis of sealings, liners etc. at (-40 to 120) °C, (0.1 to 10) MPa, (10 to 90) % RH
- Validation protocols and test rigs for hydrogen sensors (hydrogen and impurity content)
- Measurement standards for measuring odorant levels in hydrogen-enriched natural gas and hydrogen (sulfurous and sulfur-free odorants)

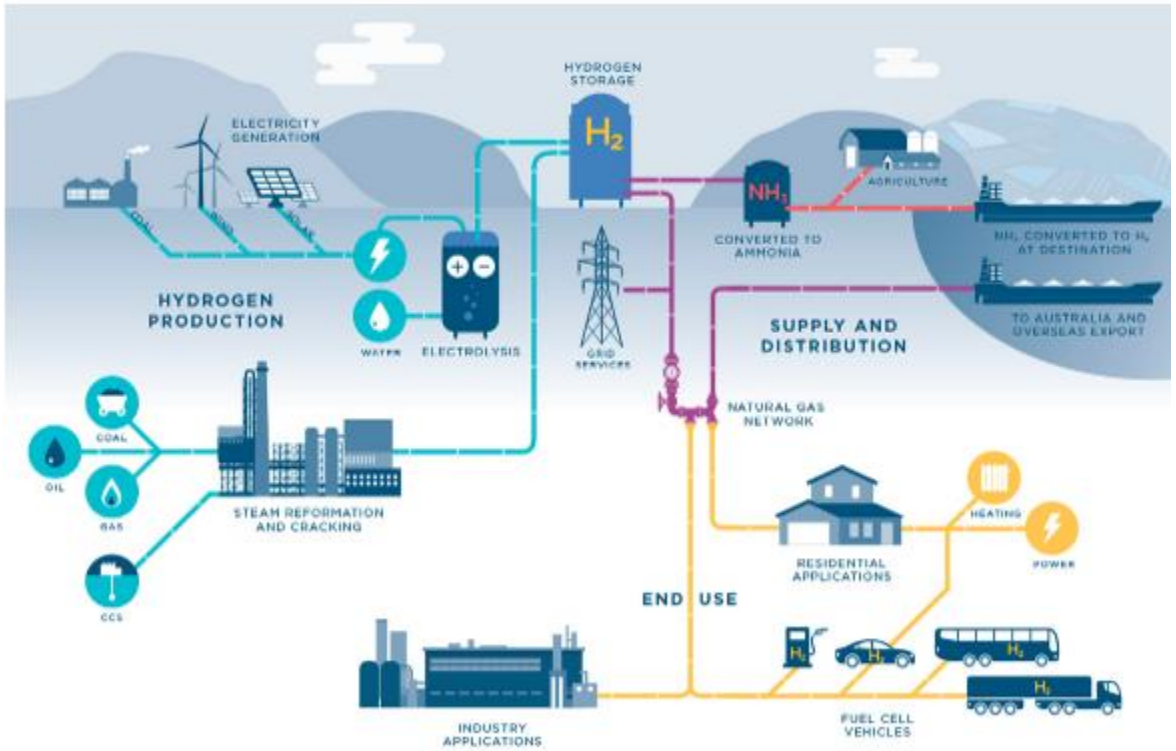






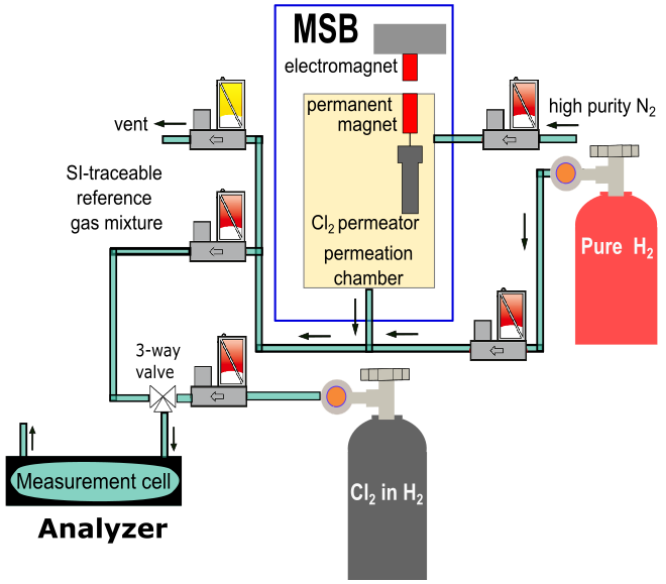
FLOW MEASUREMENT

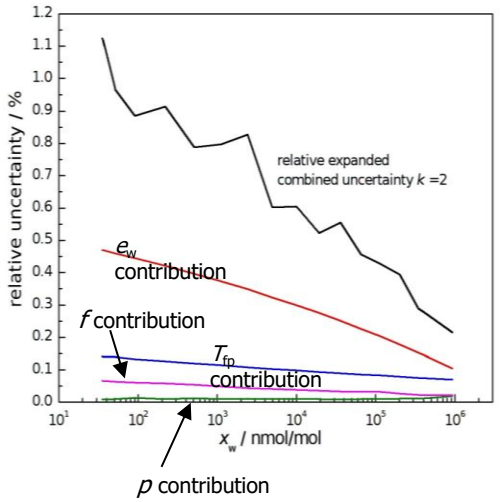
- Overview of the state-of-the-art in flow metering of hydrogen and hydrogen blends
- Intercomparison of flow measurement standards for hydrogen-enriched natural gas
- Flow standards for domestic gas meters for hydrogen, including assessment of impurity impact (up to 2 %)
- Development of metrological traceability chains for large-scale hydrogen transportation



HYDROGEN QUALITY

- Development of gas sampling methods for online and offline use
- Humidity standards for the amount fraction water in hydrogen (up to 6 MPa)
- Measurement standards for impurities typical for alkaline electrolysers (e.g., chlorine, hydrogen chloride, and water)
- Measurement standards for hydrogen quality during transportation (e.g., odorisation compounds, ammonia)

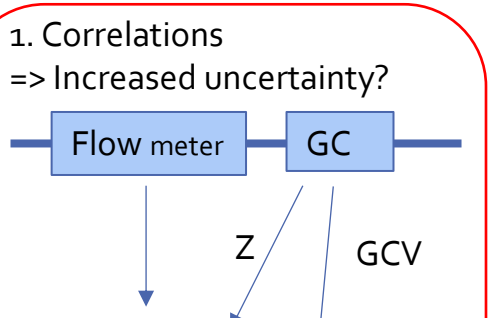




UNCERTAINTY IN FISCAL METERING

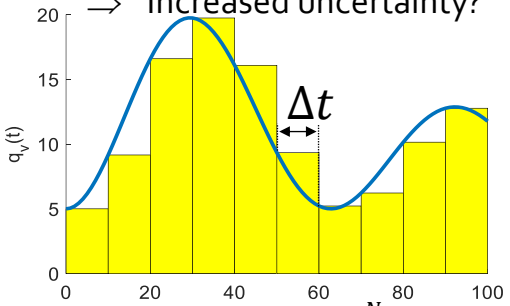
- Development of a framework for the uncertainty evaluation of the total quantity and energy provided
- Evaluating serial correlation in flow and energy
- Uncertainty of approximating the time-integration by a summation
- Risk: assuming independence makes that uncertainty shrinks with more observations than actually justified
- At the end of the day: non-credible uncertainties

1. Correlations
=> Increased uncertainty?



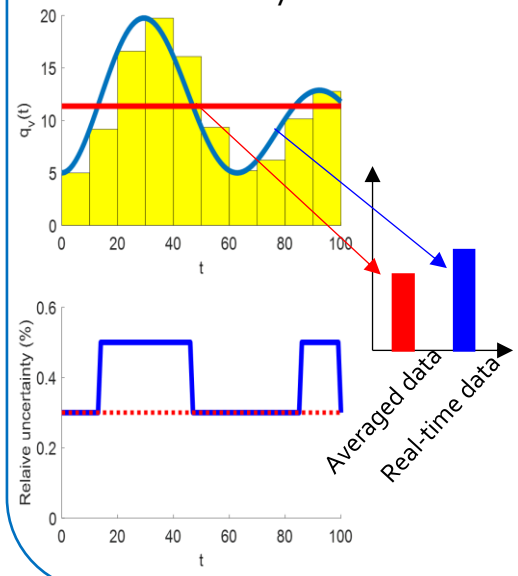
$$E = V \frac{P T_b Z_b}{P_b T Z} \times H_b$$

2. Integration over time
⇒ Increased uncertainty?



$$\int_{t_0}^{t_1} q_v(t)dt \neq \Delta t \sum_{i=1}^{N} q_{v,i}$$

3. Fluctuation in flow rates etc, but average values applied => Increased uncertainty?



PROGRAMME OF TODAY

- Timings of the lectures will be as distributed in the agenda
- Please switch off your microphone and camera when not speaking
- You can post questions in the chat, or ask them after the talk

- Have a pleasant day!

MET4H$_2$

Thank you for your attention!

Interested? Contact us at

avdveen@vsl.nl !

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

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.

EUROPEAN PARTNERSHIP

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CZECH METROLOGY INSTITUTE

le cnam

LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS LNE

UNIVERSITY OF LJUBLJANA | FS Faculty of Mechanical Engineering

21GRD05 - Metrology for the hydrogen supply chain

M36 Stakeholder meeting

Assessment and comparison of different methods to establish traceability for the measurement of hydrogen leak rates flowing to atmosphere in the range 10^{-9} mol/s to 10^{-6} mol/s

MET4H2

September 18th 2025

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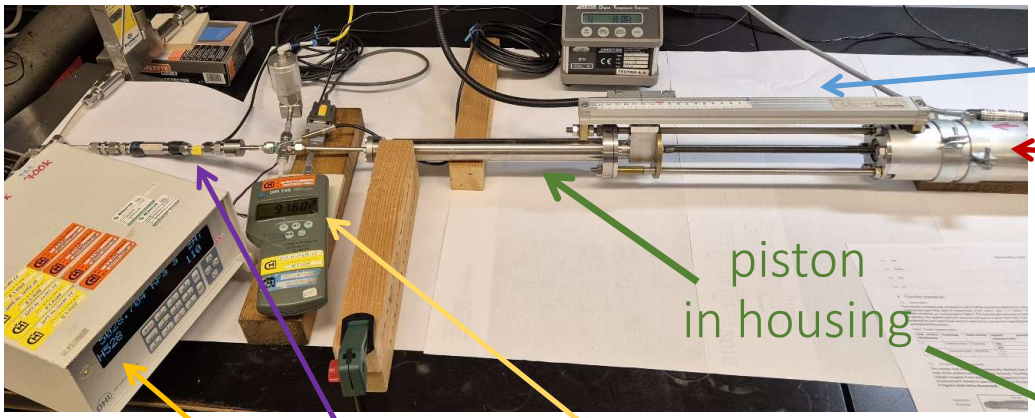
Overview

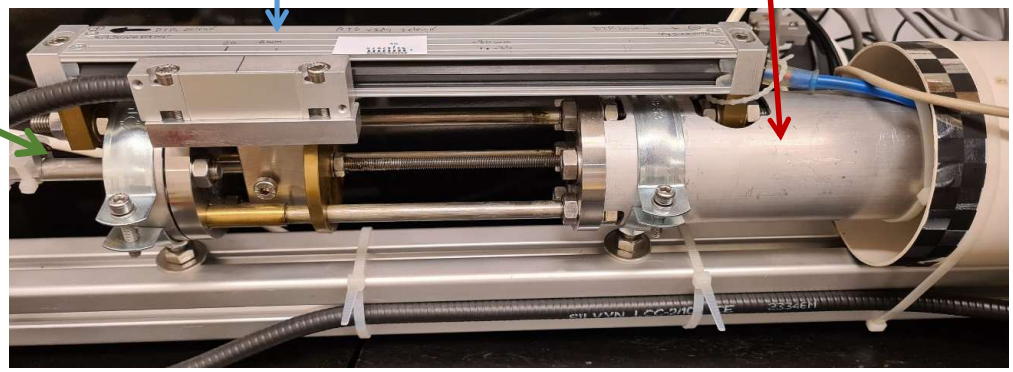
- Developed flow standards (0.003 to 1.3 sccm)
  - CMI
  - CNAM
  - LNE
  - UL
- Transfer standards and characteristics
- Comparison
  - Calibration procedure
  - Results
- Conclusion

CMI Flow standard: constant-pressure flowmeter

CMI Flow standard: constant-pressure flowmeter

Constant-pressure flowmeter OMZ consists of 2 pistons with nominal diameters 6 mm and 23 mm.



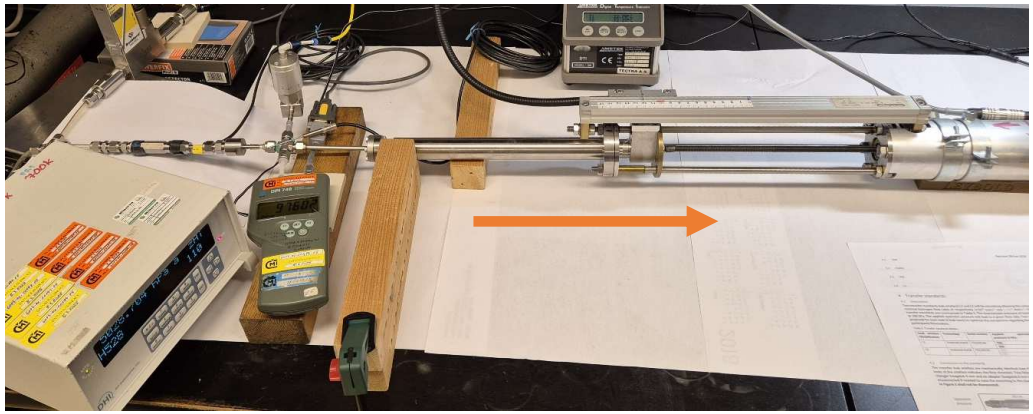


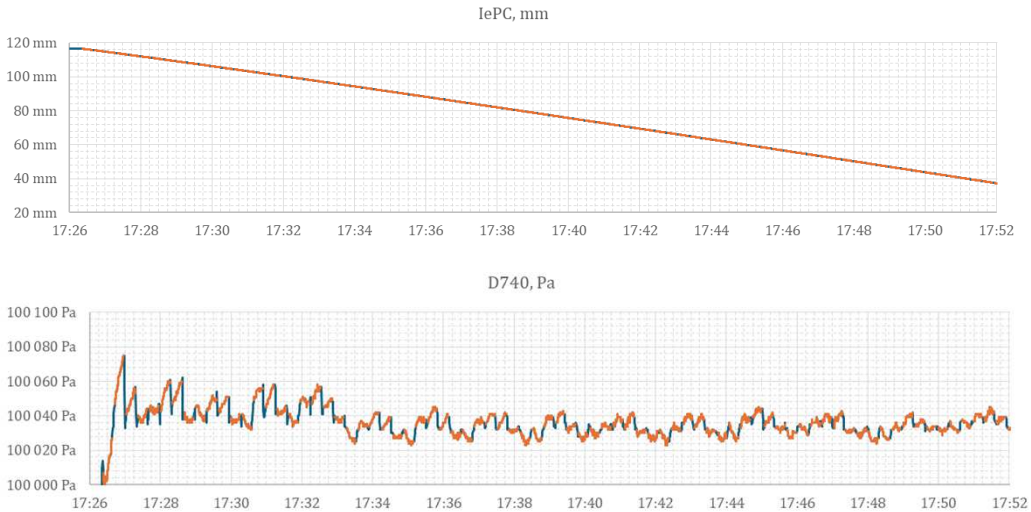
OMZ A: d 23 mm, L 250 mm, total V 100 cm³
OMZ B: d 6 mm, L 100 mm, total V 2,5 cm³

Each piston is equipped with opto-electronic position sensing and a stepper motor ensuring the movement of the piston relative to the housing.
The pistons are sealed against the housing with a Teflon seal with a rubber insert.

CMI Flow standard: principle

Constant-pressure flowmeter.



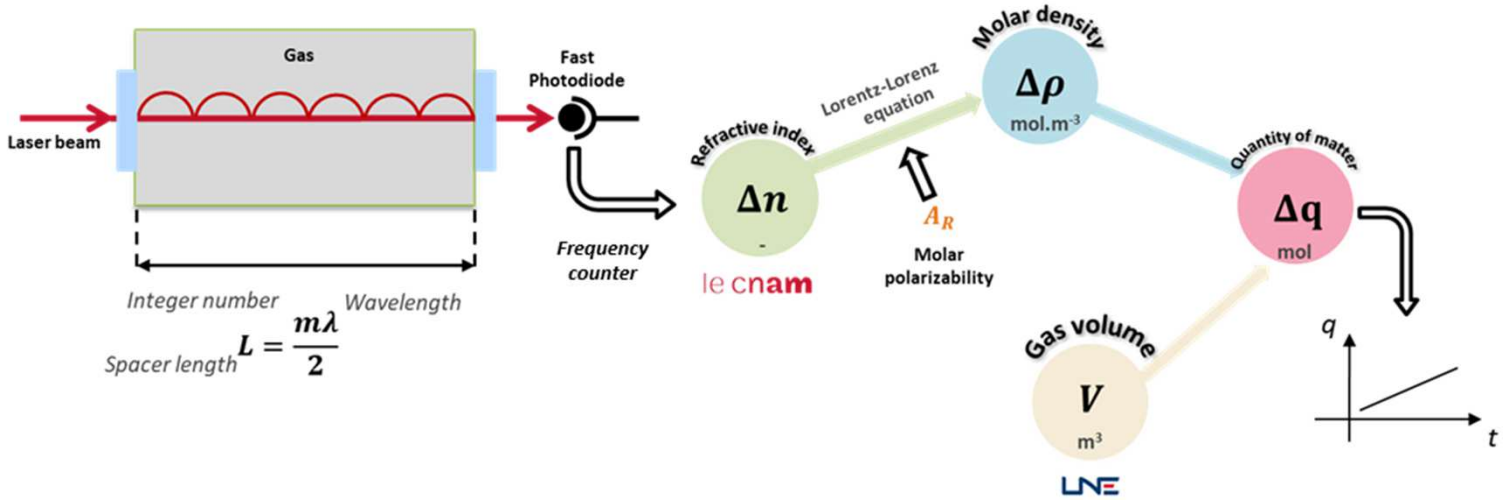


The volume of hydrogen flowing into the flowmeter from the calibrated leak is compensated by continuously extending the piston from the housing.
The piston position over time, the system pressure, and the temperatures of key system components are recorded.
Based on changes in pressure in the flow meter, the piston extension speed is adjusted to keep the pressure constant.

CNAM Flow standard based on refractometry

Fabry-Perot refractometry for leak detection at atmospheric pressure (10^{-7} to 10^{-9} mol/s) [1/4]

- **Measurement of variation of density and volume leads to quantity of matter variation over time**



Lorentz-Lorenz equation

$$\frac{n^2-1}{n^2+2} = \rho(A_R + B_R\rho + \cdots) \quad \Rightarrow \quad \Delta q = \frac{\Delta\rho V}{\Delta t}$$

Beat frequency variation between the 2 FP cavities

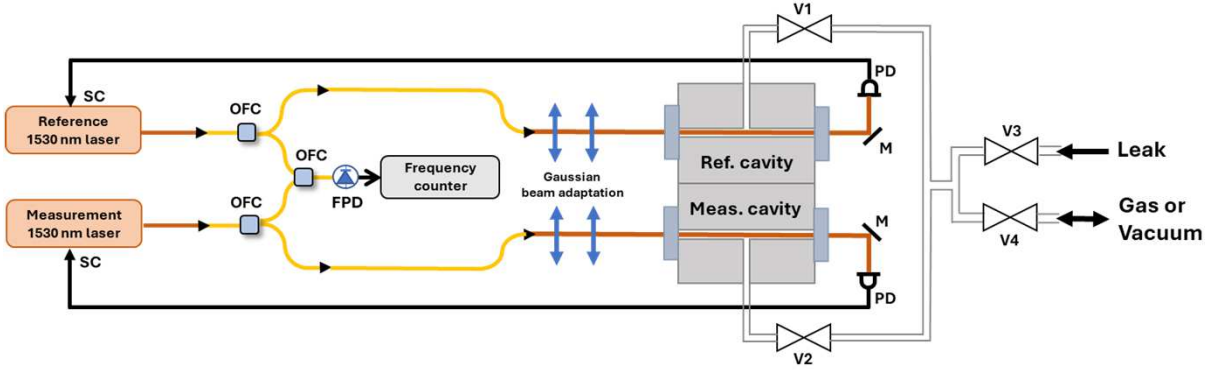
$$\Delta\rho = \frac{2}{3A_R}\left(\frac{\Delta f}{\nu_{gas}}\right) - \frac{1}{9A_R}\left(1 + 4\frac{B_R}{A_R^2}\right)\left(\frac{\Delta f}{\nu_{gas}}\right)^2$$

Laser frequency

Fabry-Perot refractometry for leak detection at atmospheric pressure (10^{-7} to 10^{-9} mol/s) [2/4]

le cnam

- **Measurement of variation of density and volume leads to quantity of matter variation over time**



$$\frac{n^2-1}{n^2+2} = \rho(A_R + B_R\rho + \cdots)$$

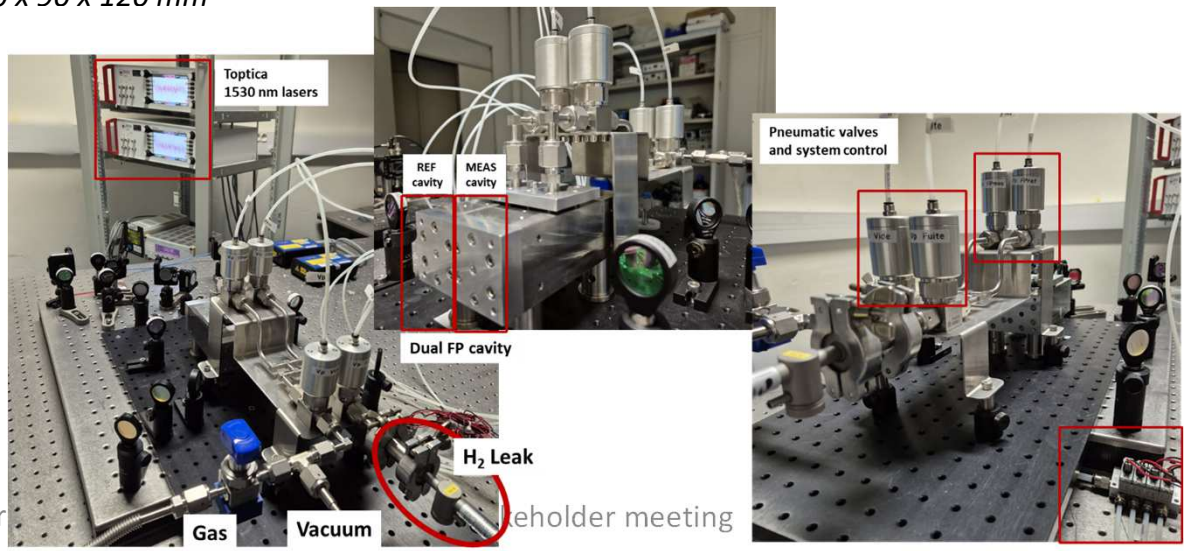
Beat frequency variation between the 2 FP cavities

$$\Delta\rho = \frac{2}{3A_R}\left(\frac{\Delta f}{\nu_{gas}}\right) - \frac{1}{9A_R}\left(1 + 4\frac{B_R}{A_R^2}\right)\left(\frac{\Delta f}{\nu_{gas}}\right)^2$$

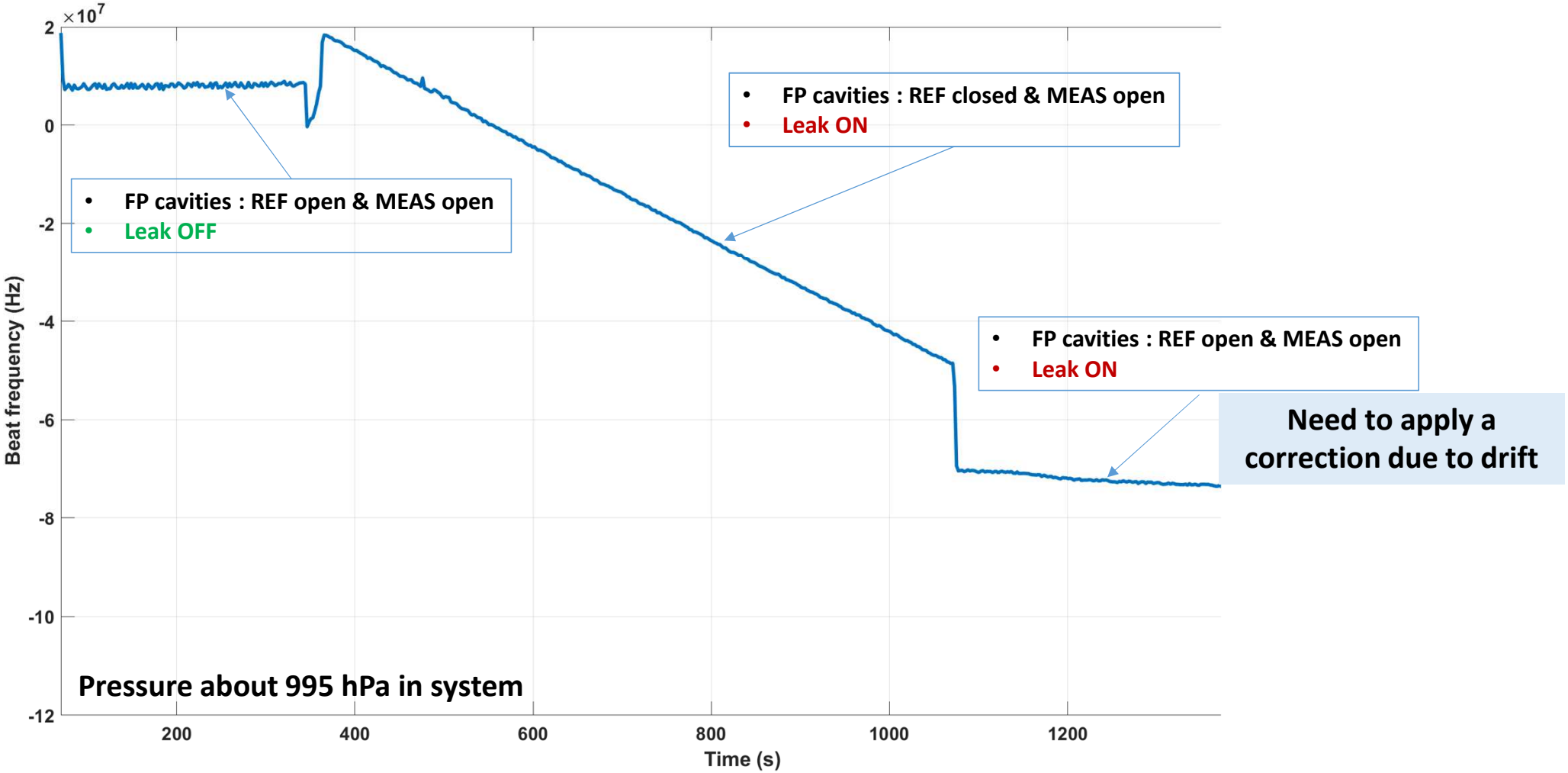
Laser frequency

$$\Delta q = \frac{\Delta\rho V}{\Delta t}$$

- *Dual Fabry-Perot (FP) cavity in Invar*
- *Toptica 1530 nm wavelength*
- *Size and volume optimization: 50 x 90 x 120 mm*

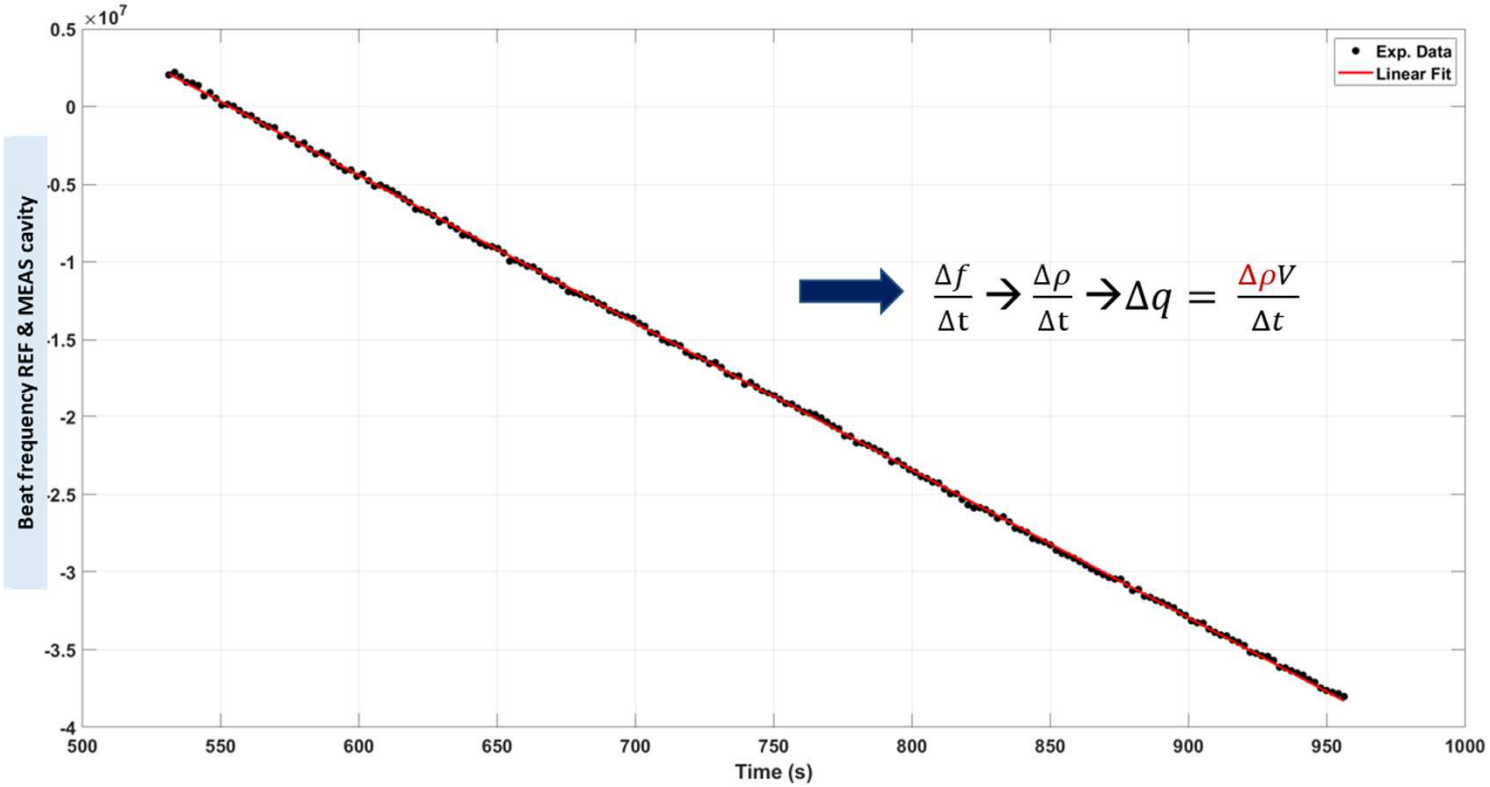


Fabry-Perot refractometry for leak detection at atmospheric pressure (10^{-7} to 10^{-9} mol/s) [2/4]



Fabry-Perot refractometry for leak detection at atmospheric pressure (10^{-7} to 10^{-9} mol/s) [2/4]

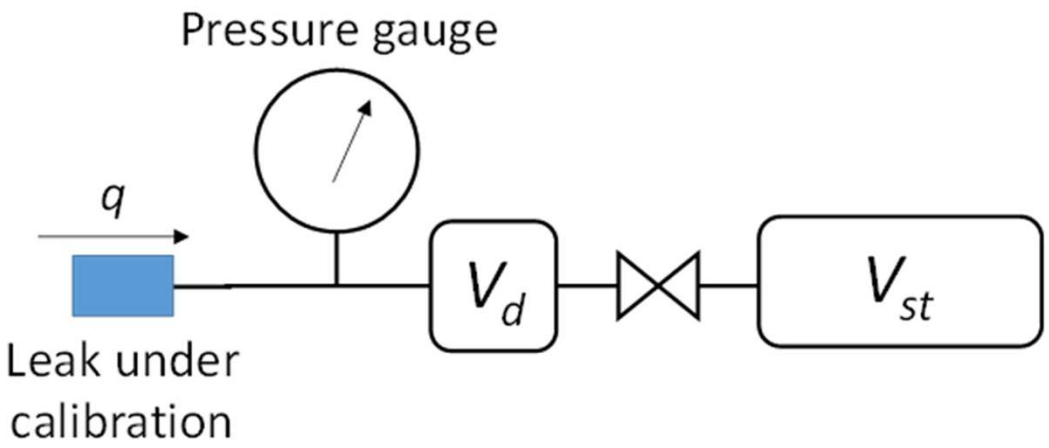
- Volume determination by LNE: $V_{\mathrm{FPR+Leak}} = 21.273(50)\ \mathrm{cm}^3$ at 20 °C.



- First uncertainty budget established
  - **Standard deviation of about 1%.**
  - Includes mainly the contribution of volume determination, the molar density changes over time (uncertainty of the fitting) and the uncertainties of both coefficients A_R and B_R.

LNE Flow standard: constant-volume flowmeter

Principle: pressure rise rate in a known volume



V_{st}: Standard volume
V_d: Dead volume

$V_m = V_{st} + V_d$

A constant flow rate in V_d then (V_d + V_{st}) allows one to determine V_d with pressure rate measurements [1]

→ Requires an optimal flow rate, ie **not too low**

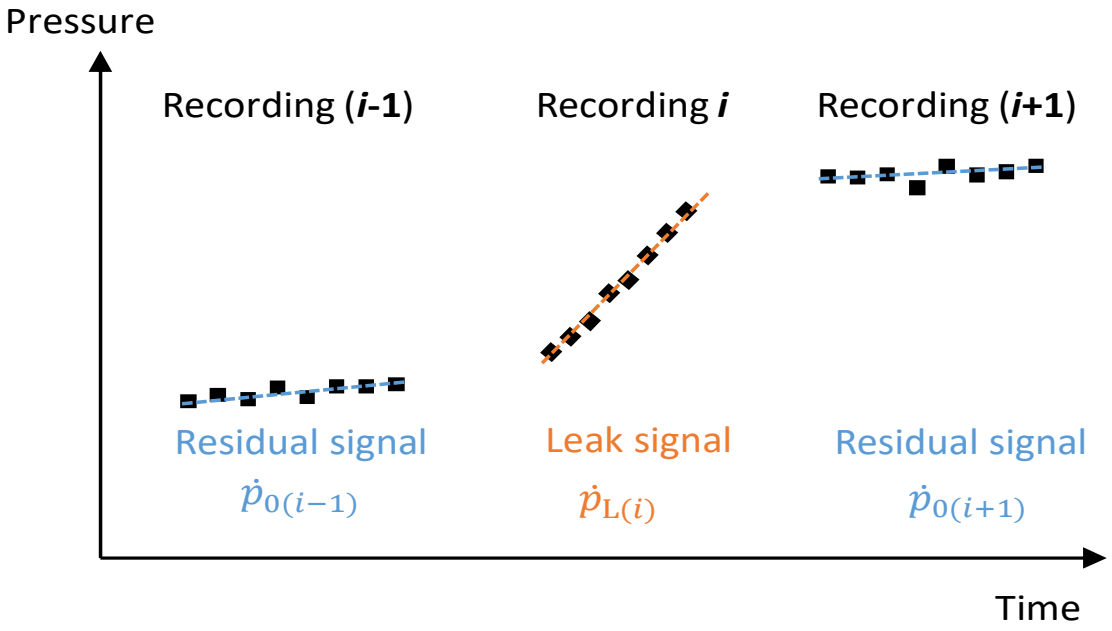
Determination of the gas flow rate in pressure and volume unit [$Pa.m^3.s^{-1}$]

$$q_{pV} = V_m \frac{dp}{dt}$$

[1] F. Boineau, M. D. Plimmer and E. Mahé, "Volume calibration using a comparison method with a transfer leak flow rate", ACTA IMEKO, vol. 9, no 5, Art. no 5, déc. 2020, doi: 10.21014/acta_imeko.v9i5.997.

Procedure of a leak measurement

Alternate of pressure recording with leak isolted from the flowmeter and leak flowing in



→ Requires stability of the residual signal

$$q_{pV} = (\dot{p}_L - \dot{p}_0) \cdot V_m$$

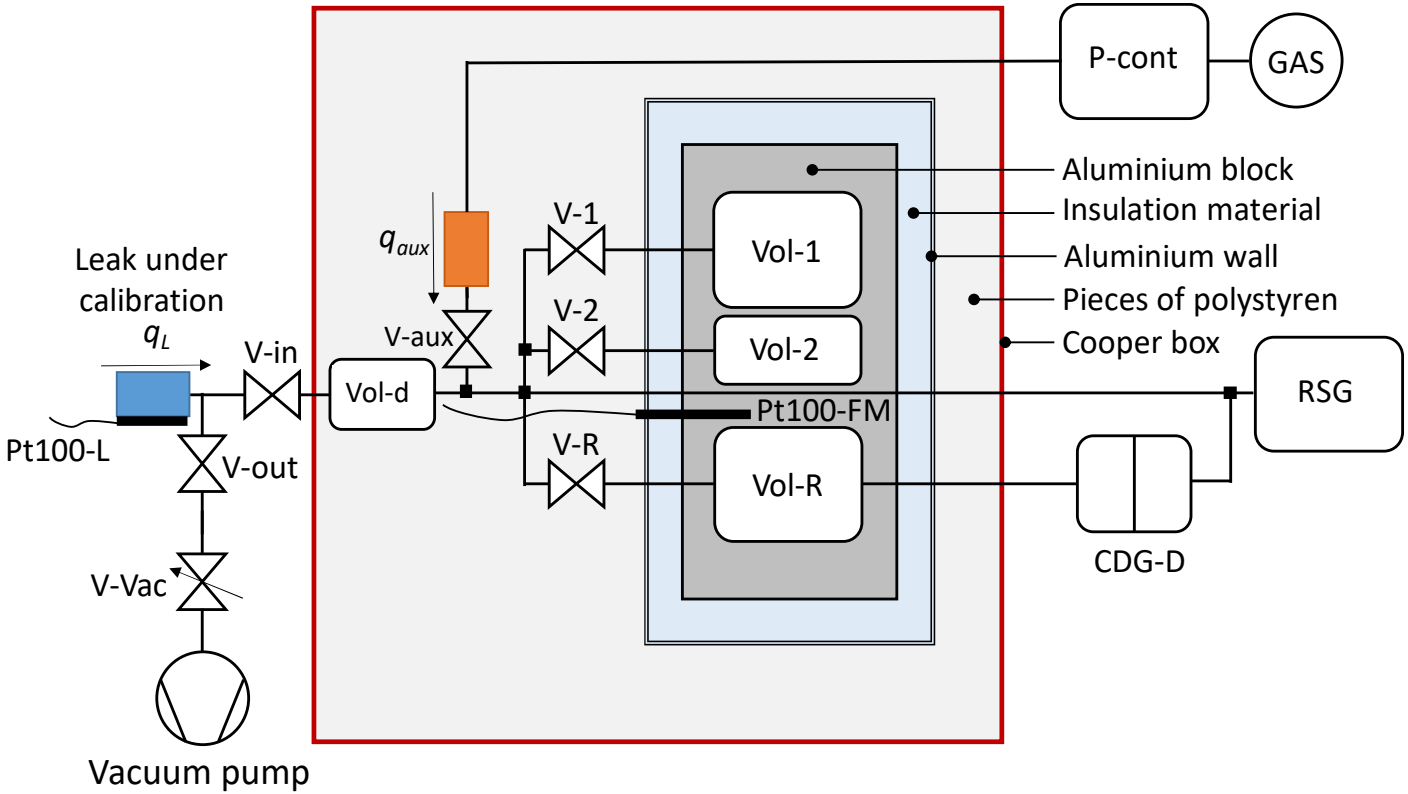
q_{pV}: flow rate in Pa.m³/s
$V_{m:}$ measurement volume

Molar flow rate of hydrogen ***q***

$$q = Z_{H2} \frac{q_{pV}}{R \cdot T_{FM}}$$

Z_{H2}: compressibility factor of hydrogen
R: molar gas constant
T_{FM}: gas temperature in the flowmeter

Design of the LNE constant volume flowmeter



q_L: Flow rate of the leak under calibration, q_{aux}: flow rate of the auxiliary leak artefact (capillary); **RSG**: Digital barometer; **CDG-D**: Differential capacitance diaphragm gauge of 1 kPa full scale; **P-cont**: Absolute pressure controller, 1000 kPa full scale; **Vol-1**: Standard volume of 1000 cm3; **Vol-2**: Standard volume of 200 cm^3 or 30 cm^3; **Vol-R**: volume of 150 cm^3 connected to the reference port of the differential pressure gauge; **Vol-d**: Dead volume of tubing, gauges, valves, *etc.*; **V-1**, **V-2**, **V-R**, **V-aux:** Pneumatic bellow valves; **V-in**, **V-out**: Manual bellow valves; **V-Vac**: Adjustable micro-leak valve; **Pt100-L**: Pt100 sensor to measure the temperature T_L of the leak under calibration; **Pt100-FM**: Pt100 sensor to measure the temperature T_{FM} of the flowmeter.

Key points:

- Optimised flow rate for V_d measurement → Auxiliary leak, replaced by a plug of mastered internal volume in the leak measurement phase
- Stability of the residual signal → High thermal inertia of the measurement volume

Calibration uncertainty

Lie between **0.16%·q** and **1.0%·q** in the range 10^{-9} mol/s to 10^{-6} mol/s

UL Flow standard: PVTt system

UL, FME - pVTt primary standard

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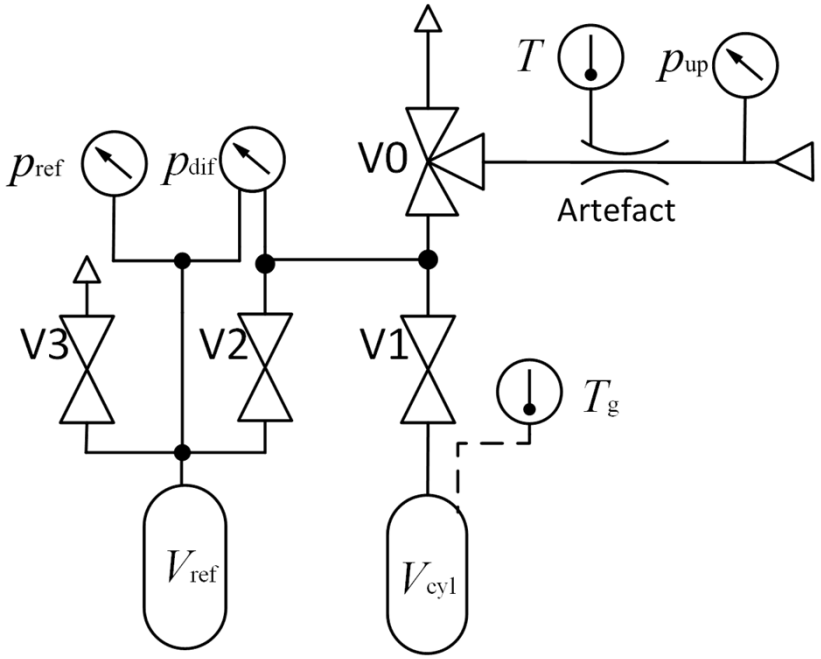
- Volumetric standard with constant volume using a static mass determination and flying start-stop method
  - Constant flow is diverted into measuring volume (V_{cyl}) for a certain time interval
  - Collection of mass flow is predominantly expressed as pressure rise
  - Flow rate range of 7×10^{-6} mol/s to 7×10^{-8} mol/s of nitrogen/dry air
  - Measurement at atmospheric conditions with max 2.5 kPa pressure rise
  - Collection time between 15 and 900 seconds
  - Measurement volume of approx. $V_{cyl} \approx 100$ cm^3.
  - System is submerged in a water bath → temp. stability



UL, FME - pVTt primary standard

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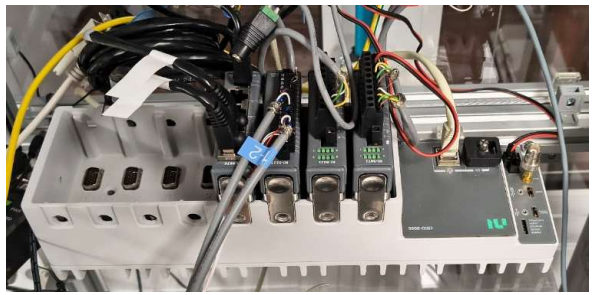

- Operated via a real-time controller equipped with dedicated modules for Pt100, digital inputs and outputs, and digital communication.
- System monitoring & data acquisition performed using LabVIEW
- Gas properties are determined with REFPROP

- N_2: Expanded uncertainty of 0.2 % (0.25 % below 1.4×10^{-7} mol/s)

- In-house validation for N_2
  - Comparison with piston prover standard with expanded uncertainty of 1×10^{-8} mol/s in the tested flow range from 7×10^{-6} mol/s to 1.8×10^{-6} mol/s
  - *En* values below 0.3

UL, FME - pVTt primary standard

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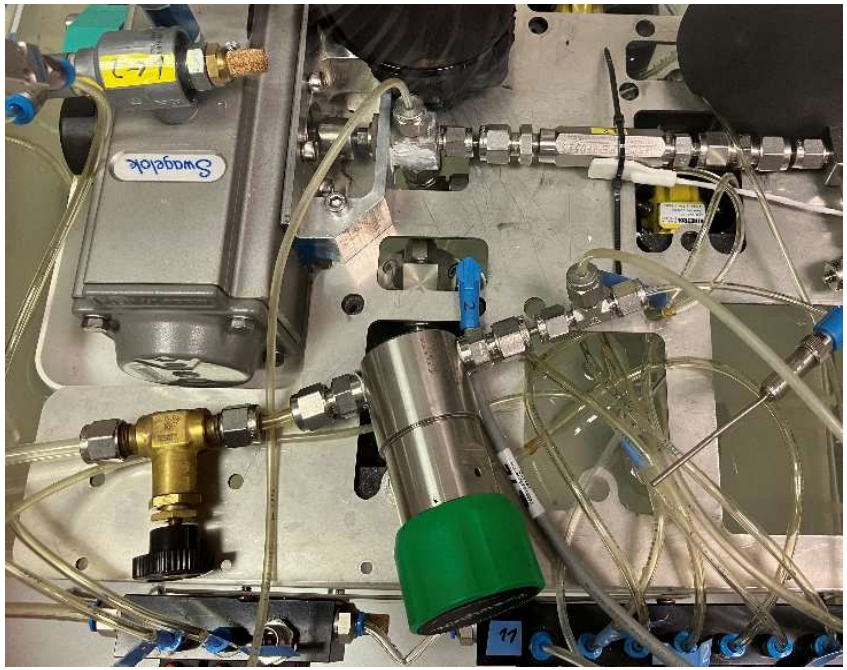
Hydrogen leak calibration (L2)

- Leak used as stable flow-rate source
  - Constant inlet pressure: 250 kPa or 500 kPa
  - Outlet connected to diverter
  - Outlet pressure: linear rise up to 2.5 kPa, average value used
- Standard uncertainty contributions:
  - Measuring volume: 0.15 %
  - Leak artefact (outlet pressure variation): 0.04–0.14%
  - Density measurement: ≈ 0.06%
  - Leakage & time: negligible
- Resulting flow-rate standard uncertainty:

0.16–0.21%



Standards comparison

Transfer standards

2 transfer standards were necessary to cover the leak flow range, available from ASC Instruments France

Leak artefact Identification	Technology	Serial number	Applied upstream pressure in kPa	Nominal flow rate in $mol \cdot s^{-1}$
L1	Metal capillary	FE210514	700	2×10^{-8}
			300	3×10^{-9}
L2	Sintered metal	FE210515	500	1×10^{-6}
			250	2×10^{-7}

Upstream pressure of H_2

Downstream pressure (Atmosphere)

Characteristics of the transfer standards

The leak rate ***q*** depends on:

- Upstream and downstream pressures
- Temperature

A stability of the standards is expected over the duration of the comparison

Transfer standard	Temperature coefficient	Uncertainty of stability
L1	$(-0.51\% \pm 0.05\%)\ K^{-1}$	1.3%
L2	$(-0.43\% \pm 0.05\%)\ K^{-1}$	0.068%

General procedure for the comparison

Temperature (T_0): 20 °C with a tolerance of ± 5 °C
Downstream pressure (p_{dw0}): 100 kPa with a tolerance of ± 5 kPa
Number of measurements per calibration: 3

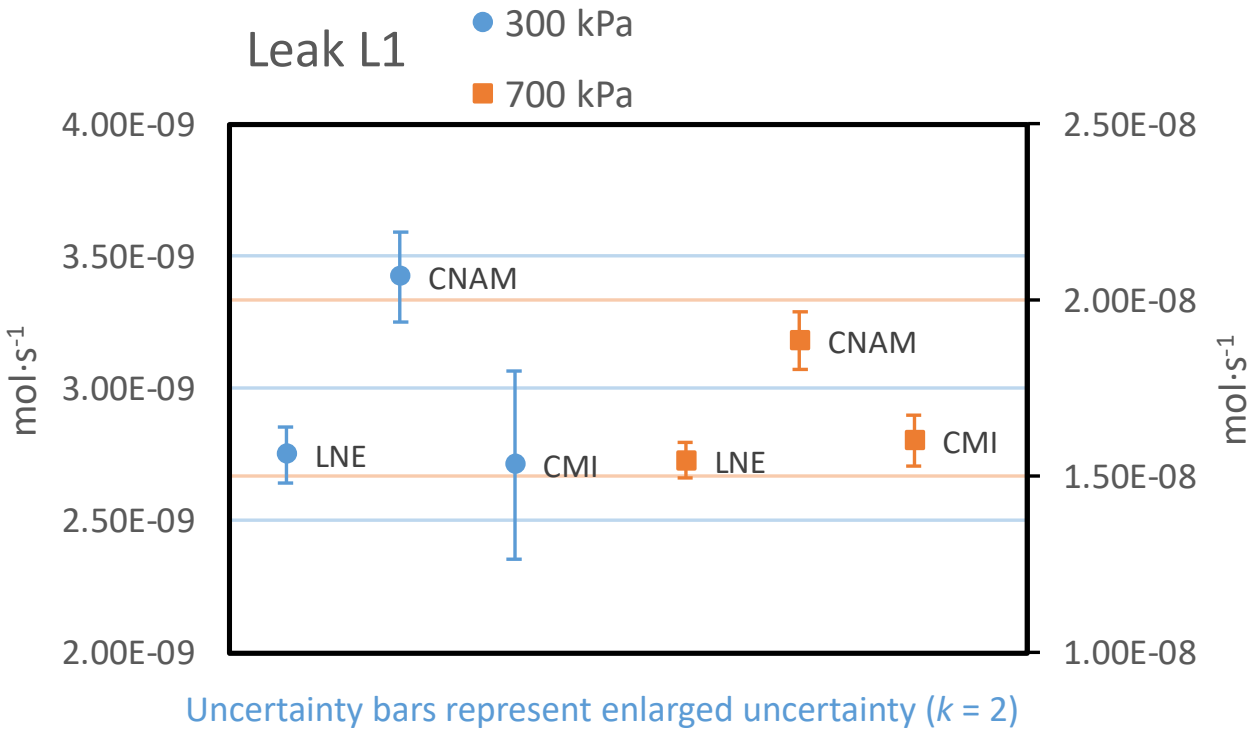
Notations used	
p_up	Applied upstream pressure and its standard uncertainty $u(p\_up)$
p_dw	Downmnstream pressure and its standard uncertainty $u(p\_dw)$
T	Measured leak temperature and its standard uncertainty $u(T)$
$q(p\_up ; p\_dw ; T)$	Measured molar flow rate and is standard uncertainty $u(q)$
T_room	Room temperature during the calibration

Laboratory name	
Date	
T_room (°C)	

Leak L1									
***p_up* nominal**	**Measurement number**	***p_up***	***u*(*p_up*)**	***p_dw***	***u*(*p_dw*)**	***T***	***u*(*T*)**	***q*(*p_up* ; *p_dw* ; *T*)**	***u*(*q*)**
kPa		**kPa**	**kPa**	**kPa**	**kPa**	**°C**	**°C**	**mol·s^{-1}**	**mol·s^{-1}**
700	1								
	2								
	3								
300	1								
	2								
	3								

From $q(p\_up ; p\_dw ; T)$, the pilot calculates the comparison flow $q_{comp} = q(p\_up_0 ; p\_dw_0 ; T_0)$

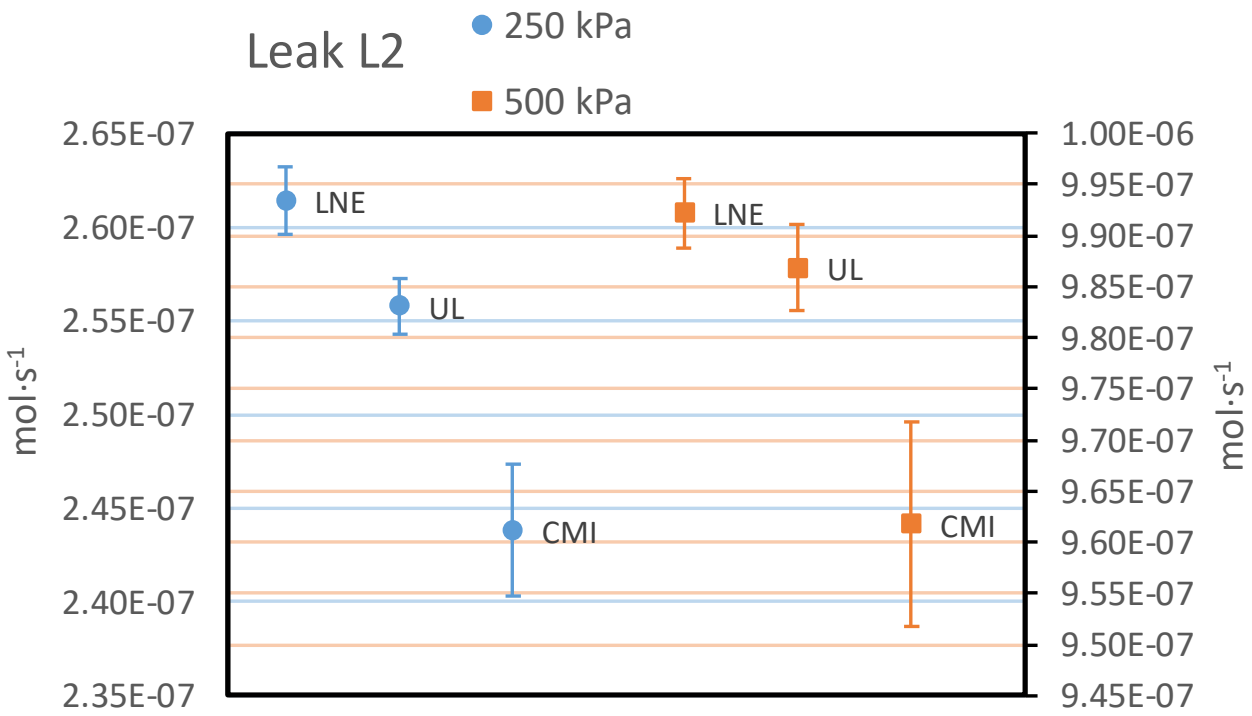
Results of the comparison (leak L1)



Uncertainty bars represent enlarged uncertainty (k = 2)

- CMI et LNE have compatible results
- CNAM results show a systematic deviation of around 20% compared with LNE results

Results of the comparison (leak L2)



- UL et LNE have compatible results for 9.9E-7 mol/s
- LNE results show a systematic deviation of around 5.5E-9 mol/s compared with UL results
- CMI results are systematically below those of LNE and UL

Conclusion

- Comparison of small hydrogen flow standards completed successfully
- Good stability of the transfer standards
- Some deviations between participants were stated
  - Measurements of small flow rates are challenging
  - Guidance to improve (eliminate errors) of the standards
  - Possible issues: leaks in the measurement system (LNA, CNAM), knowledge of hydrogen virial coefficients (CNAM), stability of the downstream pressure during a measurement (UL)
  - Possible impurities in inlet of H_2 (CMI)

Contributors

Frédéric Boineau LNE
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Jean-Pierre Wallerand CNAM
Martin Vičar CMI

Testing rigs for hydrogen sensors

Workshop Met4H2

Online

Karine Arrhenius, Oliver Büker, RISE

Shirin Khaki, NPL

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Testing rigs for hydrogen sensors

Introduction

- The competitiveness of the hydrogen supply chain depends directly on its safety and the safety of the facility where hydrogen is used, stored or transported
- Hydrogen has a very broad flammability range (4 to 74% in air) and is prone to leaks due to its small molecular size, less dense than air
- Chemical sensors respond to a particular analyte in a selective and reversible way, and are crucial technology for the safe use of hydrogen

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Testing rigs for hydrogen sensors

Safety hydrogen sensors

- Monitor the level of hydrogen to detect and/or quantify hydrogen leak: can be used to trigger alarms and activate ventilation or shut down systems to prevent hydrogen to reach flammable levels. Their working range usually covers at least up to the LEL. Current applications: Room/area monitoring for safety where hydrogen leakage may occur e.g. battery, detection of leaked hydrogen, process monitoring and control, stationary and mobile fuel cell applications

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Testing rigs for hydrogen sensors

Hydrogen purity sensors

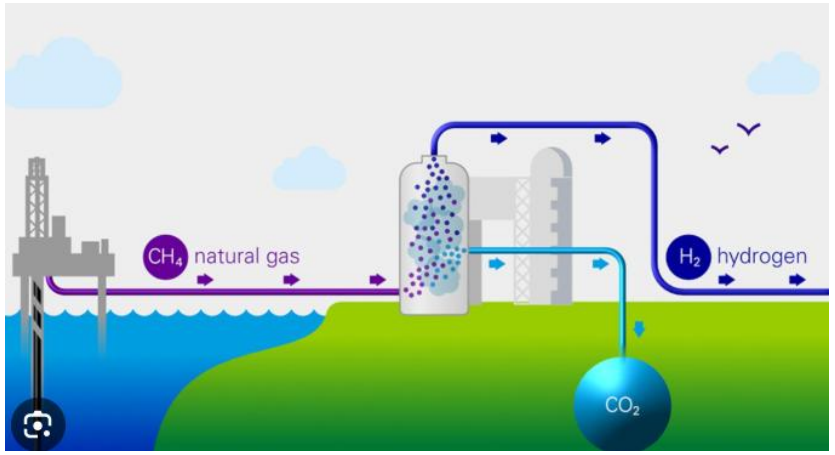
- Are used to monitor the quality of hydrogen. Example of application: quality control process to check the compliance with the requirements in the international standards (ISO 14687: 2019 or EN17124:2022) and ISO 19880-8:2024) for hydrogen fuel.
- Sensors need to be able to detect low level of components such as O2, CO, H2S, H2O in pure hydrogen.
- Limited availability: manufacturers mainly propose existing solutions for other matrices (air, N2).
- Must be checked for hydrogen by ensuring that the hydrogen itself will not give rise to a signal before further testing.
- These sensors must be intrinsically safe

Testing rigs for hydrogen sensors

Hydrogen in gas mixtures sensors

- Hydrogen can be injected into the existing natural gas network where it can be transported to the consumers.
- Amount of hydrogen must be controlled so the H2/CH4 mixture satisfies the gas quality requirements of the pipeline set by legislations and standards.

- H2 produced by steam methane reforming reaction: Gas produced contains 2 to 10 vol-% CH4 as residual



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Testing rigs for hydrogen sensors

What do we do in Met4H2?

- Review of the state-of-the-art including techniques, existing protocols, test rigs, applications
- Development of a protocol to metrologically test sensors
- Development of two rigs to test sensors
  1. NPL: rig able to test 1 to 5 sensors for at least one contaminants in H2
  2. RISE: rig able to test different types of sensors
- Test of the protocol using both rigs
- Write guideline on validation, calibration and verification of sensors

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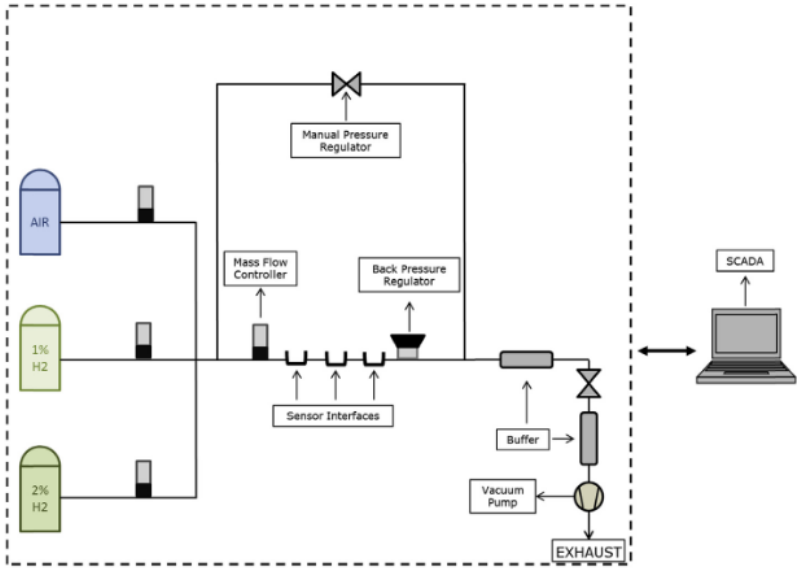
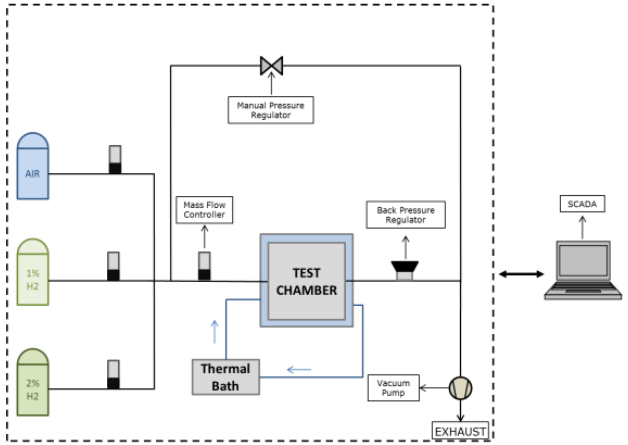
Testing rigs for hydrogen sensors

Protocol

Two common methods to test sensors



Flow-through test



Chamber test

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Testing rigs for hydrogen sensors

Protocol

Testing of each metric clearly defined in a table

	What to do	Evaluation of results	Pressure conditions	Comments
Precision	6-15 replicates for at least 10 min during a short timescale using a single test gas having a volume fraction at the midpoint of the measuring range using a flow at the midpoint of the flow interval. Calculate the standard deviation	Calculate the standard deviation of the replicates	0.8 to 1.2 bar, kept constant within ±0.1 bar throughout the duration of the test 15°C and 25°C kept constant within ±2 °C throughout the duration of the test 20 % and 80 % within ±10 % throughout the duration of the test.	For sticky" impurities*, the duration of the test should be extended (to the time needed to obtain a stable signal). A reference analytical instrument can be used to confirm that the sensor is exposed to the amount of analyte present in the test gas

Testing rigs for hydrogen sensors

Protocol

Covers:

Precision

Trueness/accuracy

Response time

Stability and drift

Selectivity or cross-interference

Limit of quantification

Nominal range, saturation

Resolution

Hysteresis

Reversibility

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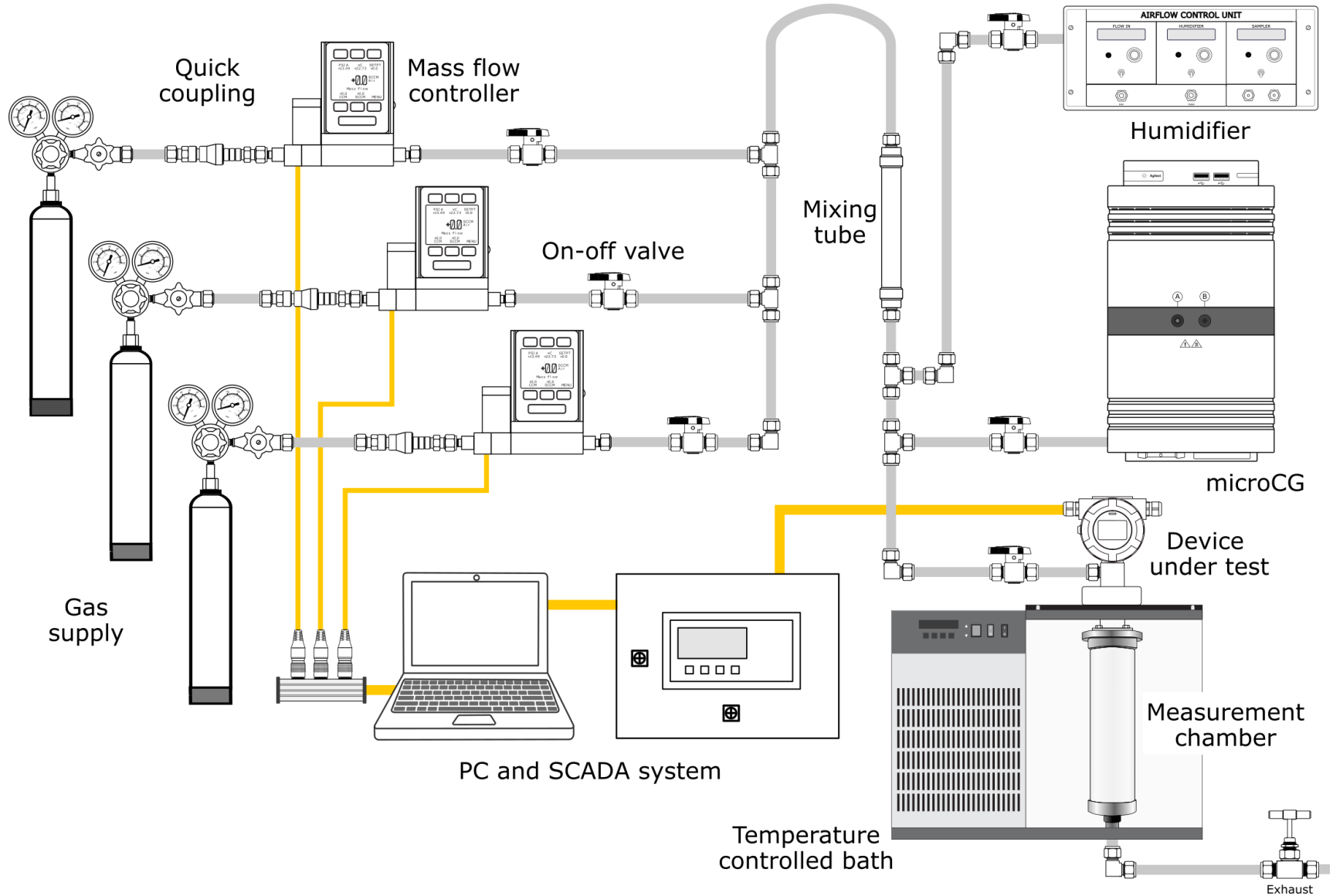

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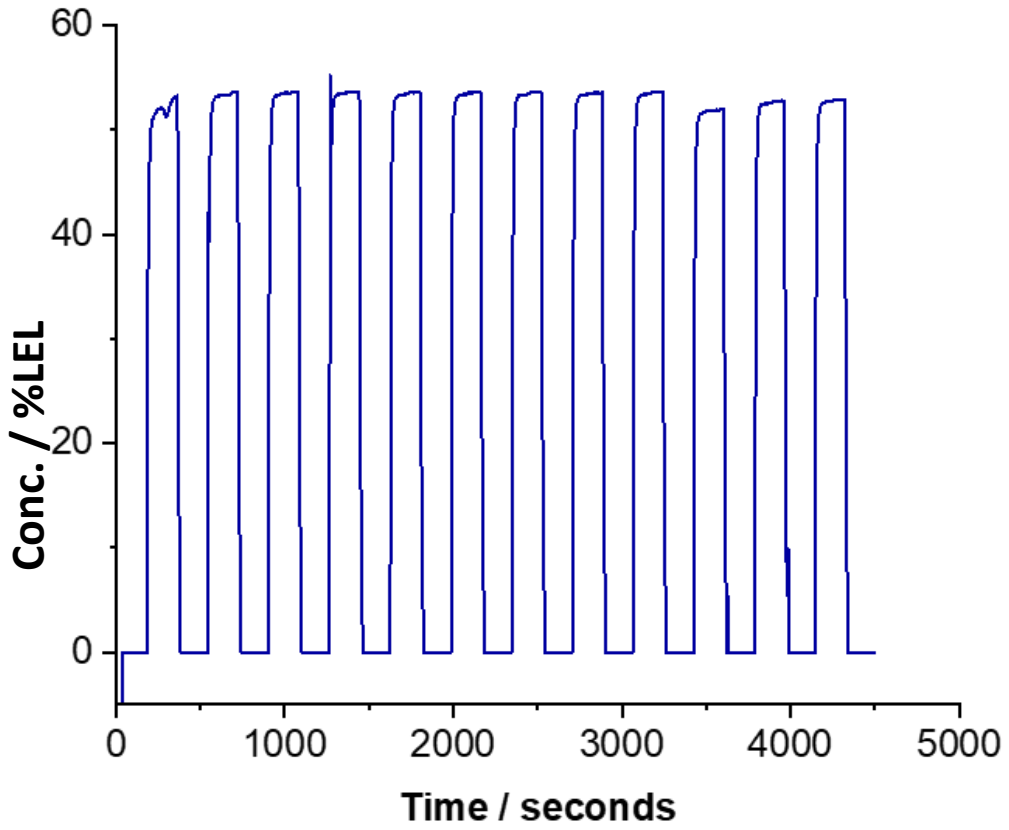
Sensor performance evaluation: precision

The consistency of repeated measurements and is a measure of the standard deviation of results obtained by carrying replicate measurements. The precision can be expressed as repeatability.



Replicates at 2.153 vol-% (around 54%LEL)
LEL= Lower explosive limit Lowest concentration of a gas that can ignite and cause explosion if an ignition source is present.

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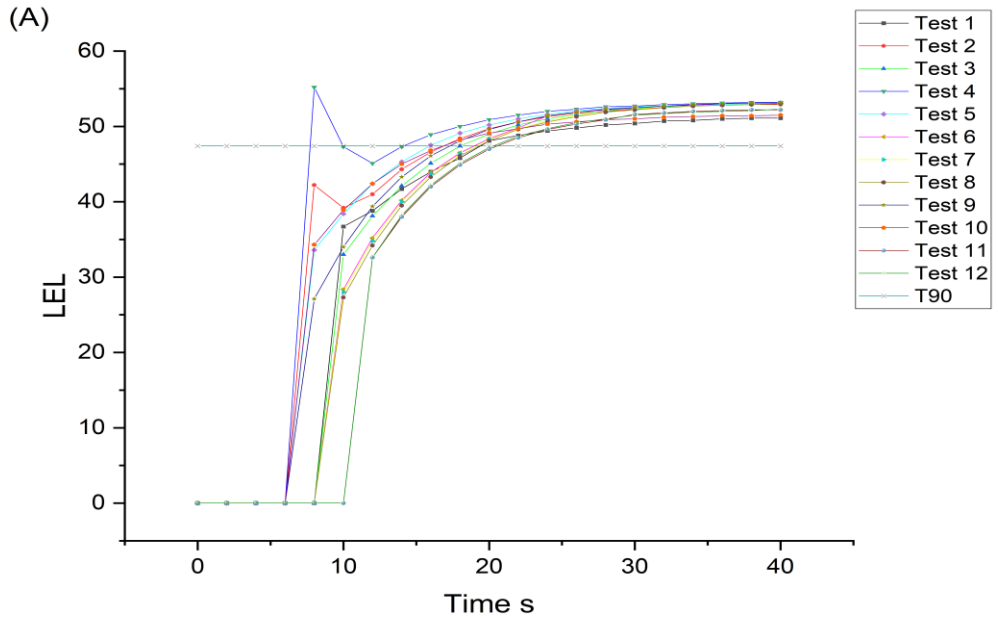
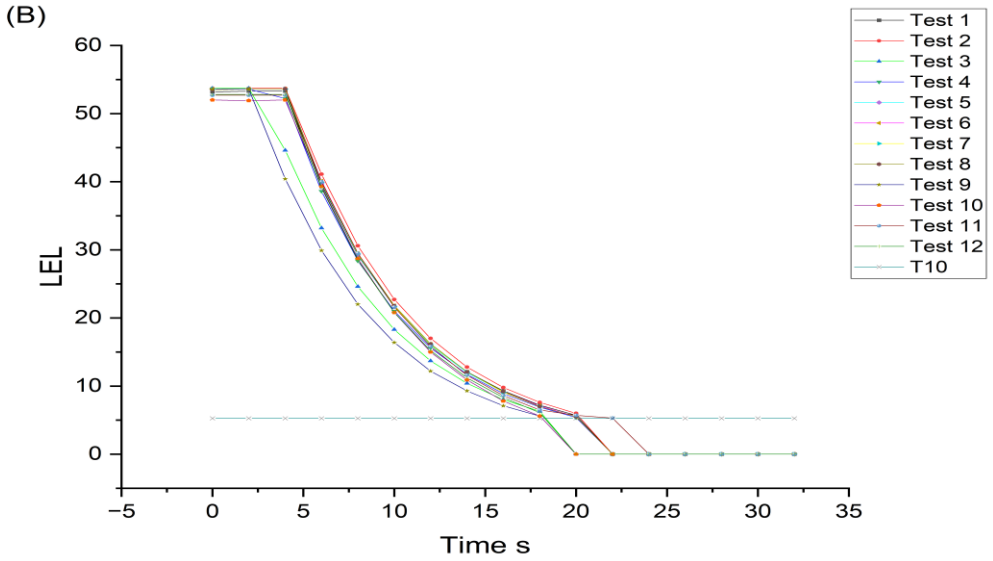
Sensor performance evaluation: Response time

T90 corresponds to the time to reach 90% of the applied target gas concentration or its stable reading. The recovery time **T10** is defined as the time to fall to 10% of final value after step removal of measured variable.

- .





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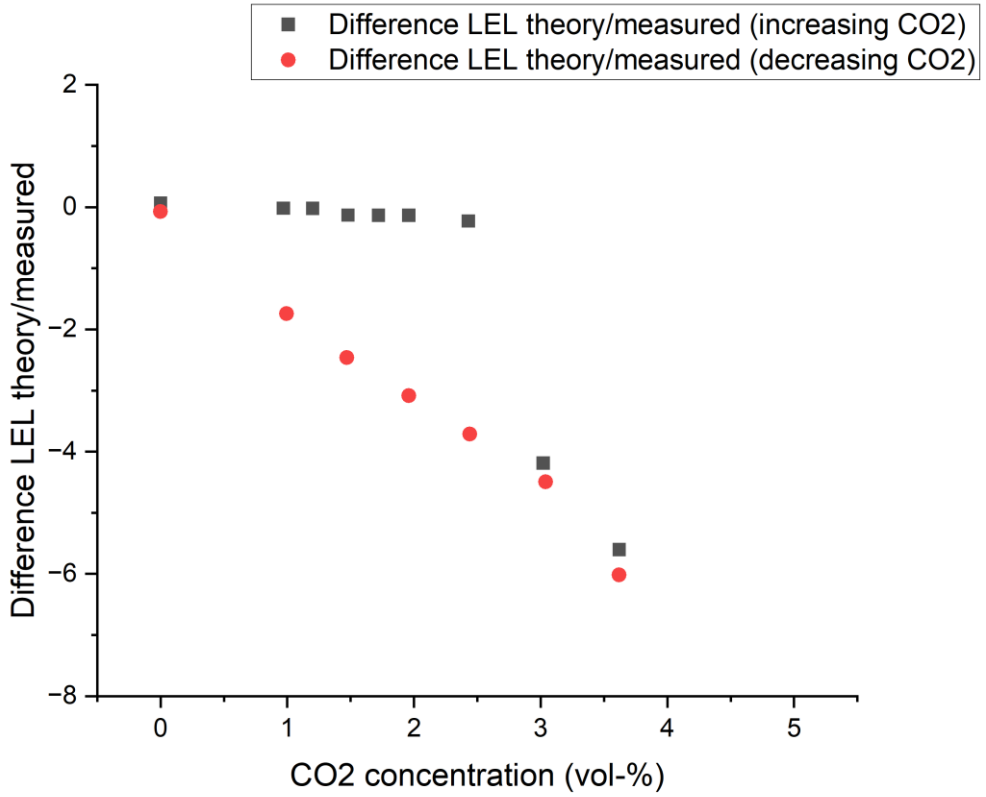
Sensor performance evaluation: Cross-sensitivity

Sensors are designed to be selective to a specific compound or to a certain type of compounds.

In the presence of some non-targeted compounds, a signal may be produced leading to errors in the measurement of the target compound (either higher or lower than predicted).



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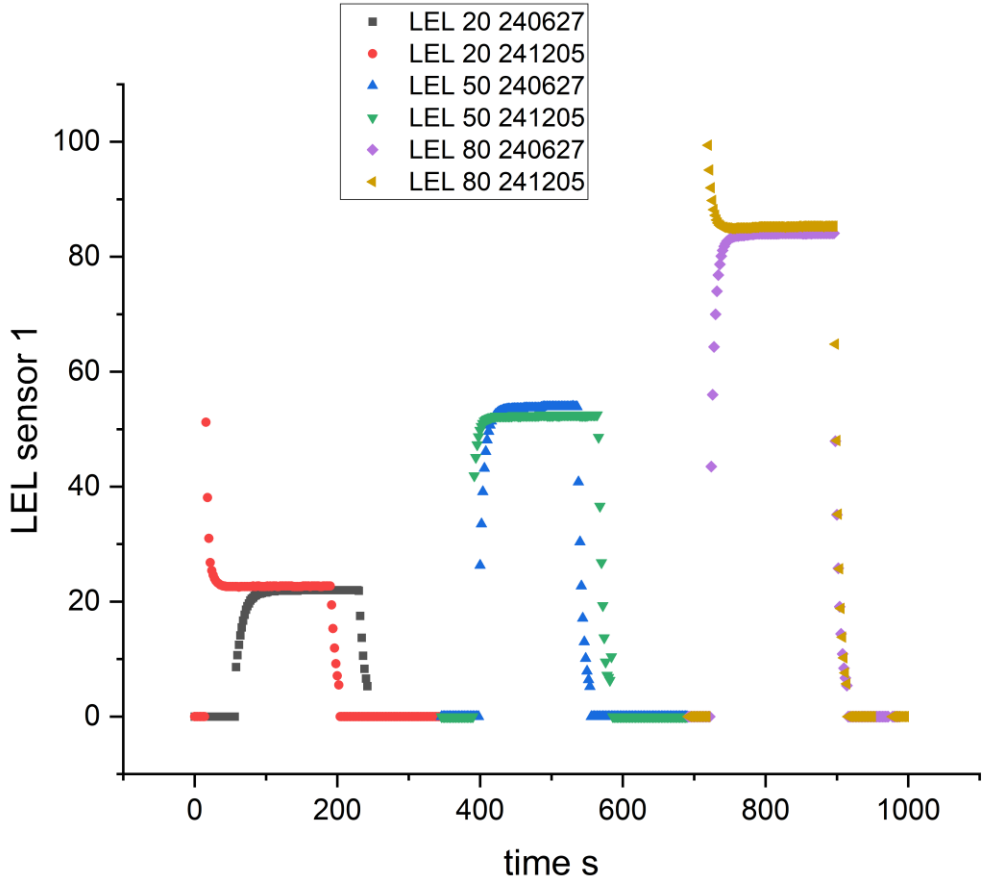
Stability

Drift is a temporal change in the response of an instrument to a constant concentration. Drift implies that the performance of a measuring instrument changes, and re-calibration must be performed.



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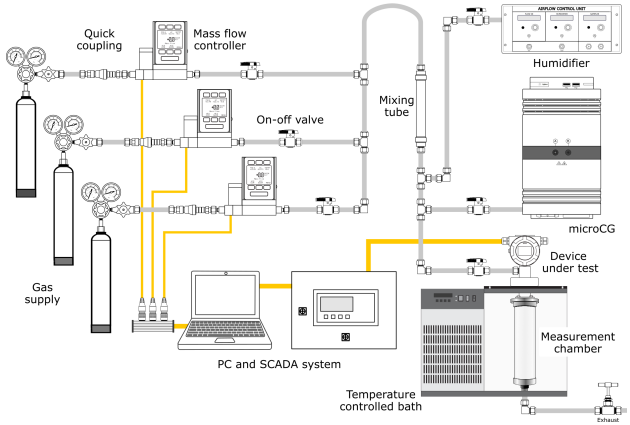
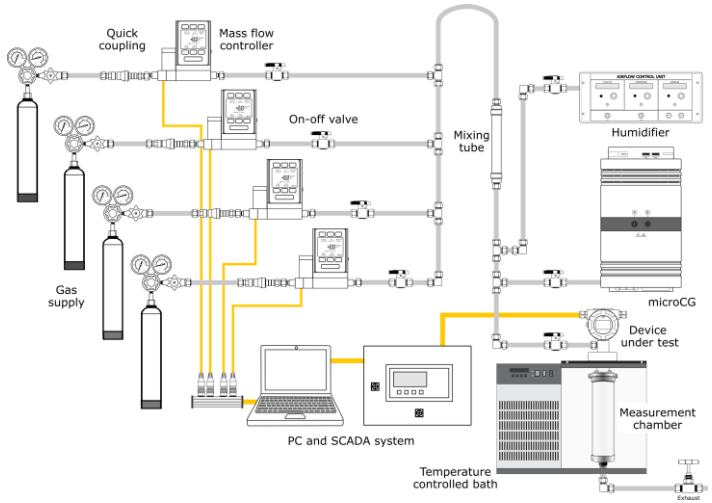
Extension of the rig

The rig was used in another project to test the capability of selected sensors to detect gases which occur during an early thermal runaway event (battery)



New design

Initial design consisted of 3 gas lines
Another gas line has been added for another project



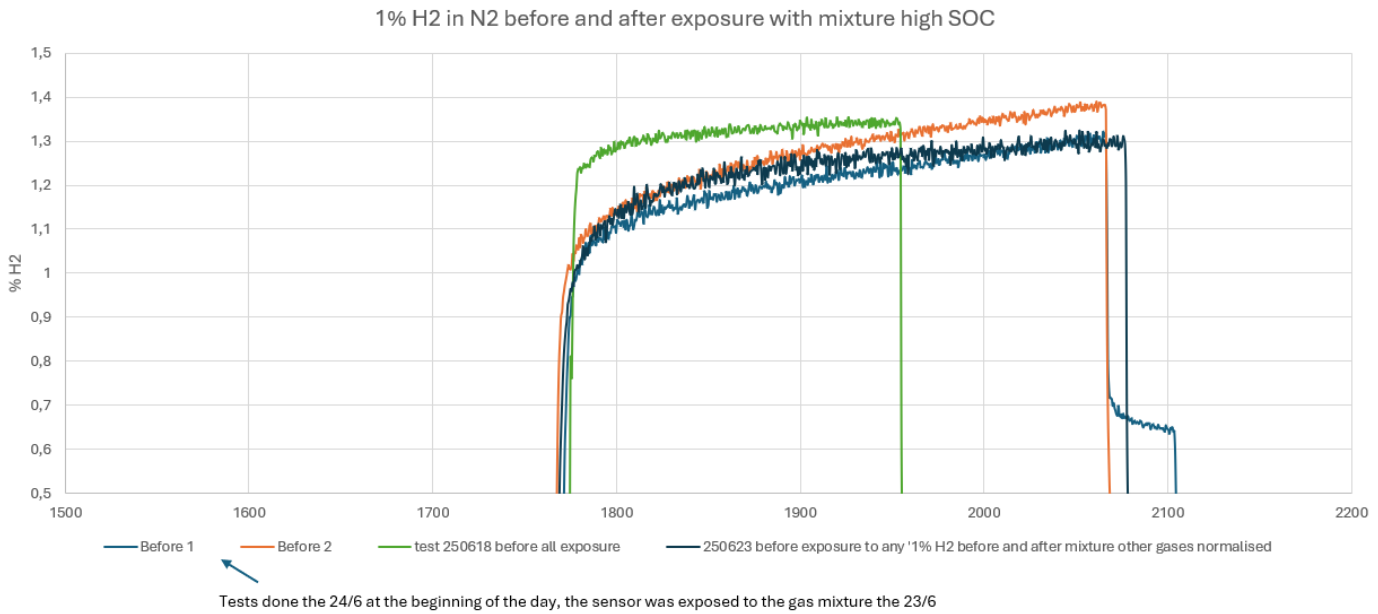
New utilisation of the rig

The rig was used to test a hydrogen sensor which exhibited kinetic problems when left in the air of the lab

Results

Flow 24/6: 1250 ml/min
Flow 23/6: 2000 ml/min
Flow 18/6: 1410 ml/min

The sensor for some reason seems to be affected just from being standing in the lab



Rig for sensor testing impurities

+ Rapid change of amount fraction i.e. from 0.5 to 100 ppm in a few seconds;

+ Rapid change of pressure up to 10 barg (140 psig);

+ Traceability to NPL's PRM;

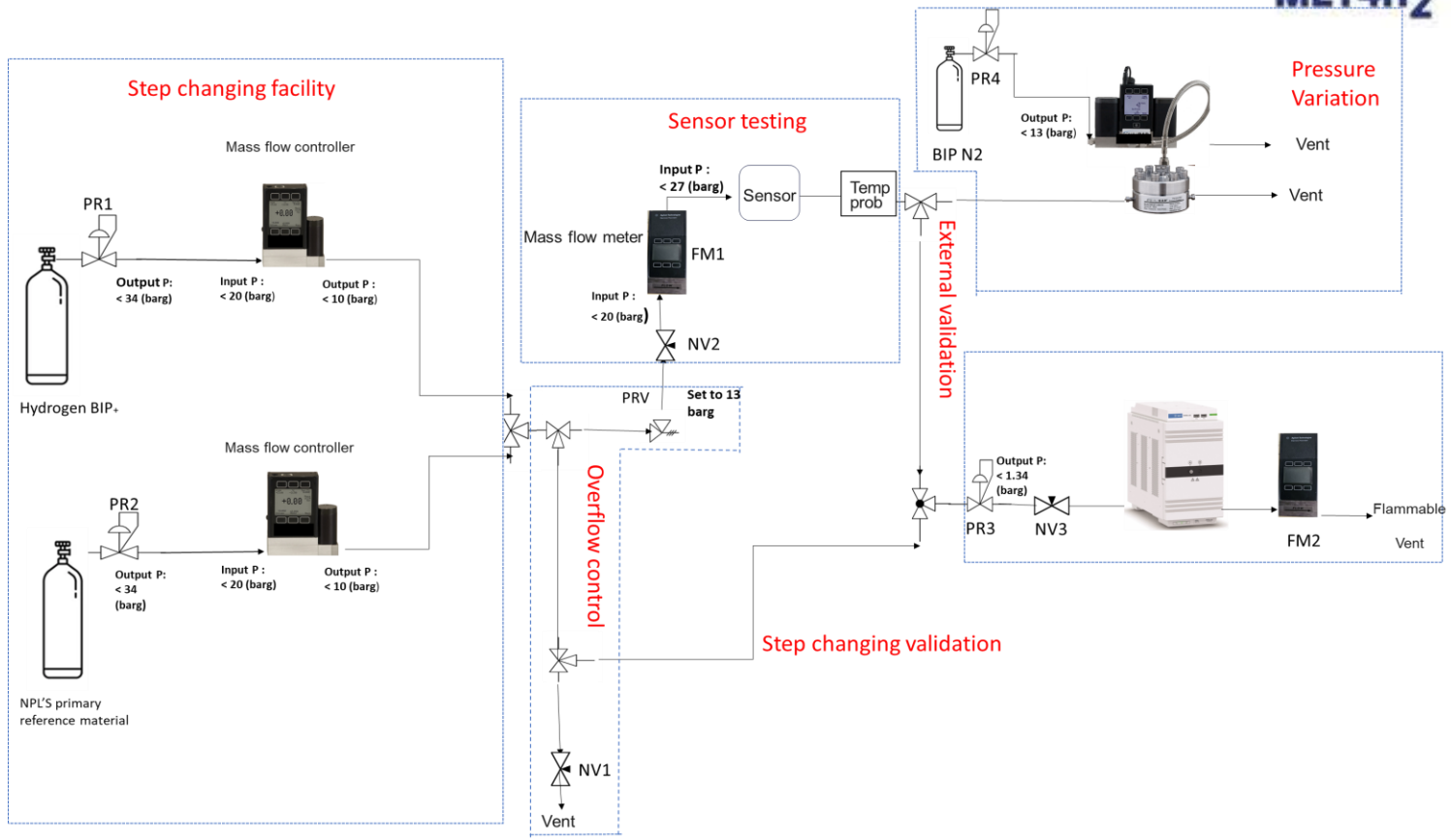
+ Constant monitoring of the temperature of the gas;

+ Flexible flow rate;

+ Compatible with most contaminants in H_2

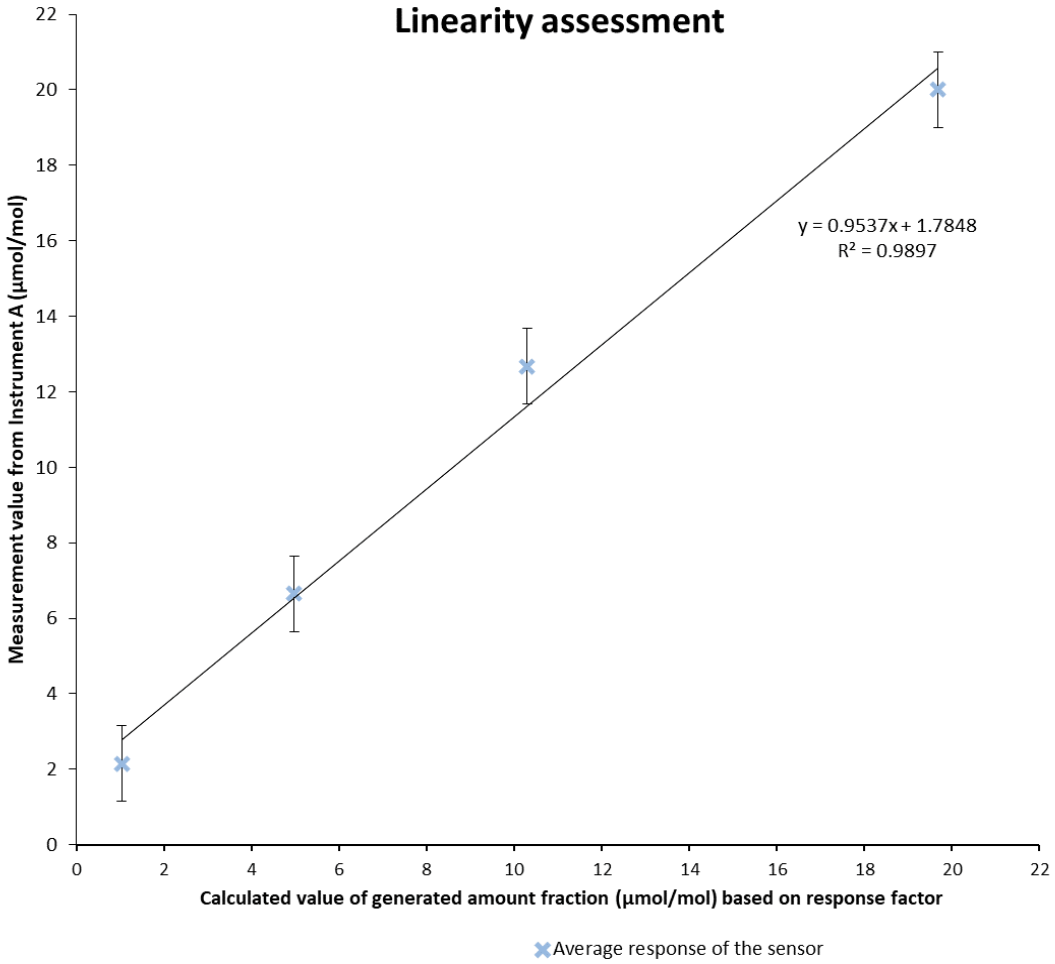
+ External validation of amount fraction delivered to sensor via a parallel line to NPL calibrated gas analyser;

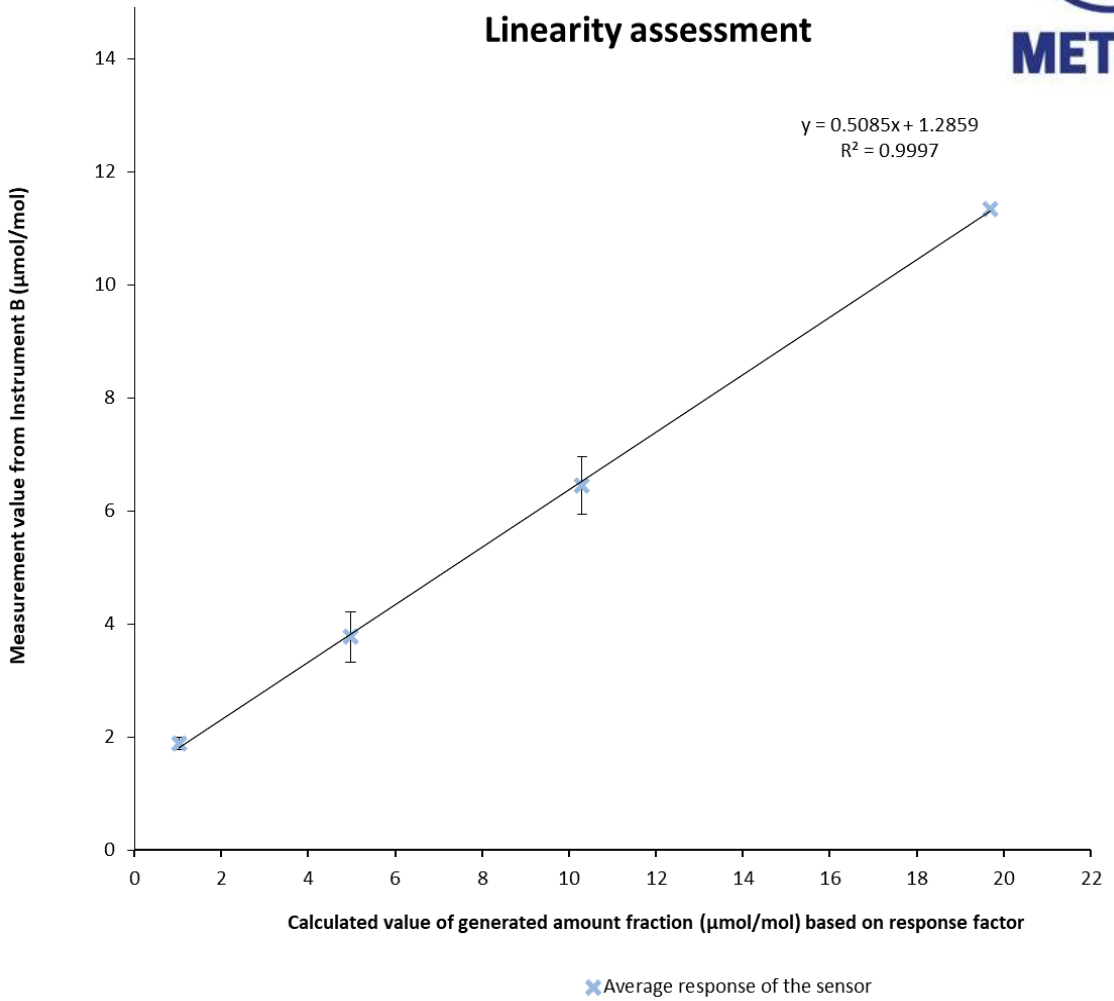
+ Validation of amount fraction generated by the step changing facility via a parallel line to NPL calibrated gas analyser;



Achievements: compatible with most contaminants in H2 (i.e., O_2 from 0.5 to 20 µmol/mol); fast response (< 20 seconds)

Linearity





NPL National Physical Laboratory

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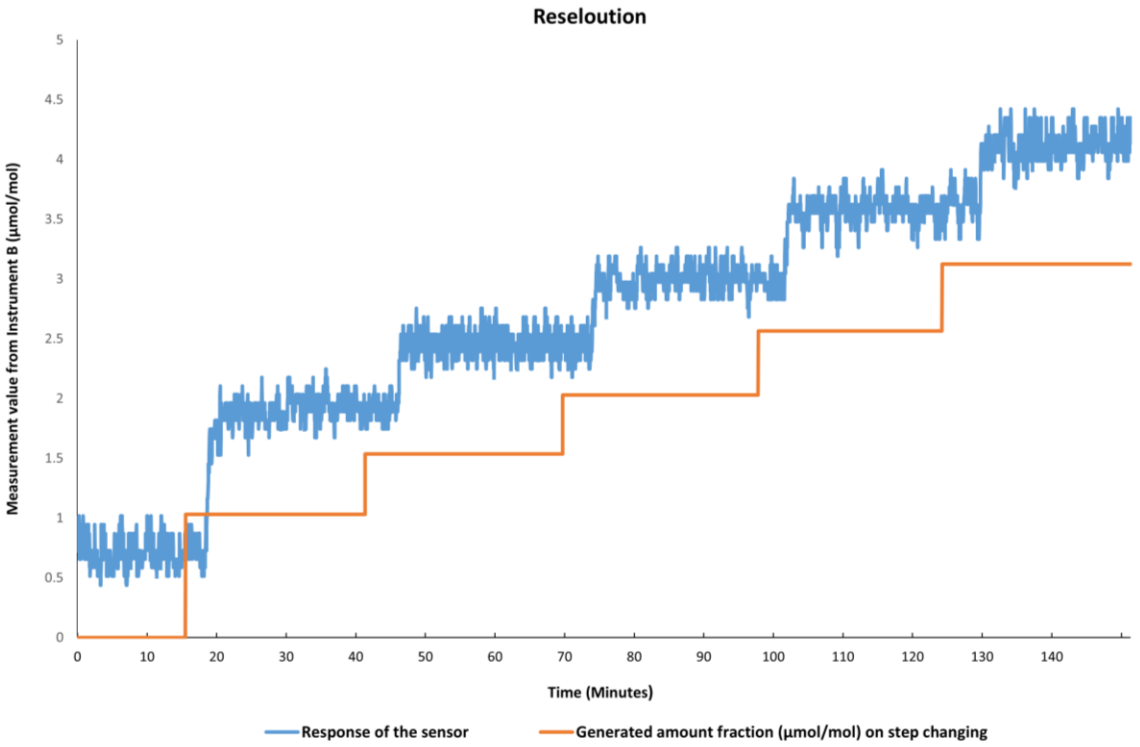
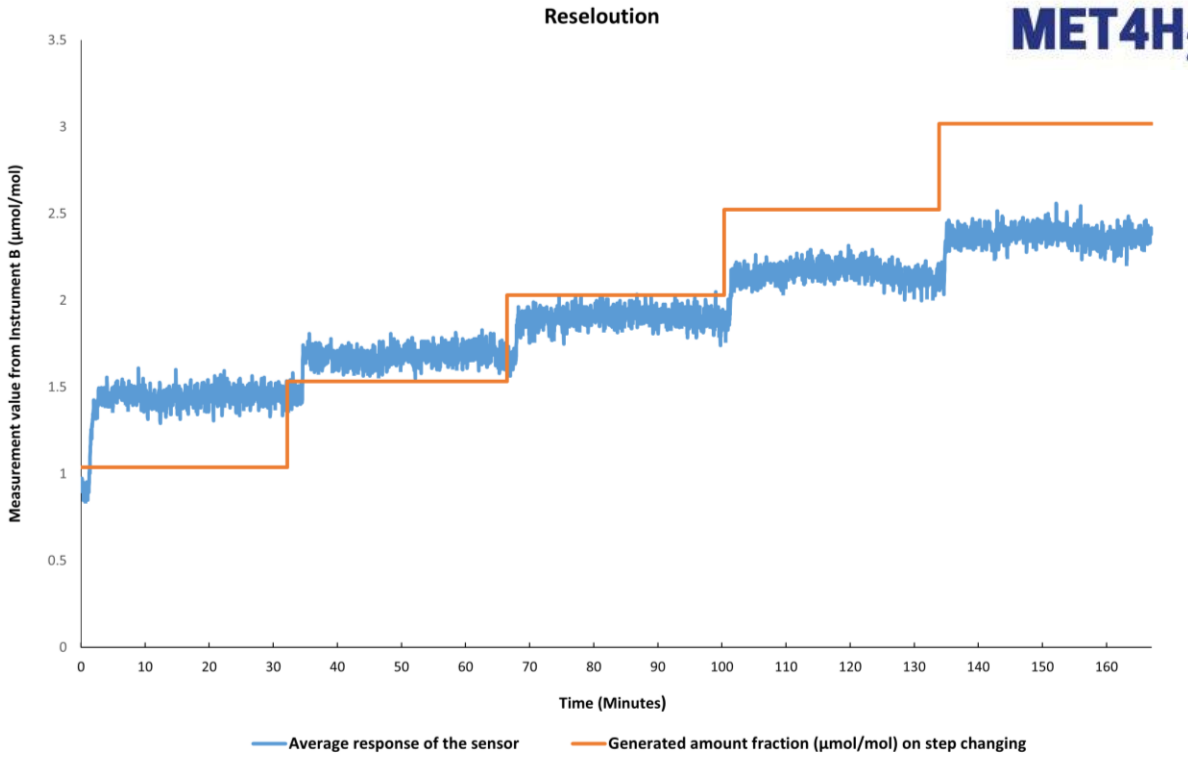
Resolution





Initial generated amount fraction (µmol/mol) on step changing	Generated amount fraction (µmol/mol) on step changing	Generated step incerment	Change incerment recorded by Sensor A	Change incerment recorded by Sensor B
1.038	1.534	0.496	0.498	0.248
1.534	2.029	0.495	0.610	0.228
2.029	2.524	0.494	0.567	0.257
2.524	3.017	0.493	0.547	0.215

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Testing rigs for hydrogen sensors

Metrological guidelines for the validation, calibration and verification of hydrogen sensors used within the hydrogen supply chain for quality control

Validation of sensors

Implies demonstrating that a given sensor is able to perform the measurements it is intended to do. Evaluation of the metrics and comparison of the results with end-user´s needs

Verification of sensor

Can be defined as the process of ensuring that the data provided by the sensors remains accurate and consistent over time.

Other definitions: checking the performances against specifications provided by the sensor´s developer or site verification: check some metrics online

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Testing rigs for hydrogen sensors

Guidelines

Adjustment of sensor
Process entails adjusting the response of a sensor to align its output accurately with its input by a recognized reference. This operation can be needed if the sensor´s output show a bias or a drift of response with time

Calibration of sensor
Operation performed on a sensor that, under specified conditions

1) Established a relation between the values with associated uncertainties provided by measurement standards and corresponding indications with associated uncertainties of the sensor
2) Uses this information to establish a relation for obtaining a measurement result from an indication given by the sensor

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Testing rigs for hydrogen sensors

Guidelines

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Testing rigs for hydrogen sensors

For more information

A1.3.1 – Review state-of-the art sensors
A1.3.2 – Protocol to test sensors
A1.3.3 – rig developments
A1.3.4 – Test of the rig/protocol (several reports)
A1.3.5 – Metrological guidelines for the validation, calibration and verification of hydrogen sensors used within the hydrogen supply chain for quality control (deliverable 2) – contains an updated version of the protocol

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Testing rigs for hydrogen sensors

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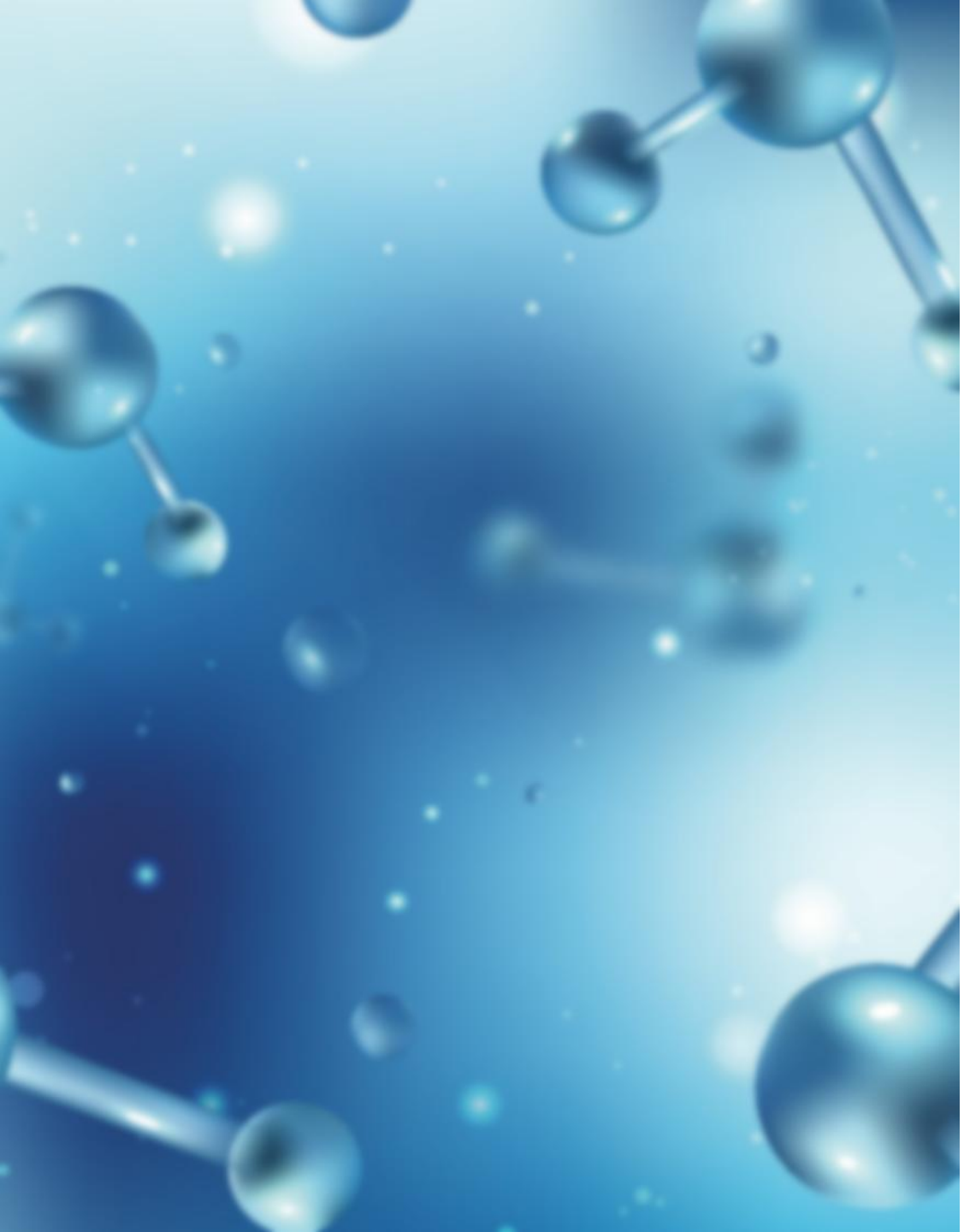

MET4H2

PERFORMANCE OF FLOW METERS AND CALIBRATION FACILITIES FOR BLENDS OF H2 AND NG AND PURE H2 WITH 98% PURITY

M36 Stakeholder meeting
18 September 2025
Hamidou SOUMARÉ

CESAME-exadébit SA

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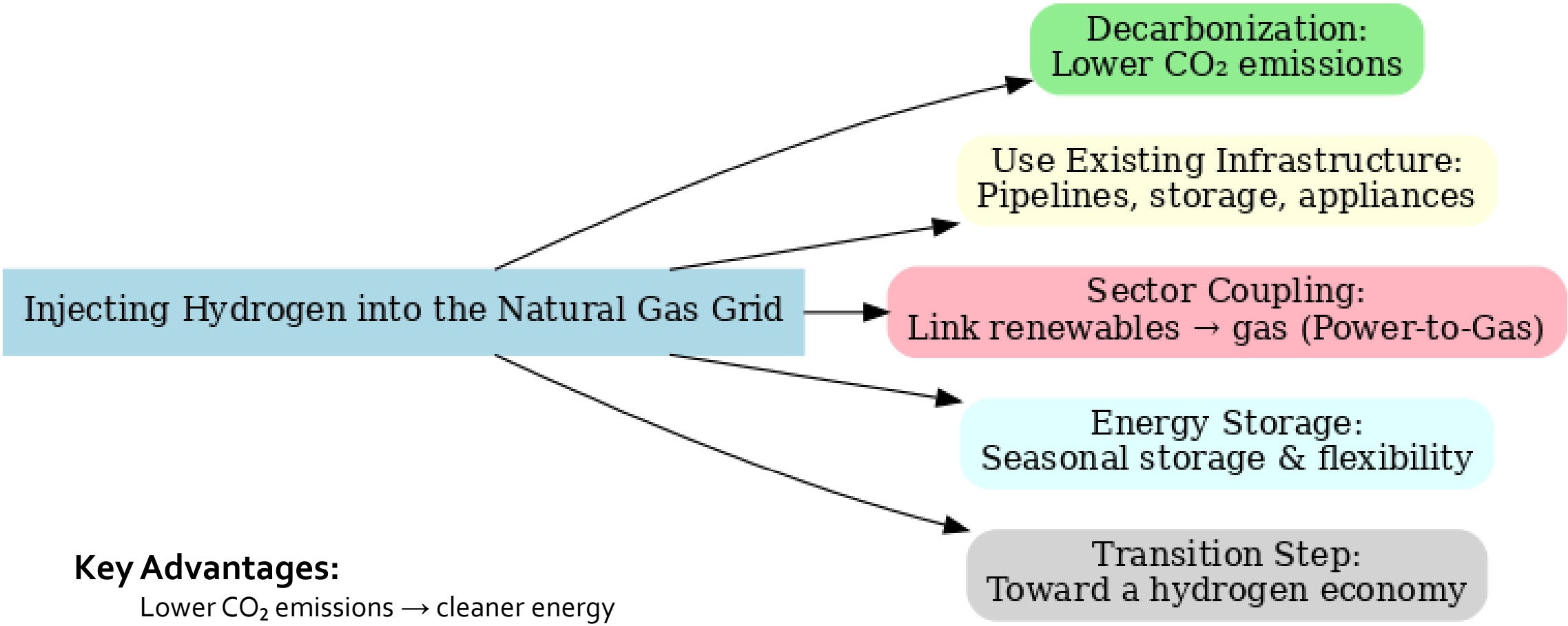
MET4H2

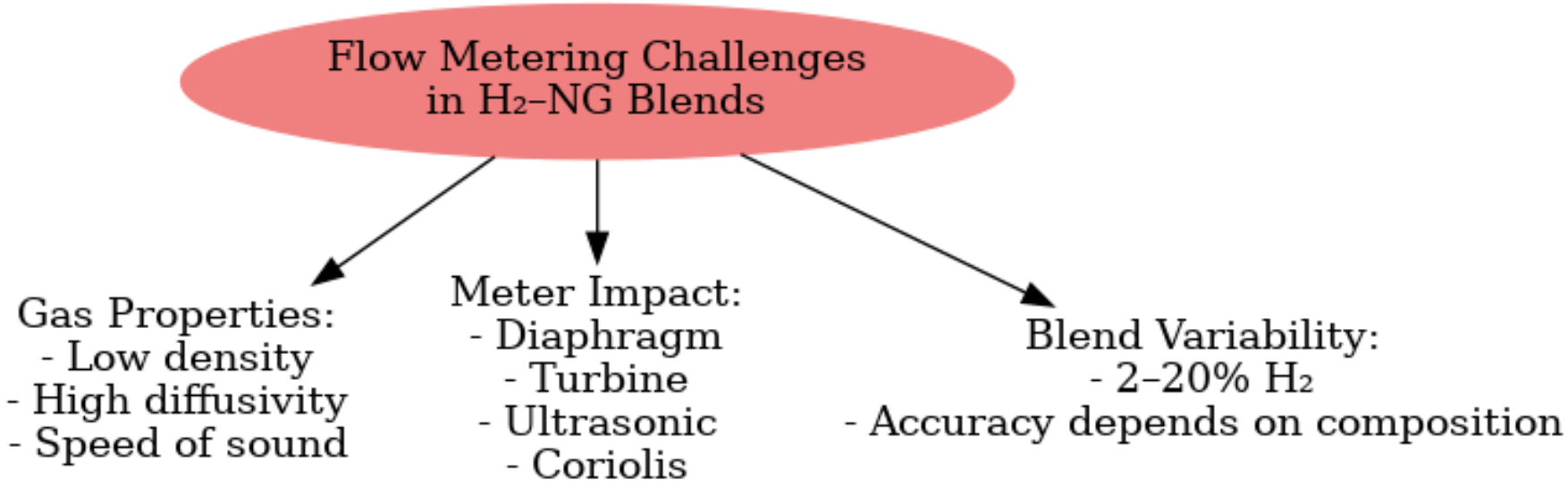
INTRODUCTION



Key Advantages:

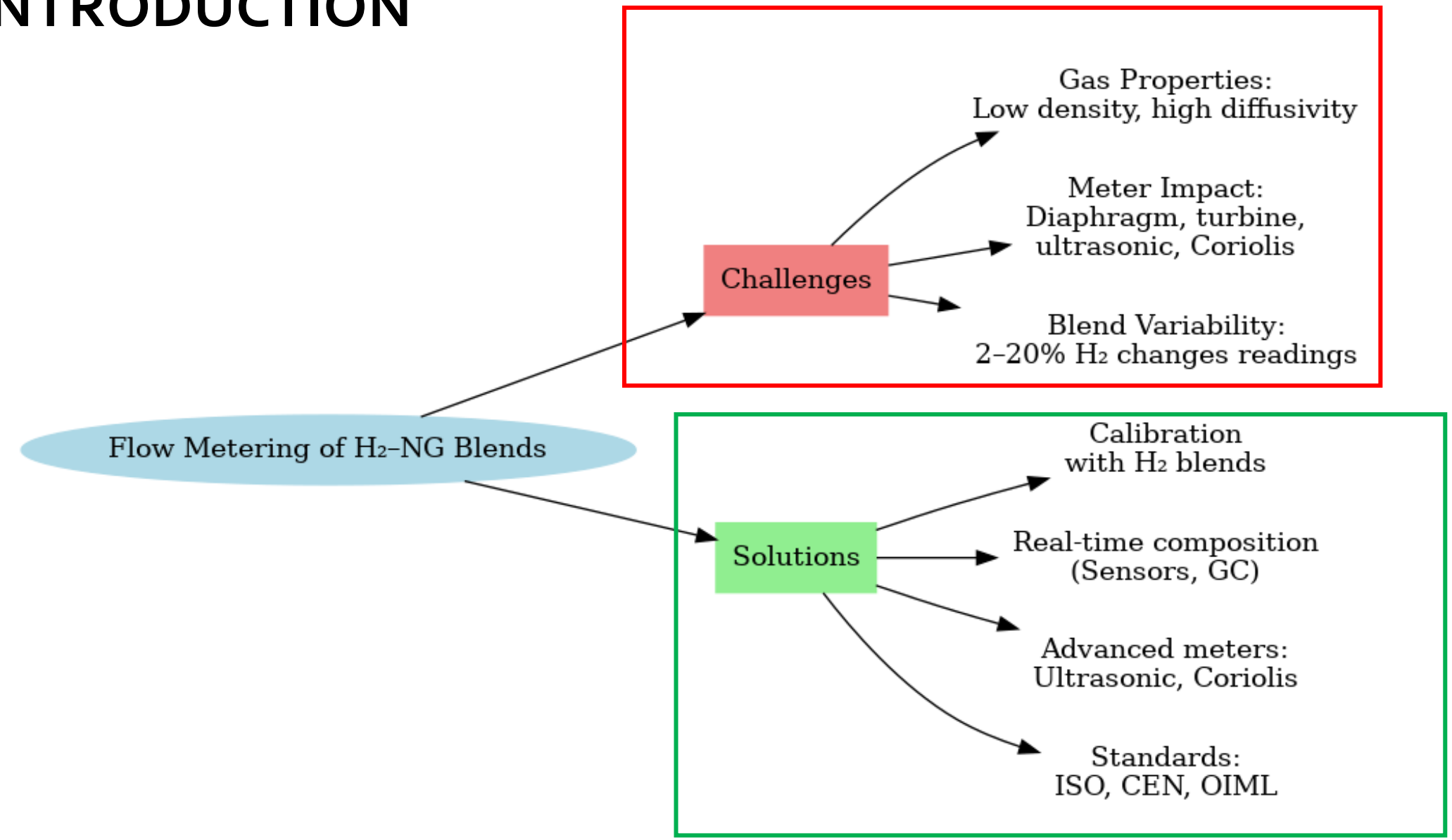
- Lower CO_2 emissions ⟶ cleaner energy
- Use existing pipelines & appliances
- Store surplus renewable electricity
- Seasonal & large-scale energy storage
- Improves energy security & independence
- Step toward a full hydrogen economy

INTRODUCTION



Main Challenges: Hydrogen's unique gas properties, impact on traditional meters, and variability of blend composition affect measurement accuracy.

INTRODUCTION



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ASPECTS THAT REQUIRE EVALUATION & STRATEGIES

Operational

- Metering accuracy may degrade (low density, high speed of sound).
- Pressure variations require tight control.
- Continuous gas-quality checks.
- Facility limits: materials, blending ratios, metering specs, storage, combustion.
- Maintain grid flexibility without losing safety/reliability.

Safety

- Metal embrittlement of pipelines/compressors/storage.
- Leaks at joints/seals → explosion & fire hazards.
- Combustion differences (Wobbe, flame) may require system changes; CO risk.
- Strengthen fire detection/suppression/management.
- Environmental impacts from leaks or non-RES H_2.
- Ensure compatible electrical equipment (e.g., ATEX).

Economic

- Infrastructure upgrades to handle hydrogen.
- End-user switching costs for appliances/systems.
- Variable H_2 production costs → price instability.
- H_2–NG separation can be complex and energy-intensive.

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MET4H2

GAS METERS: TECHNOLOGIES & HYDROGEN IMPACT

❑ Turbine gas meters: principle and design

- Principle: a bladed rotor turns with the gas flow; pulses are counted to indicate volume.
- Performance improves with higher gas velocity and/or pressure (greater driving force).
- Non-idealities reduce linearity: blade/hub/tip drag and bearing friction.
- Use case: preferred for medium to high flow-rate applications.
- Construction by nominal pressure (PN):
  - Body: ductile iron or steel; hard-anodized aluminium for low PN (≤PN16).
  - Rotor: typically, aluminium (>DN150), polyacetal/Delrin, or less often stainless steel.
  - Shaft & bearings: stainless steel (lubricated).
- Flow conditioning: upstream flow straightener minimizes swirl/asymmetry.
- Rotor specifics: usually 16/20/24 blades at ~30° or 45° inclination.

GAS METERS: TECHNOLOGIES & HYDROGEN IMPACT

❑ Turbine gas meters: H_2 impacts

Measurement

- Negligible impact up to ~10% vol H_2 in NG.
- At 16–32 barg, blends up to ~30% behave ~like NG (Reynolds).
- Higher H_2 → lower density → narrower turndown; effects near Qmin.
- Higher volumetric flow → overload risk.

Operations & Maintenance

- Overload: no specified limit on indication error ⇒ no firm accuracy claim in overload.
- Installation broadly unaffected; ensure adequate upstream flow conditioning.
- Design life ≈25 years; recalibration ≥5 years; lubrication, inspections, spin tests.
- Check lubricant compatibility with H_2/NG blends with manufacturer.

Certification

- Manufacturers claim process capability ~25–100% H_2 (model-specific).
- Custody transfer requires EU Type Examination Certificate for declared H_2 content.
- Some meters already certified for ~30% vol H_2 in NG.

GAS METERS: TECHNOLOGIES & HYDROGEN IMPACT

❑ Rotary piston gas meters : principle and design

- Use case: preferred for low–medium flow rates in transmission & distribution.
- Measuring principle: two counter-rotating figure-8 rotors (impellers) trap & displace fixed volumes;
  - ➢ Pressure differential across inlet/outlet drives the rotors; synchronization via external gears.
  - ➢ Four equal volumes are moved per full rotation (four-phase cycle).
- Variants: 'Twin' design (two rotor pairs shifted 45°) supports higher flow rates.
- Typical ranges: cyclic volume ≈ 0.25–>5 dm^3; rotor speed ≈ 700–5700 rpm.
- Construction: body in aluminium or cast/ductile iron (PN25/PN40); steel for high pressure (up to PN100);
  - ➢ Cartridge/rotors usually aluminium; bearings & shafts typically stainless steel; Delrin/synthetics also used.
- Clearances between rotors and body prevent excessive ΔP & wear; rotors do not contact each other.
- Measurement nuance: slip/leakage through clearances causes a small discrepancy from ideal displacement;
  - ➢ Leakage magnitude depends on gas viscosity.

GAS METERS: TECHNOLOGIES & HYDROGEN IMPACT

MET4H2

❑ Rotary piston gas meters: H_2 impacts

Measurement

- Validated up to ~20% vol H_2 in NG: errors within MPE; slight negative bias (NewGasMet).
- Long-term tests at 20% vol H_2: no operational degradation observed.
- Higher H_2 lowers gas density → may reduce turndown; effects most visible near Qmin.

Materials & Leakage

- Uncertain behaviour at higher H_2: aluminium alloys not well characterized; ductile cast iron shows ductility loss.
- No public H_2-leakage studies; lower viscosity of H_2 (~8.8 vs ~10.9 µPa·s at 20°C) suggests higher leakage → reduced rangeability at Qmin.
- Overload effects in the long term remain inconclusive.

Operations & Manufacturer Claims

- Installation largely unchanged; design life ≈ 25 years.
- Maintenance: lubricate rotor & timing gears; check oil ~6-monthly; oil change ~5–8 years; confirm lubricant compatibility with H_2/NG.
- Manufacturers: many allow ~30% vol H_2; several claim 100% H_2 (process use).
- Ensure ATEX compliance for H_2/H_2NG service on installed meters.

GAS METERS: TECHNOLOGIES & HYDROGEN IMPACT

❑ Ultrasonic gas meters: principle and design

- Deployed in both distribution and transmission networks (suited to high flow rates).
- Two measurement methods:
  - ➢ Transit time: compute flow from the difference in upstream vs. downstream pulse transit times.
  - ➢ With no flow, $\Delta t = 0$ (transit time $\propto$ 1/speed of sound).
  - ➢ With flow, co-flow pulse accelerates and counter-flow pulse decelerates; larger Δt at higher velocity.
  - ➢ Doppler: infer flow from frequency shift of ultrasonic waves scattered by moving gas molecules.
- Form factors:
  - ➢ Inline (wetted sensors) — body in carbon steel or 316 stainless steel; handles very high pressures (up to PN 420) and large sizes (DN up to 1600).
  - ➢ Clamp-on (external sensors on pipe wall).
- Transducers: piezoelectric ceramic disks operating ~100–300 kHz; typically >200 kHz to mitigate noise.

GAS METERS: TECHNOLOGIES & HYDROGEN IMPACT

❑ Ultrasonic gas meters: H_2 impacts

Measurement & Performance

- 5% vol H_2 → ~+12.3% speed of sound; may exceed ISO 14236 threshold (475 m/s) for domestic meters.
- Experimental tests: high measurement accuracy maintained up to ~10% vol H_2.
- Transmission devices: survey indicates suitability at least up to ~30% vol H_2; one model tested to 100% H_2.

Materials & Design

- Inline (wetted) bodies often carbon steel/316 SS: H_2 can reduce ductility, fracture toughness and accelerate fatigue crack growth; long-term behaviour still uncertain.
- Clamp-on sensors (non-wetted): material issues not expected as sensors do not contact the gas.

Deployment & Compliance

- Installation: broadly similar to turbine/rotary; simulations show H_2% and distance from mixing point can matter.
- Maintenance: annual checks (transducer-tube coupling, wall corrosion, transducer status); need for extra frequency not yet established.
- Clamp-on: suitable for process use but not EU type-approved → not for custody transfer.
- Domestic ultrasonic: manufacturers confirm suitability up to ~20% vol H_2; ATEX compliance is the main limiting factor.

GAS METERS: TECHNOLOGIES & HYDROGEN IMPACT

❑ Diaphragm gas meters: principle and design

- Deployment: common in NG distribution; limited to low-flow process use in transmission.
- Measuring principle: two deformable-wall chambers isolate known gas volumes;
  - ➢ Each chamber ≈ one-quarter of the cyclic volume; measurement = count of fill/empty cycles.
- Construction: body (pressurized gas), diaphragms, valve covers/seats, linkage to valves/index, index drums.
- Materials: historic leather/animal skin → modern fabric (cotton/nylon) vulcanized with rubbers (nitrile, neoprene, Viton, etc.).
- Evolution: reduced weight, greater compactness, lower cost, improved accuracy and stability.

GAS METERS: TECHNOLOGIES & HYDROGEN IMPACT

MET4H2

❑ Diaphragm gas meters: H_2 impacts

Measurement & Accuracy

- Generally considered composition-insensitive; literature shows no effect up to ~10% vol H_2 in NG.
- At ~20% vol H_2: mixed findings — GHRYD saw −1% to +2.5% error; other studies reported only ~0.3–0.8% change below 0.1 Qmax.
- Up to ~40% vol H_2: deviations <1%; temperature-compensation had stronger influence than gas composition.
- Durability checks up to ~17% vol H_2 across 0.013–5 m^3/h: very small differences; no extra capacity required.

Materials, Leakage & Permeation

- Safety focus: leakage/permeation risk depends on membranes and wetted parts — material-specific by model.
- H_2 permeation through elastomers remains incompletely characterized; more testing needed.

Operations, Overload & Manufacturers

- No change indicated to installation/ordinary maintenance rules; short-term overload is possible.
- Higher H_2 may increase noise and cycle frequency; long-term wear needs experimental verification (may motivate larger meters).
- Model-dependent impact: two makers claim pure H_2 capability; only one supported by tests to 100% H_2 (the other to ~30% H_2).

GAS METERS: TECHNOLOGIES & HYDROGEN IMPACT

❑ Thermal mass gas meters: principle and design

- **Overview:**
  - Proven in distribution & transmission grids
  - Stable operation (>10 years)
  - Measure mass flow via cooling effect on heated element
- **Principle:**
  - PT100 RTD ⟶ measures gas temperature
  - Platinum heater ⟶ heated element
  - Flow ∝ power to maintain ΔT or temperature difference
- **Operating Modes:**
  - CCA: Constant ΔT, flow ∝ current (most common)
  - CTA: Constant current, flow ∝ ΔT variation
- **Design:**
  - Configurations: Inline | Insertion | Capillary (low-flow)
  - Materials: Aluminium enclosure, SS/Hastelloy wetted parts, PT100 + Platinum heater

GAS METERS: TECHNOLOGIES & HYDROGEN IMPACT

MET4H2

❑ Thermal mass gas meters: H_2 impacts

- **Gas Composition Effects:**
  - Accuracy depends on viscosity, density, specific heat
  - Capillary type: correction factors possible (EN group H, low CO_2/N_2)
  - Accuracy deteriorates if composition changes without compensation
- **Hydrogen Mixtures:**
  - Successfully used with ≤10% H_2
  - Early meters less reliable above 2% H_2
  - Accuracy worsens beyond 10% H_2 (per tests)
  - No uniform conclusion in literature
- **Material Compatibility:**
  - C-22 Hastelloy: high H_2 permeability, tensile impact risk
  - C-276 Hastelloy: susceptible to H_2 embrittlement
  - Limited evidence on maintenance / battery life impact
- **Industrial vs. Domestic Meters:**
  - Industrial: most claim up to 100% H_2, only one EU-approved model
  - Domestic: approved up to 2% H_2; poor accuracy at 23% H_2
  - Dedicated models exist for 23% H_2 and >98% H_2

GAS METERS: TECHNOLOGIES & HYDROGEN IMPACT

❑ Coriolis gas meters: principle and design

- **Overview:**
  - Used for custody transfer since 1995
  - Proven reliable for NG mass flow measurement
- **Working Principle:**
  - Based on Coriolis force
  - Tubes vibrate at resonant frequency
  - Flow induces phase shift in tube oscillations
  - Sensors detect asymmetry proportional to flow rate
- **Design:**
  - Two main components:
    - Sensor (primary element)
    - Transmitter (secondary element)
  - Configurations: single tube, dual tube, etc.
  - Designs aim to minimize external disturbances

GAS METERS: TECHNOLOGIES & HYDROGEN IMPACT

❑ Coriolis mass gas meters: H_2 impacts

- **Performance:**
  - Tested for H_2 refuelling (high pressure)
  - Safe use with ≤10% H_2NG (literature)
  - Reliable up to 30% H_2 at 16–32 bara (with compensation)
  - Manufacturers confirm suitability for up to 100% H_2
  - Works well due to density-based detection (vibration frequency)
  - Limitation: small meters → low sensitivity in low-mass, high-volume flows
- **Material Considerations:**
  - Critical: components in direct contact with H_2 (sensors, measuring devices)
  - Common alloys: 304L, 316/316L, 904L, Hastelloy C22
  - 316/316L SS: modest ductility loss, strength increase → suitable
  - High-Ni austenitic steels (>7% Ni): suitable for H_2
  - 304 SS: high susceptibility to H_2 embrittlement & cracking
  - 904L: limited data, no major yield strength change
- **Other Aspects:**
  - Careful material selection & leak prevention essential
  - No clear evidence on installation & maintenance impact

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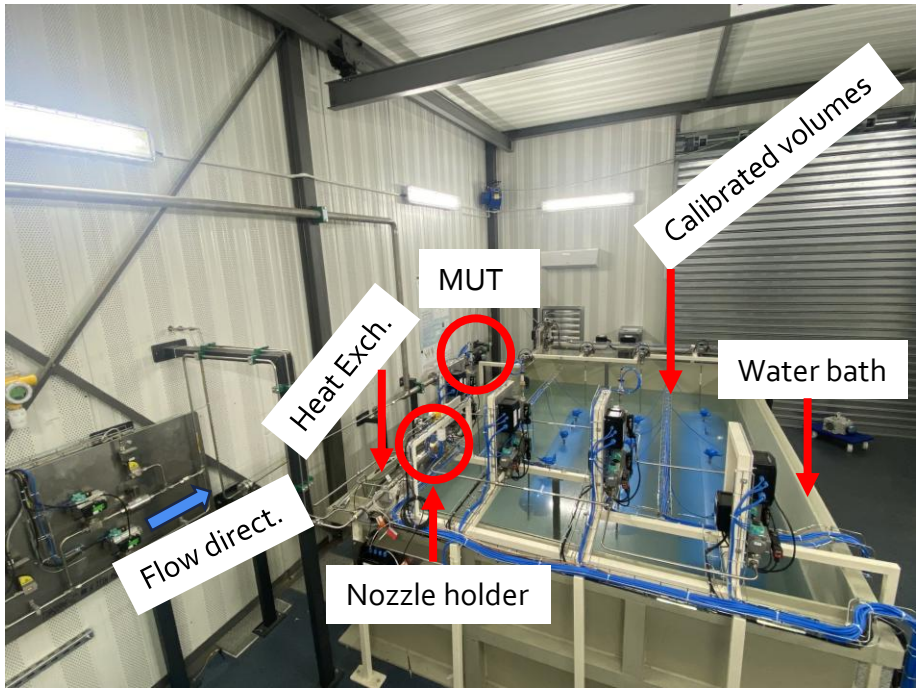
MET4H2

TEST BENCHES FOR H2NG BLENDS

- CESAME's PVTt bench

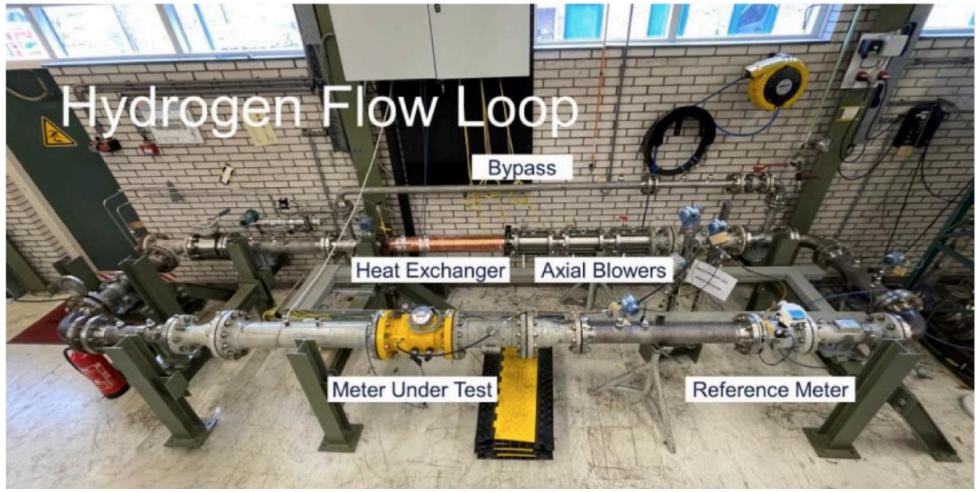


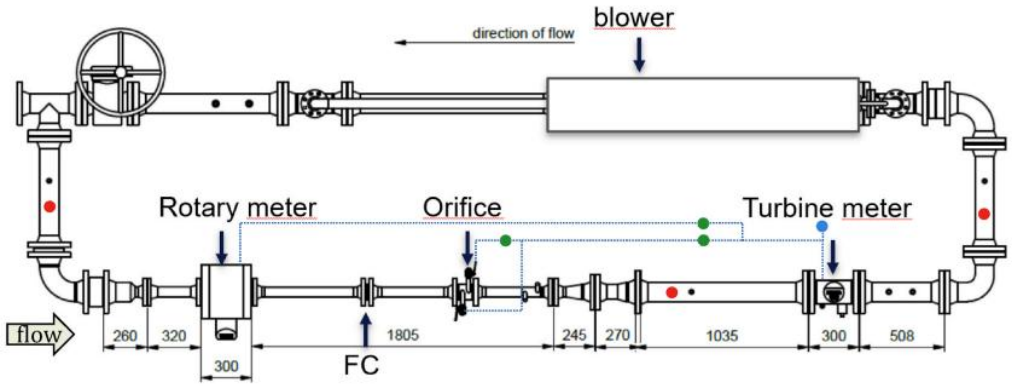
SPECIFICATIONS:

- Based on PVTt method.
- Near 100% and H2NG blends up to 20% H2 (to date).
- Up to 20 kg/h and an upstream max pressure up to 80 bar.
- Uses H2 or CH_4 or H2CH_4 blends as flow sources.
- Uses calibrated volumes (LNE) and sonic nozzles as references.
- The targeted facility uncertainty is about ±0.3 % (k = 2).

TEST BENCHES FOR H2NG BLENDS

- **DNV test bench**





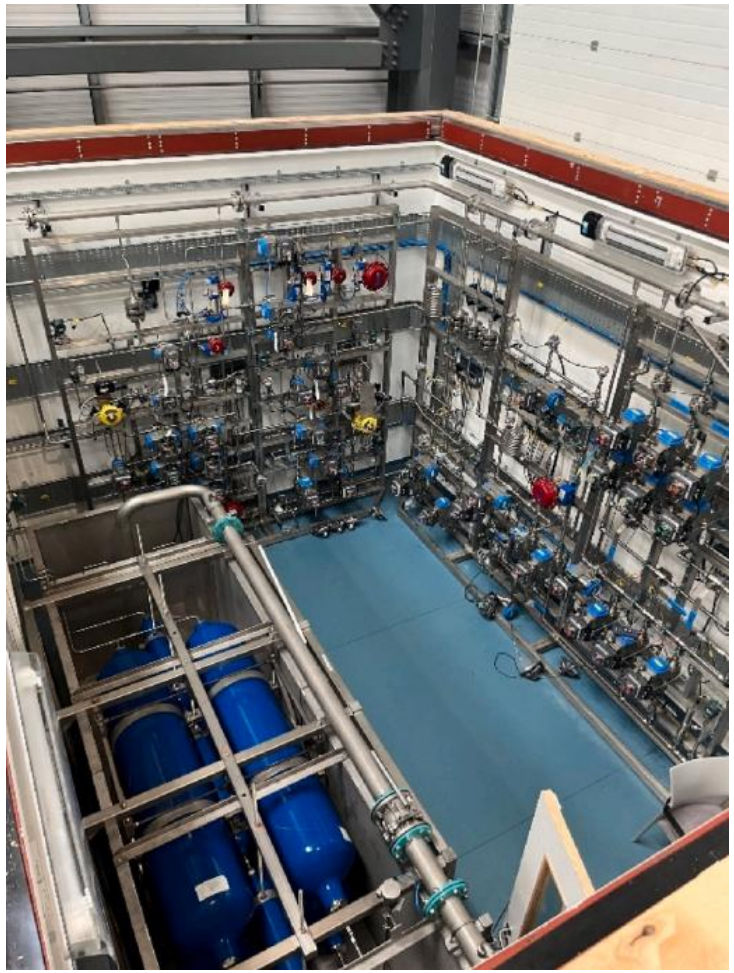
SPECIFICATIONS:

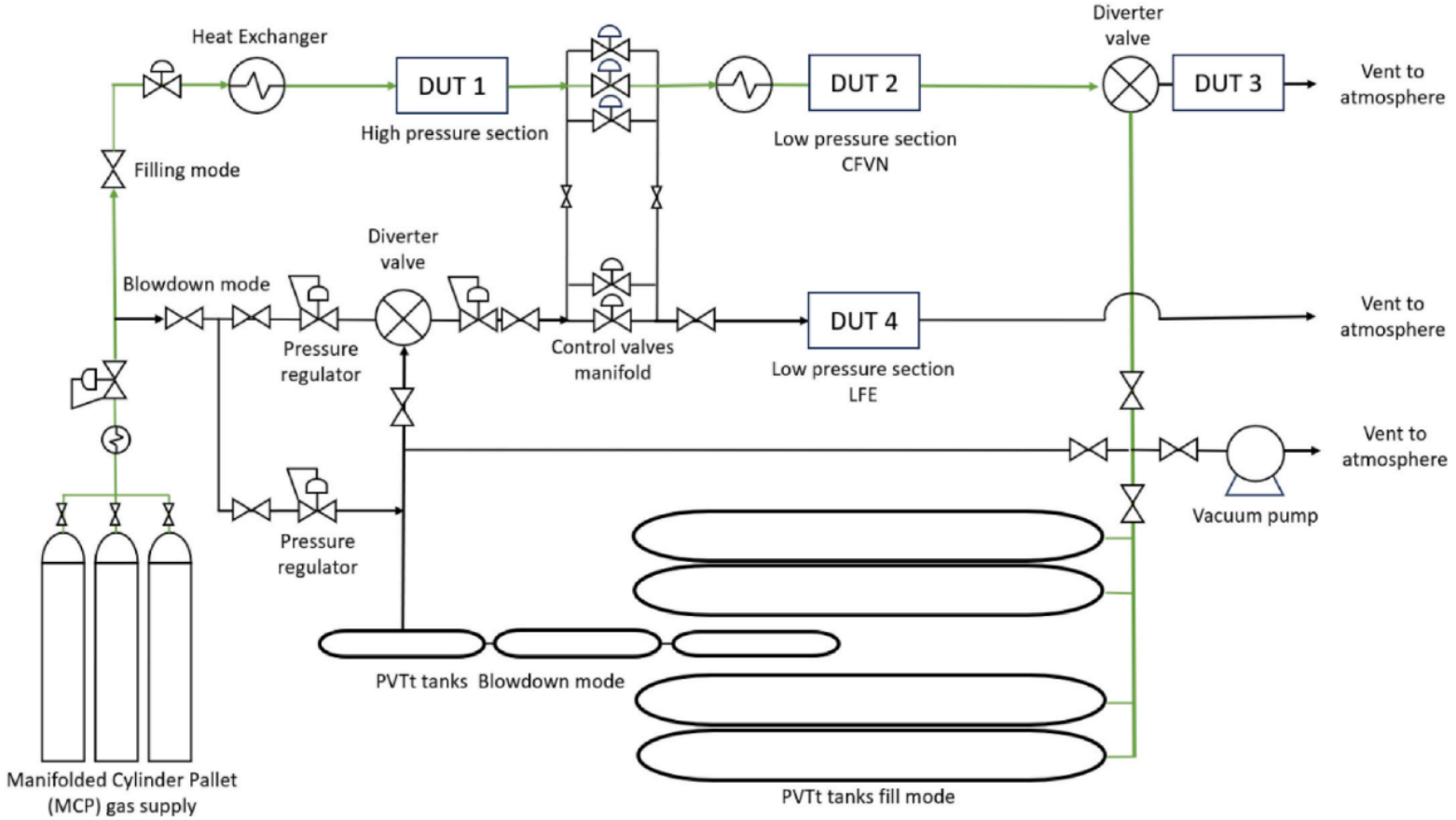
- Near 100% and H2NG blends up to 30% H2.
- Closed loop driven by a blower.
- Uses a turbine meter as a reference meter, calibrated on multiple gases and at multiple pressures at traceable labs.
- The resulting facility uncertainty is estimated between ±0.3 % and ±0.5 % (k = 2).

Test Fluids:	Nitrogen, hydrogen, methane, carbon dioxide
Flow Range:	5 m^3/h to 500 m^3/h
Test Section:	1-inch to 6-inch
Operating Pressure:	0 bar(g) to 40 bar(g)
Temperature Range:	Ambient (20 °C)
Reference system:	Turbine meter (PTB model corrected)
Claimed reference uncertainty:	±0.3 to ±0.5 % (k = 2)

TEST BENCHES FOR H2NG BLENDS

- **NEL test bench**





TEST BENCHES FOR H2NG BLENDS

- **NEL test bench: specifications**

Test Fluids:	Nitrogen, hydrogen, methane, carbon dioxide
Flow Range:	0.006 Sm^3/h to 100 Sm^3/h
Test Sections Nominal Size:	1″, 0.5″
Operating Pressure at DUT 1:	0 bar(g) to 120 bar(g)
Operating Pressure at DUT 2 and DUT 3:	0 bar(g) to 30 bar(g)
Operating Pressure at DUT 4:	0 bar(g) to 2 bar(g)
System Design Pressure:	PN200 (valves and piping only – instrumentation only suitable for operating pressure as to obtain the best uncertainty)
Temperature Range:	Ambient
Fill Mode Collection Volume:	4 × 200 L collection tanks
Blowdown Collection Volume:	3 × 11 L collection tanks
Uncertainty:	±0.1 % (k = 2).

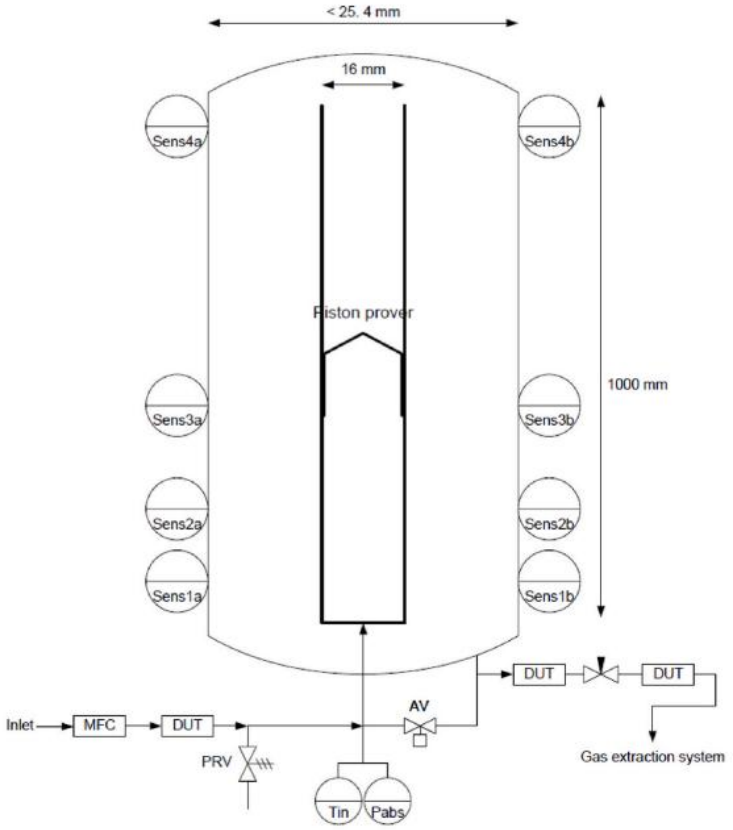
- N_2, H_2, CH_4, CO_2
- Uncertainty around ±0.1 % (k=2).
- Used for calibration of secondary flow standards, such as : CFVN, LFEs or any meters irrespective of their technologies.
- Calibrate secondary reference standards up to 30 bar(g) and other devices using the SRS up to 120 bar (g).
- Flow range: 0.006 Sm3/h to 100 Sm3/h.

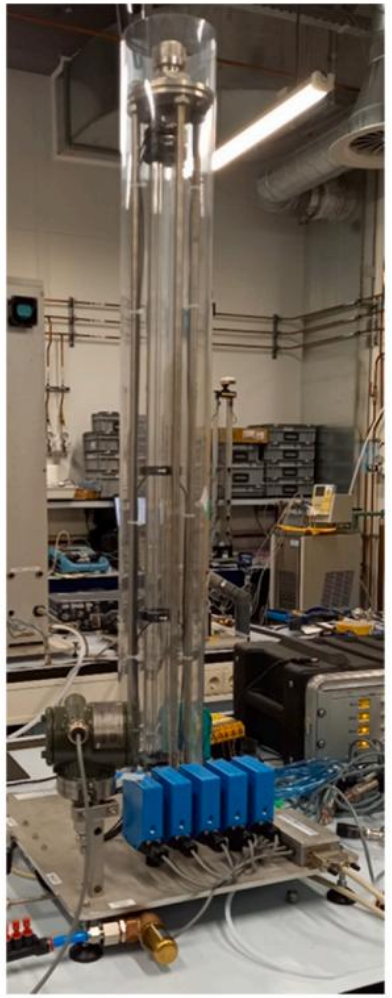
TEST BENCHES FOR H2NG BLENDS

- **VSL's test facility**

  - ✓ Mercury-seal piston prover.
  - ✓ Low flow.
  - ✓ 3 different discrete volumes
  - ✓ Volumes determined traceably to SI.

Test Fluids:	Nitrogen, air, methane, hydrogen, carbon dioxide, other gases
Flow Range:	0.006 Sm^3/h to 0.6 Sm^3/h
Operating Pressure Upstream DUT position:	0 bar(g) to 9 bar(g)
Operating Pressure Downstream DUT positions:	0 bar(g) to 9 bar(g)
System Design Pressure:	10 barg
Temperature Range:	Ambient (20 °C)
Uncertainty:	±0.22 % (k = 2)





TEST BENCHES FOR H2NG BLENDS

- GAZ SYSTEM test bench

Specifications	Value
Operation mode	Closed loop
Static pressure range	(8 ÷ 54) barg
Volumetric flow range	(8 ÷ 6000) m³/h
Gas temperature range	(16 ÷ 24) °C
Nominal diameter of the tubing	Nominal: DN50, DN80, DN100, DN150, DN200, DN250 i DN300; Optional: DN350 i DN400
Accredited uncertainty (k=2)	Calibration of turbine meters: CMC = 0,22% for flow rates (1600 ÷ 4000) m³/h CMC = 0,28% for flow rates (8 ÷ 1600) m³/h Calibration of ultrasonic meters: CMC = 0,22% for flow rates (1600 ÷ 6000) m³/h CMC = 0,29% for flow rates (13 ÷ 1600) m³/h
CMC: Calibration and Measurement Capability	

LWG Operating Modes

- **Closed-loop mode**
  - Used when **flow ≤ 6,000 m³/h** and **pressure drop < 1 bar**
  - Requires ~**400 kW** to power the blower
  - Ensures **stable calibration conditions → better repeatability**
- **In-line mode**
  - Used when flow/pressure drop **exceeds closed-loop limits**
  - Flow generated by **compressor station downstream**

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MET4H2

EXPERIMENTAL RESULTS FOR SOME METERS (THOTH2 PROJECT)

MET4H2

❖THOTH2 Project

- ✓ **Focus**: Accurate measurement of **H_2NG mixtures** (up to 100% H_2).

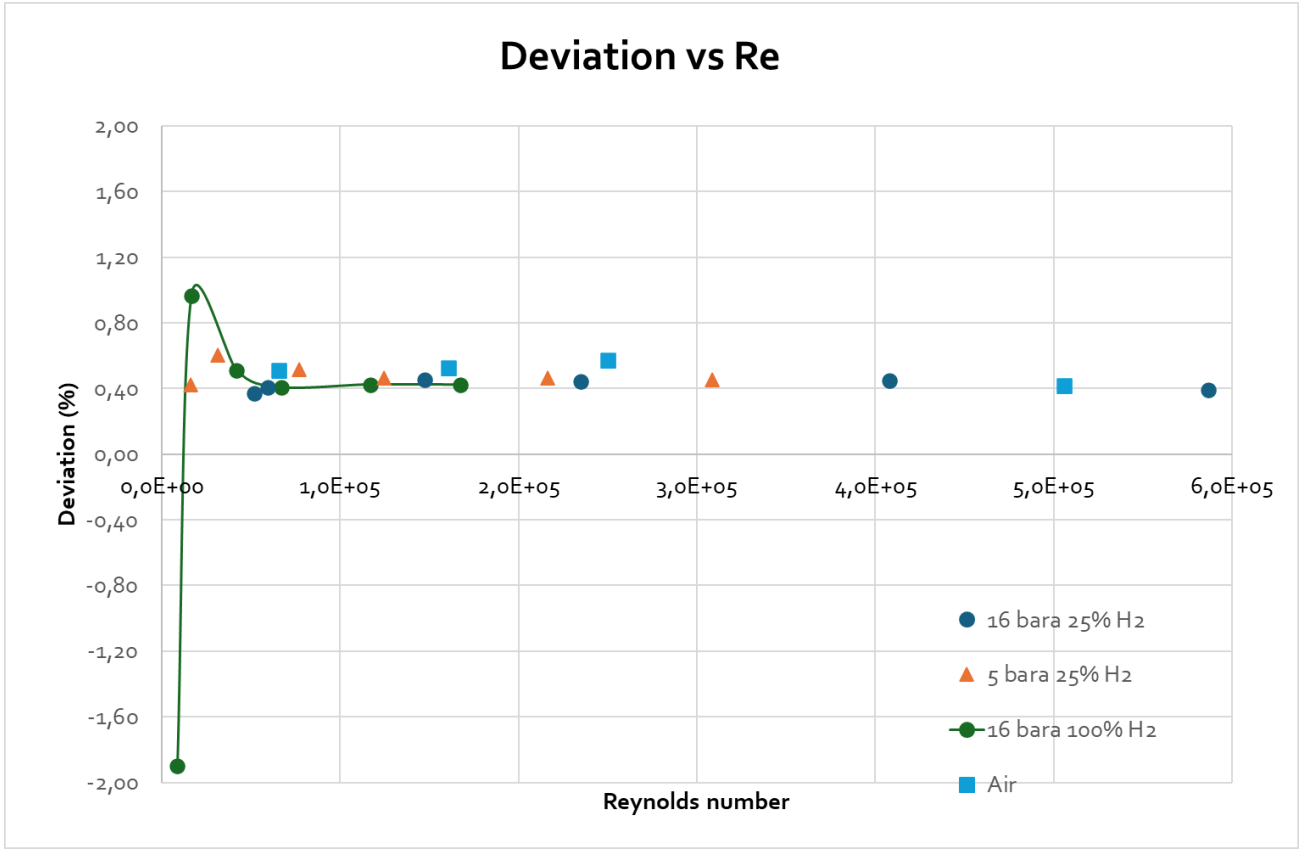
- ✓ **Goals:**
  - Define standards for measuring device performance at different H_2 blends.
  - Verify safety and durability of devices.
  - Recommend solutions to overcome barriers.

- ✓ **Key Players**:
  - **SNAM** coordinates integration of 14 partners.
  - Industry experts: Natran, GAZ-SYSTEM, Enagás, INRETE.
  - Metrology: CESAME, INRIM, METAS.
  - R&D & technology: UNIBO, INIG, FBK, ENEA, CSIRO.
  - Communication: GERG (visibility, EU projects).

- ✓ **Impact**:
  - Accelerates transition to the **H_2 economy**.
  - Contributes to **REPowerEU** and **NextGenerationEU**.
  - Establishes an **R&D Hub** to:
    - Develop/update international standards.
    - Foster innovation in H_2NG measurement.
    - Support the H_2 value chain using EU gas infrastructure.

EXPERIMENTAL RESULTS FOR SOME METERS (THOTH2 PROJECT)

- Elster SMRI – G160 (TURB METER)



❖ **16 bara – 25% H_2**
- Deviation is very stable around **+0.3 to +0.5%**.
- Minimal variation, even at high Reynolds numbers.
- **Most regular curve** → best precision and stability.

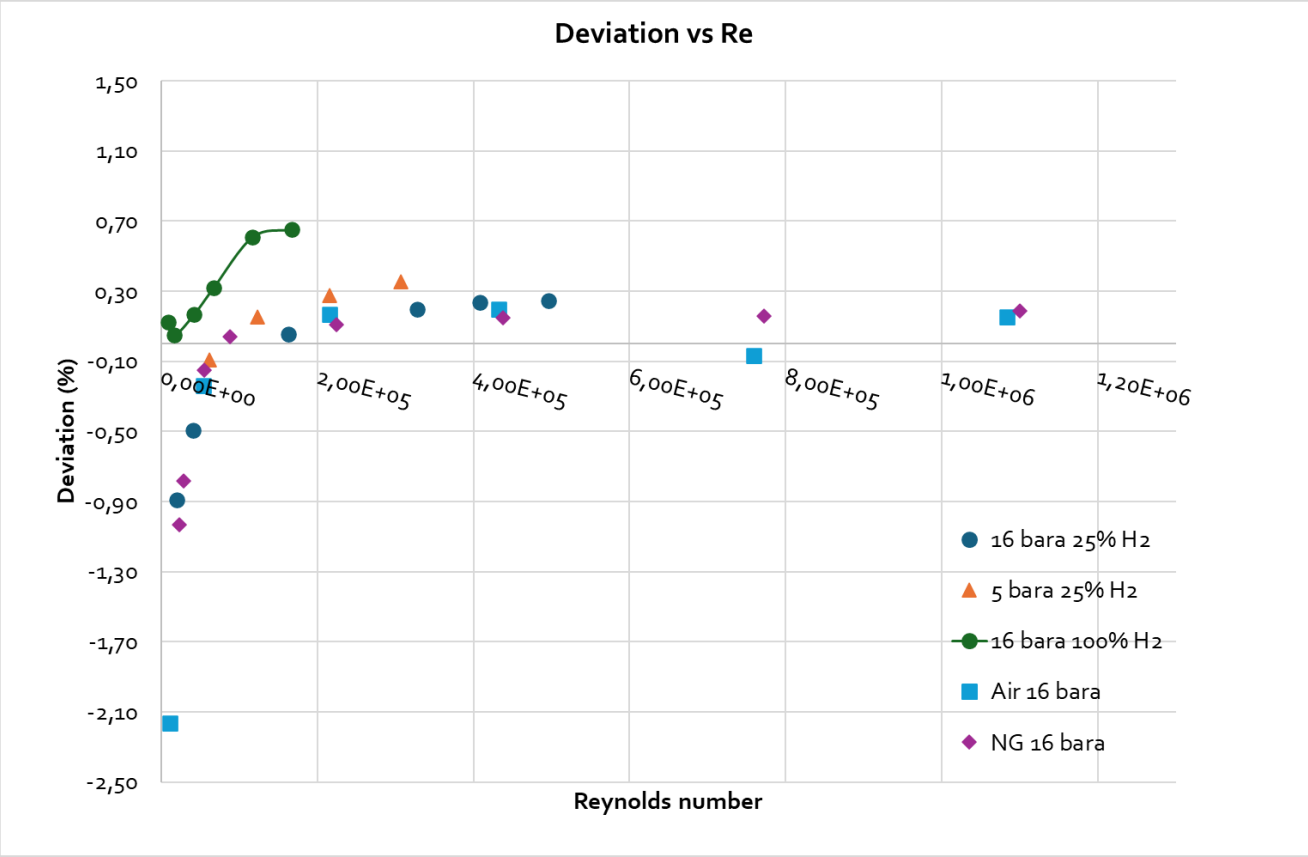
❖ **5 bara – 25% H_2**
- Very similar to the 16 bara – 25% H2 one.
- Slightly more oscillations at low Reynolds.
- Lower pressure does not significantly affect accuracy.

❖ **16 bara – 100% H_2**
- **Highly unstable at low Reynolds**: deviation strongly negative (**≈ –2%**) then a sharp positive peak (**≈ +1%**).
- Stabilizes around **+0.4%** at medium/high flow.
- Shows that **pure hydrogen is difficult to measure at low flow,** but accuracy improves at higher flow.

❖ **Air**
- Starts near **+0.5% deviation**.
- Gradually decreases with increasing Reynolds.
- Drops below zero at high flow (**≈ –0.09% at ~1.2×10^6**).
- Clear tendency to **underestimate flow at high rates**.

EXPERIMENTAL RESULTS FOR SOME METERS (THOTH2 PROJECT)

- DELTA S3 – G250 (ROT MET)



❖ **16 bara – 25% H_2**
- Deviation remains close to **0% to +0.3%** after low Reynolds.
- Some small oscillations at the beginning but stabilizes well.
- **Stable and reliable** behavior across the flow range.

❖ **5 bara – 25% H_2**
- Slightly higher deviation than the blue curve (**+0.2 to +0.3%**).
- Shows similar stability at higher Reynolds.
- Lower pressure does not significantly degrade accuracy.

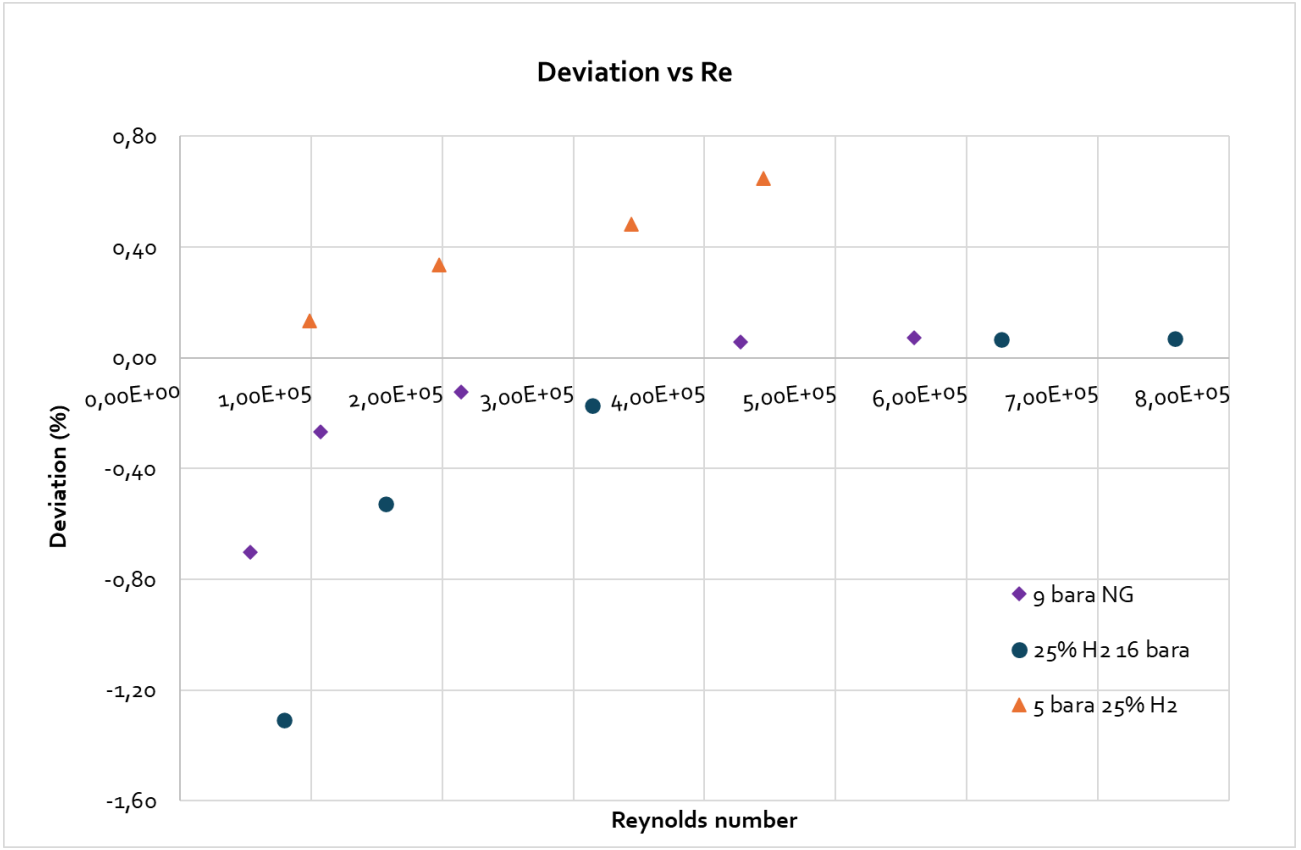
❖ **16 bara – 100% H_2**
- At low Reynolds: starts around **–0.1%**, rises quickly to about **+0.7%**.
- Stabilizes at medium Reynolds with deviation **~+0.6–0.7%**.
- Higher deviations than H_2 blends, especially at low flow.

❖ **Air – 16 bara**
- Large negative deviation at very low Reynolds (**≈ –2%**).
- Improves with flow, approaching **–0.1% to –0.2%**.
- Tends to underestimate flow, especially at low Reynolds.

❖ **Natural Gas (NG) – 16 bara**
- Starts slightly negative (**~–0.9%**) at low Reynolds.
- Increases gradually, stabilizing near **+0.2%** at higher Re.
- Shows **better alignment** at higher flows compared to air.

EXPERIMENTAL RESULTS FOR SOME METERS (THOTH2 PROJECT)

- KROHNE– DN100 (USM)



❖ **16 bara – 25% H_2**

- Starts with a significant negative deviation (≈ –1.2%) at low Reynolds.
- Improves gradually, approaching zero deviation as Reynolds increases.
- At higher Reynolds (>6×10⁵), deviation stabilizes close to 0%.
- Behavior: underestimates at low flow, accurate at higher flow.

❖ **5 bara – 25% H_2**

- Always positive deviation, starting around +0.2%.
- Deviation increases with Reynolds, reaching up to +0.7% at ~5×10⁵.
- Behavior: systematic overestimation, more pronounced at higher flow.

❖ **Natural Gas (NG) – 9 bara**

- Begins slightly negative (≈ –0.6%).
- Increases steadily with Reynolds, moving towards 0%.
- At high Reynolds (~5×10⁵–8×10⁵), deviation becomes slightly positive (≈ +0.1–0.2%).
- Behavior: better than H_2 at low flow, slightly overestimates at high flow.

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CONCLUSION & PERSPECTIVES

❑ Conclusions

- Hydrogen blending into NG grids is technically feasible but introduces **significant metering challenges**.
- Performance strongly depends on **gas properties** (density, diffusivity, speed of sound) and **meter type**.
- Experiments show reliable measurement for blends up to **10–30% H_2**; pure H_2 requires further development.
- European **test benches and calibration facilities** provide robust validation environments.

❑ Perspectives

- Establish and update **international standards** (ISO, CEN, OIML) for H_2NG measurement.
- Drive **innovation in meter technologies** (ultrasonic, Coriolis, thermal mass) for high H_2 concentrations.
- Deploy **real-time gas composition monitoring** to improve accuracy and safety.
- Address **long-term material compatibility and durability** under hydrogen service.
- Contribute to **EU decarbonisation goals** (REPowerEU, NextGenerationEU) and accelerate the **hydrogen economy**.

MET4H$_2$

Thank you for your attention!

Hamidou SOUMARÉ

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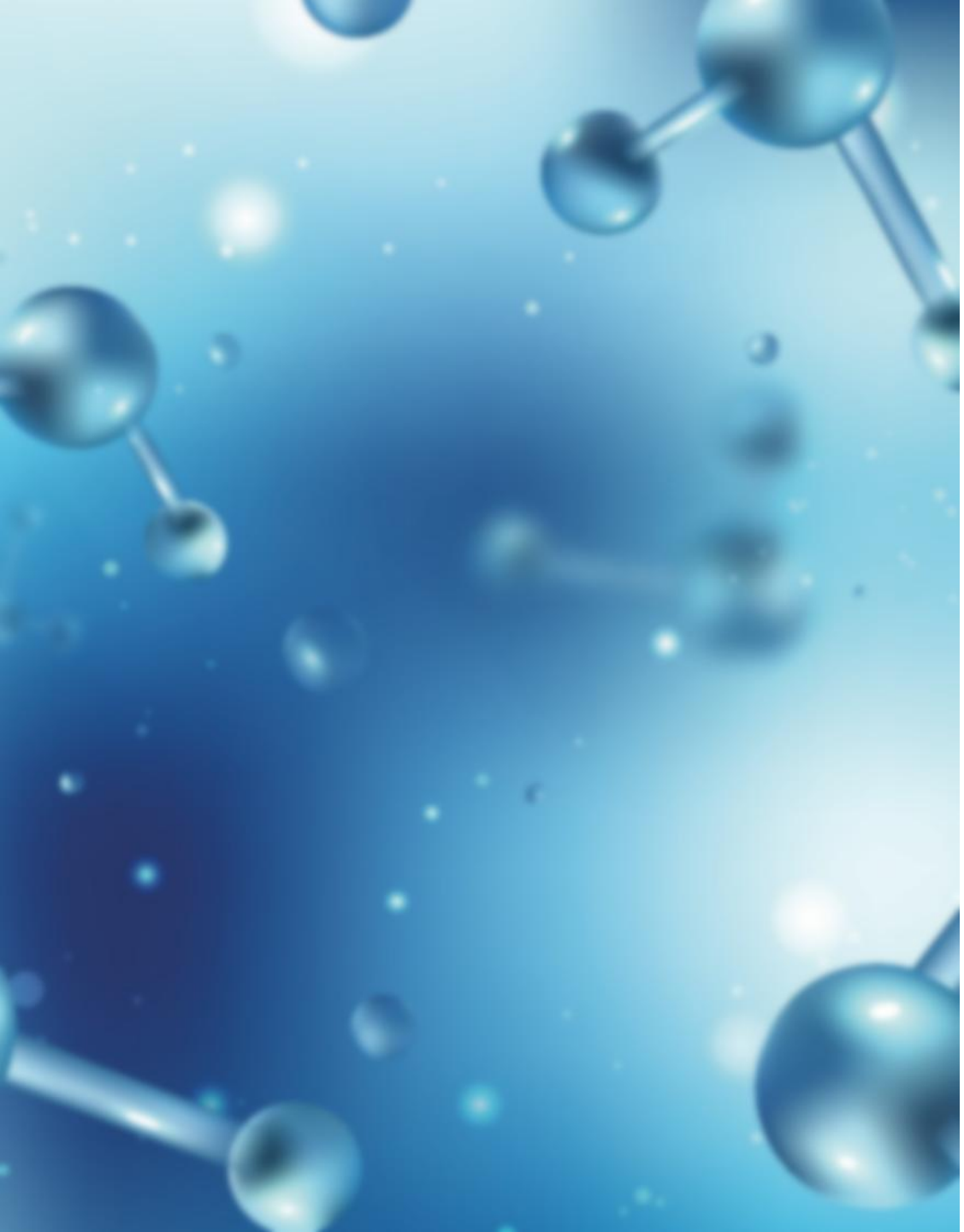

TRACEABILITY CHAINS FOR HYDROGEN FLOW METERING WITH FLOW RATES ABOVE 0.2 KG/MIN AND THREE OPTIONS FOR ENSURING TRACEABILITY FROM ESTABLISHED PRIMARY STANDARDS FOR THE 2030 EUROPEAN INDUSTRY AND HYDROGEN COMMUNITY

M36 Stakeholder Workshop
18 September 2025, Virtual venue
Marc de Huu, METAS

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MET4H2

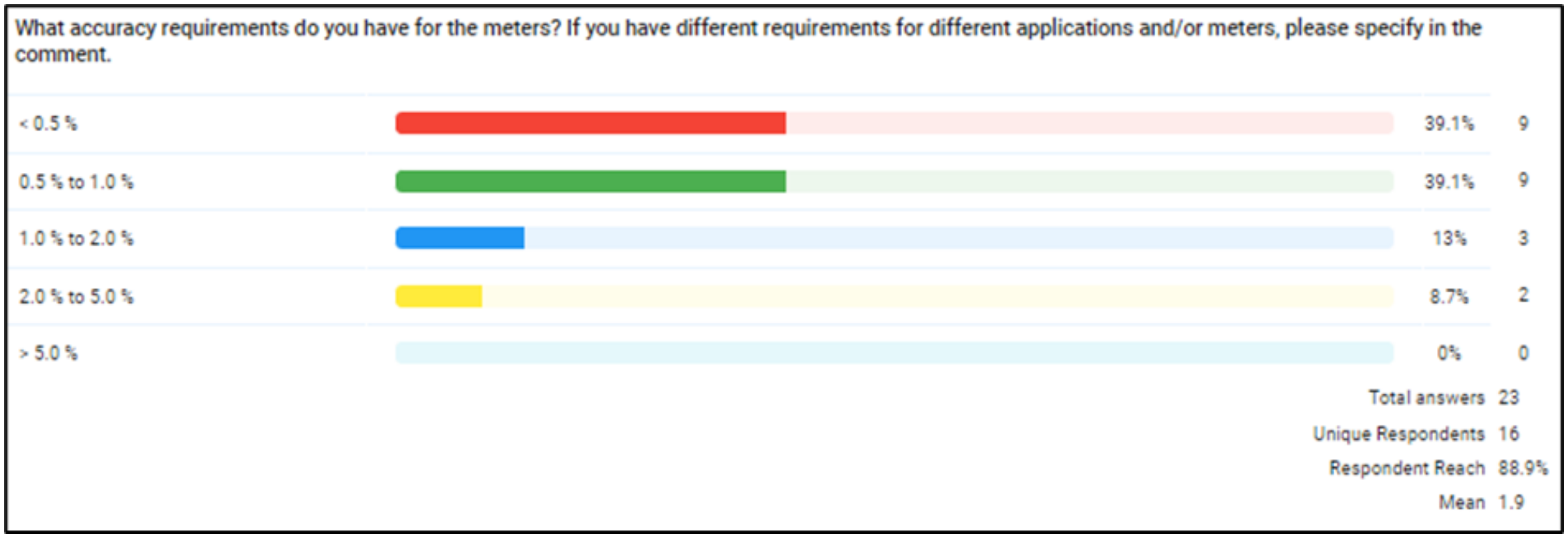
- Overview (2 min)
- Traceability needs based on stakeholder needs (5 min)
- Presentation of traceability chain (15 min)
- Summary (1-2 min)

OVERVIEW

- Hydrogen to play a role in the decarbonisation of gas networks
- New metrological techniques and testing infrastructures are required to support the use of hydrogen
- Flow measurement is required for:
  - Process monitoring and control
  - Fiscal metering
  - Billing and custody transfer
- Lack of traceable calibration facilities to perform R&D and certification (at start of project)
- Lack of accuracy data to specify appropriate testing methods
- End users unable to select suitable flow meter for H2 and HENG

TRACEABILITY NEEDS BASED ON STAKEHOLDER NEEDS

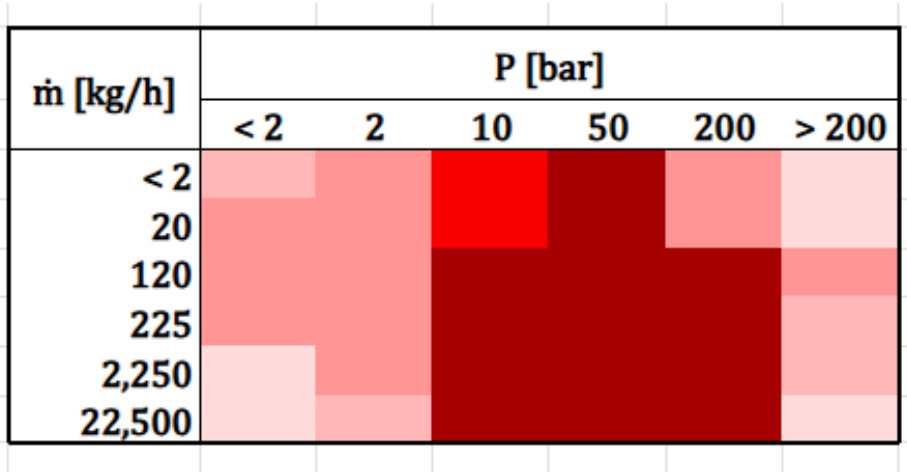
- **A2.4.1: Survey for relevant flow metering points for large-scale hydrogen applications**
- **A2.4.2: Listing stakeholders for the questionnaire and collecting results**
  - 75 people contacted, 17 responses



TRACEABILITY NEEDS BASED ON STAKEHOLDER NEEDS

- **A2.4.1: Survey for relevant flow metering points for large-scale hydrogen applications**
- **A2.4.2: Listing stakeholders for the questionnaire and collecting results**
  - 75 people contacted, 17 responses

Demand from the survey A2.4.2				
q [Nm^3/h]		ṁ [kg/h]	Answers	[% of Responses]
0 t0 25	0	to 2	5	29
25 to 250	2	to 23	7	41
250 to 1350	23	to 122	12	71
1 350 to 2500	122	to 225	12	71
2 500 to 25000	225	to 2,250	12	71
25 000 to 250000	2250	to 22,501	9	53



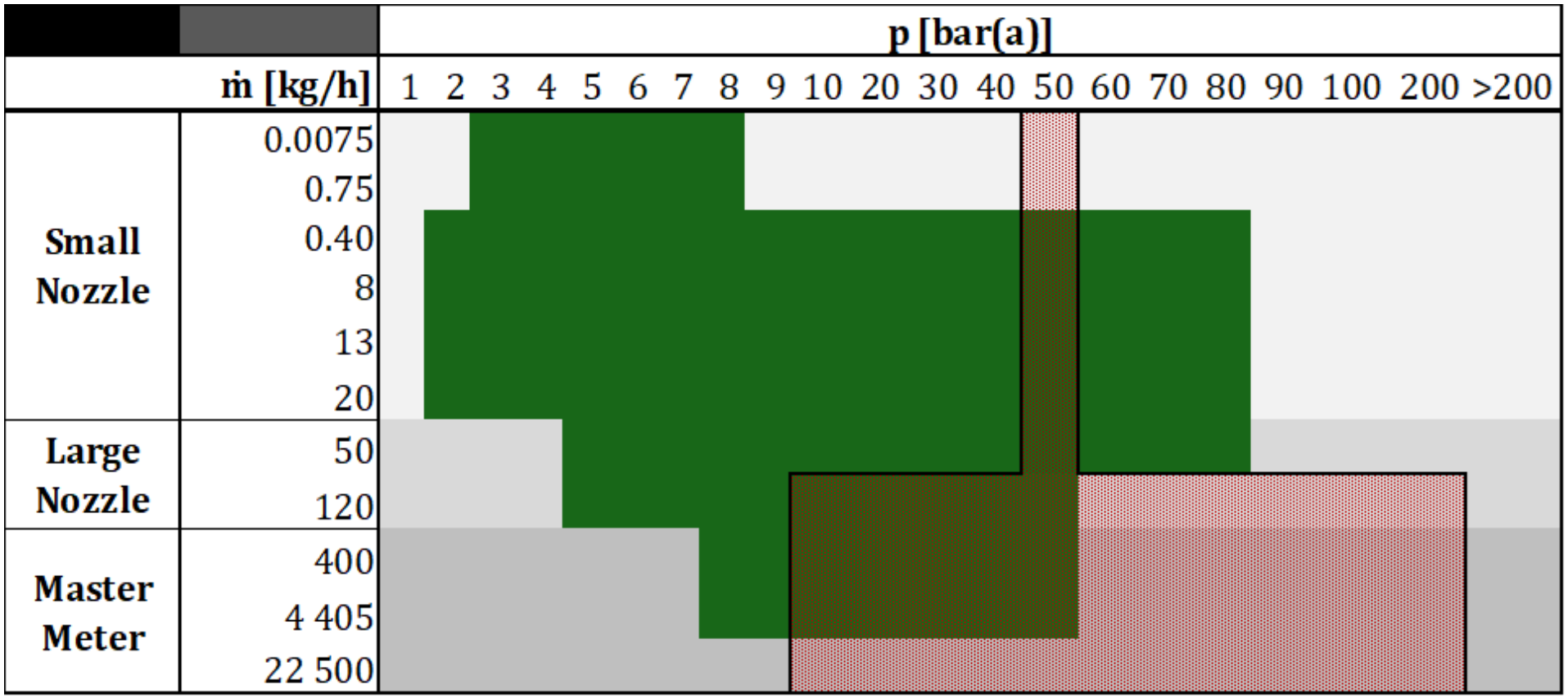
OVERVIEW OF HYDROGEN CALIBRATION FACILITIES IN EUROPE 2025

MET4H2

EU Hydrogen calibration facility in kg/h

Calibration facility	Min Flow [kg/h]	Max Flow [kg/h]	Pressure [bar(a)]	Tempera-ture [°C]	Traceability to/ Reference master meter	Media	Pressure	Pressure unit
University of Ljubljana	0.0075	0.75	1 - 7	20 ±5°C	Piston Prover	H2	1 -7	bar(a)
TÜV SÜD NEL	0.035	3	3 - 5	20	PVTt	H2	3 - 5	bar(a)
CESAME EXADEBIT	0.4	20	2 - 81	20	PVTt	H2	1	bar(g)
NaTran	0.4	160	1 - 30	20	Nozzles	H2		
DNV HyFLG flow loop	2.5	125	5 - 40	20 ±5	Master Meter NG and Air	air	5 - 40	bar(a)
RMA H2-Loop	3	4 405	8 - 51	?	Nozzle Master Meter	H2	8 - 51	bar(a)

SUMMARY OF HYDROGEN TRACEABILITY CHAIN IN EUROPE 2025



Indicate the survey demands for flow.

Indicate the demands with most response for calibration according to the survey.

Indicate the existing calibration facilities for hydrogen.

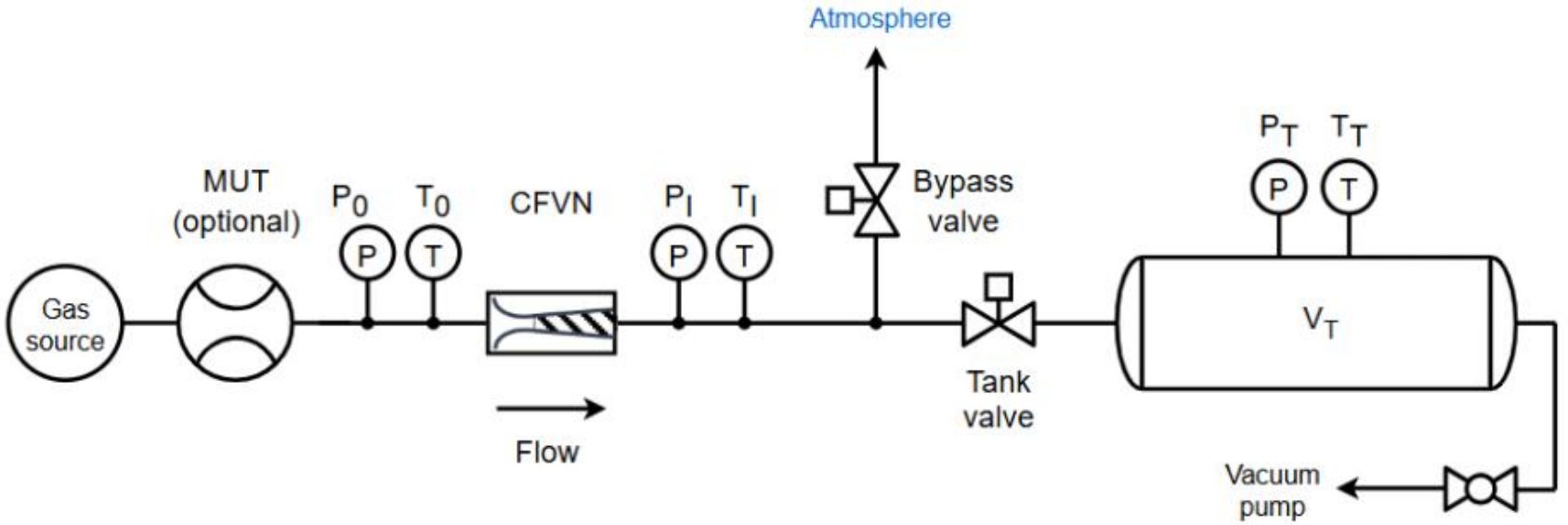
TRACEABILITY CHAIN (SEE PROJECT H2FLOWTRACE)

- Achieve required uncertainty for the calibration of meters (0.5 %)
- Primary standard for traceability
- Use well-established technology for unit dissemination
- Scaling-up (bootstrapping, several smaller meters in parallel)
- Calibration with substitute substances?

TRACEABILITY CHAIN (SEE PROJECT H2FLOWTRACE)

- Achieve required uncertainty for the calibration of meters (0.5 %)

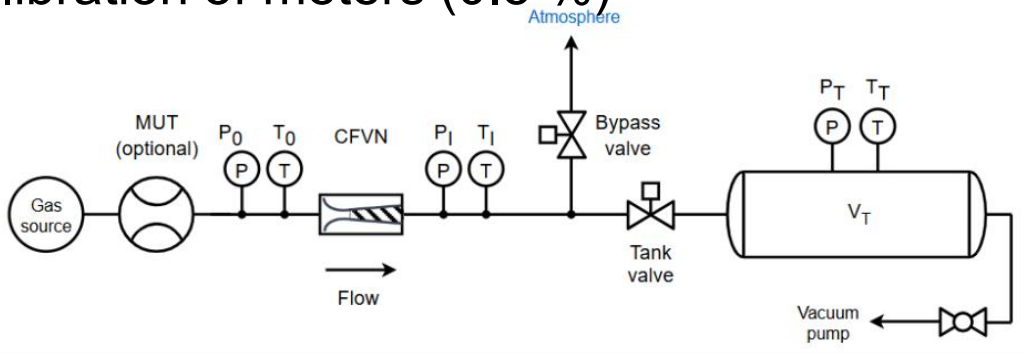
- Primary standard for traceability: pVTt (Pressure-Volume-Temperature-time)



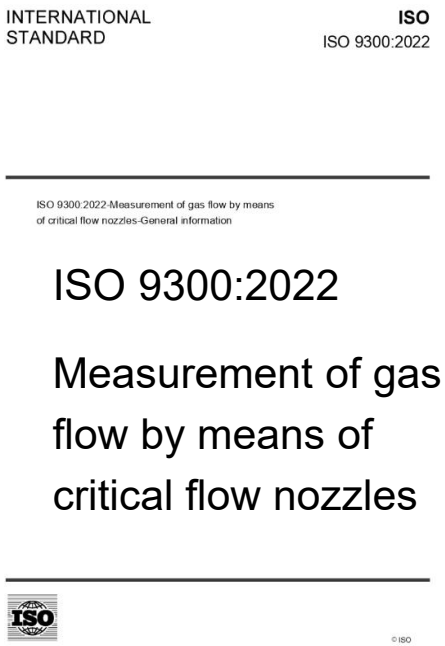
$$\dot{m} = \frac{V_T \cdot (\rho_{T,final} - \rho_{T,initial}) + V_I \cdot (\rho_{I,final} - \rho_{I,initial})}{t_{final} - t_{inital}}$$

TRACEABILITY CHAIN (SEE PROJECT H2FLOWTRACE)

- Achieve required uncertainty for the calibration of meters (0.5 %)
- Primary standard for traceability



- Use well-established technology for unit dissemination
- Scaling-up (bootstrapping, several smaller meters in parallel)
- Calibration with substitute substances?


INTERNATIONAL STANDARD

ISO
ISO 9300:2022

ISO 9300:2022-Measurement of gas flow by means of critical flow nozzles-General information

ISO 9300:2022

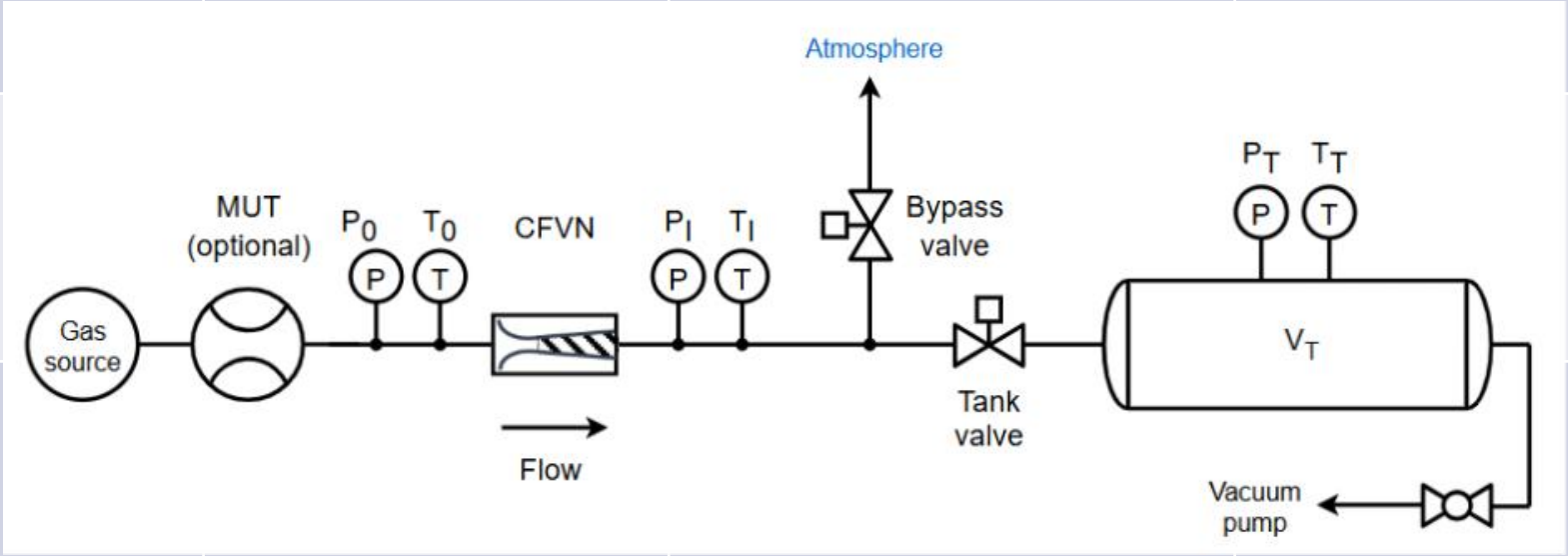
Measurement of gas flow by means of critical flow nozzles

ISO

© ISO

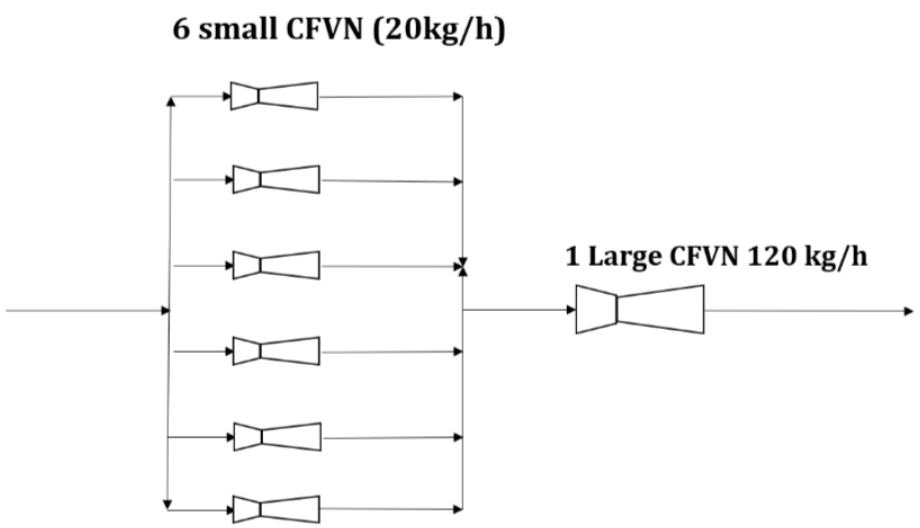
TRACEABILITY CHAIN (SEE PROJECT H2FLOWTRACE)

Stage	Standard	Calibrated device	Flow and pressure range	Target expanded uncertainty of calibrated device
1 H_2 HENG	Primary (pVTt)	Six CFVN (Set A)	Up to 20 kg/h (0.1 to 5.1) MPa	0.15 %
2 H_2 HENG	Nozzles			
3 H_2 NENG	Nozzles			



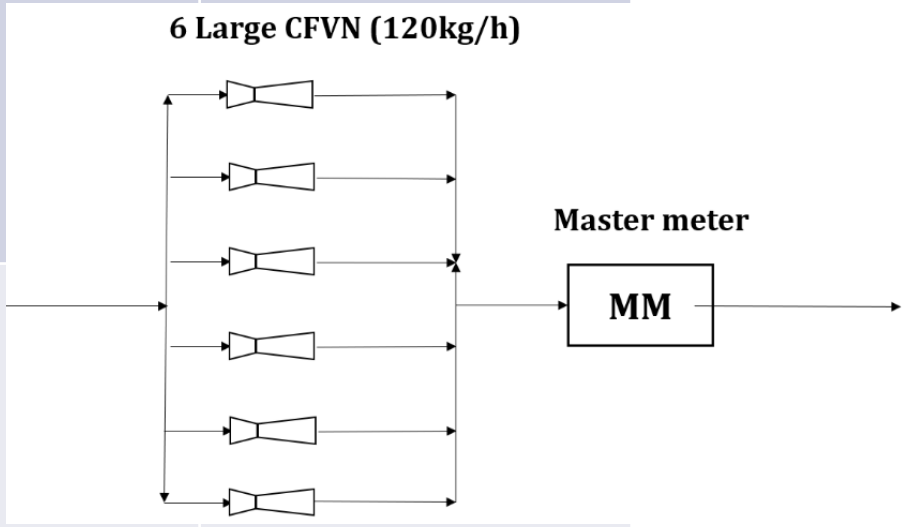
TRACEABILITY CHAIN (SEE PROJECT H2FLOWTRACE)

Stage	Standard	Calibrated device	Flow and pressure range	Target expanded uncertainty of calibrated device
1 H_2 HENG	Primary (pVTt)	Six CFVN (Set A)	Up to 20 kg/h (0.1 to 5.1) MPa	0.15 %
2 H_2 HENG	Nozzles Set A	Six CFVN (Set B)	Up to 120 kg/h Up to 3.3 MPa	0.20 %
3 H_2 HENG	Nozzles Set B	Skid with master meters	Up to 720 kg/h Up to 6.2 MPa	



TRACEABILITY CHAIN (SEE PROJECT H2FLOWTRACE)

Stage	Standard	Calibrated device	Flow and pressure range	Target expanded uncertainty of calibrated device
1 H_2 HENG	Primary (pVTt)	Six CFVN (Set A)	Up to 20 kg/h (0.1 to 5.1) MPa	
2 H_2 HENG	Nozzles Set A	Six CFVN (Set B)	Up to 120 kg/h Up to 3.3 MPa	
3 H_2 HENG	Nozzles Set B	Skid with master meters	Up to 720 kg/h Up to 6.2 MPa	0.30 %



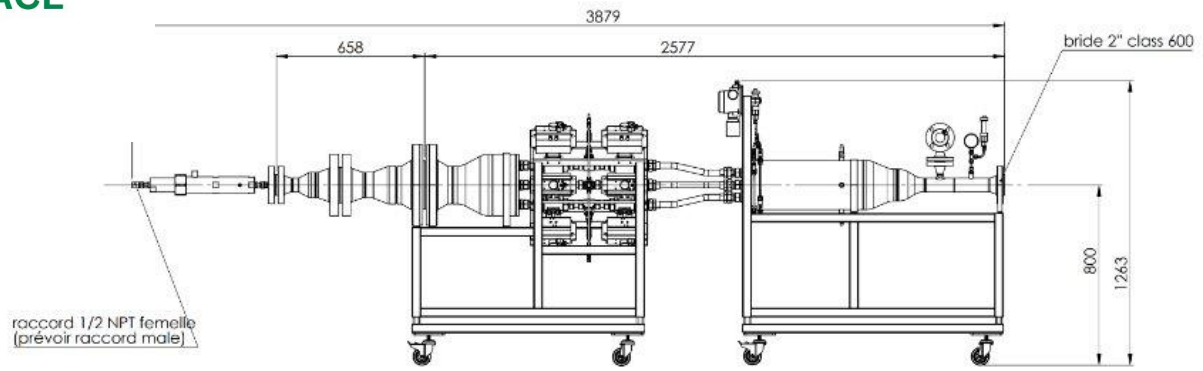
TRACEABILITY CHAIN

H2FLOWTRACE

MET4H2

Small-Scale Transfer Skid (SSTS)

- Under construction
- House all nozzles from Set A to calibrate nozzle from set B one at a time (120 kg/h)
- House all nozzles from Set B to calibrate master meters one at a time (720 kg/h)



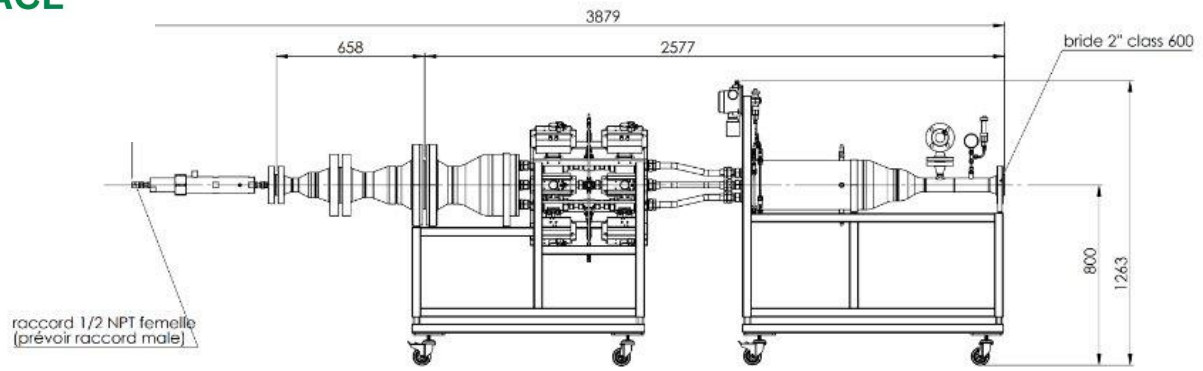
TRACEABILITY CHAIN

H2FLOWTRACE

MET4H2

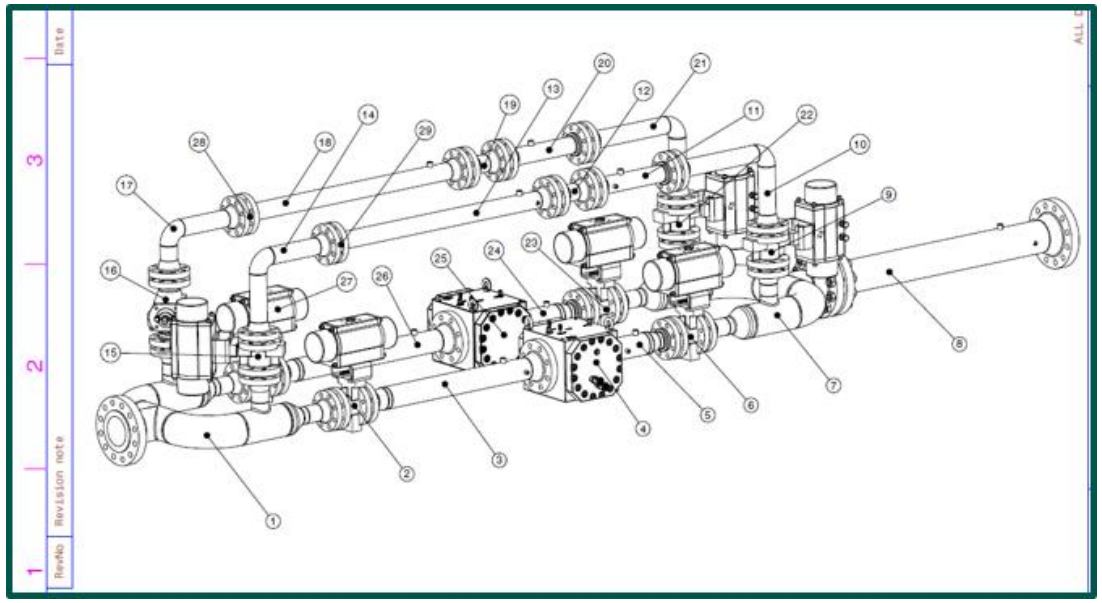
Small-Scale Transfer Skid (SSTS)

- Under construction
- House all nozzles from Set A to calibrate nozzle from set B one at a time (120 kg/h)
- House all nozzles from Set B to calibrate master meters one at a time (720 kg/h)



Large-Scale Transfer Skid (LSTS)

- Under construction
- House master meters to be calibrated with SSTS



SUMMARY

- A lot happened related to hydrogen flow metering during this project
- Traceability chain for hydrogen up to high flow rates is under construction
- Critical flow Venturi nozzles to be used as backbone for the dissemination
- H2FlowTrace is the next link in the calibration chain

Thank you for your attention

Marc de Huu, METAS

Marc.dehuu@metas.ch

NPL
National Physical Laboratory

MET4H2

Inter-comparison on trace water in hydrogen standards over the nominal range from 0.5 µmol mol^{-1} to 50 µmol mol^{-1} with conclusions and recommendations for future improvements

Paul Carroll (NPL), Dragos Buculei (NPL), Stephanie Bell (NPL), Matthijs Panman (VSL), Rugiada Cuccaro (INRIM),Vito Fernicola (INRIM), Rezvaneh Nobakht (INRIM), Alexander Fateev (DTU)

M36 Stakeholder meeting

2025-09-18

EUROPEAN PARTNERSHIP
Co-funded by the European Union
METROLOGY PARTNERSHIP
EURAMET

Introduction

- Need for water vapour measurement in hydrogen
- How task meets aims of the project
- Principle of an ILC
- Protocol details
- Standards involved in the ILC
- Dew-point temperature and amount fraction value considerations
- Results
- Conclusions / Future Recommendations

Background

- Water vapour measurement is a key parameter for hydrogen quality in the supply chain.
- The requirement to monitor water vapour is a cross-cutting issue over the entire hydrogen supply chain.
- Need water to remain in gas phase at outdoor temperatures and at tank pressures up to 70 MPa (700 bar).
- ISO 14687-2 regulates maximum permitted H_2O level at 5 µmol mol^{-1}
- Reliable measurement of water vapour content is needed by the hydrogen industry (for both quality laboratories and onsite analysers).
- One of the main challenges is to achieve or access a reliable and traceable water vapour standard in the range of 0.5 µmol mol^{-1} to 50 µmol mol^{-1} in hydrogen.

Current status of humidity calibration

Hygrometers are typically

developed, tested, and calibrated in atmospheric air or nitrogen

but

often used in other gases and at other pressures

Sensor performance can be affected by use at elevated pressure and by the gas medium of use, depending on sensing principle.

Metrology infrastructure exists for air humidity at all scales (NMI standards, traceable calibration, accreditations)

But, for humidity in other gases and pressures replicating industrial conditions has only recently been established.

Solution required

- Primary humidity traceability to provide calibrations representative of industrial conditions experienced by hygrometers in the real world.
- Many different hygrometer types used to make measurements of humidity in industrial applications.
- Different units depending on measurement principle, commonly dew-point temperature (°C) and amount fraction of water vapour (μmol mol^{-1}).
- Calibration of hygrometers should be performed using references with traceability to national standards.
- Where possible the calibration should be performed in hydrogen, at the pressure of use.

WP3: Quality control

Develop the metrological tools to ensure reliable and traceable measurements necessary to apply appropriate quality control on hydrogen throughout the supply chain to support the transition into green hydrogen

- Provide a good practice guide and new sampling system for industry in order to sample hydrogen gas representatively [Task 3.1]
- Demonstrate equivalence between water vapour gas standards and new and innovative portable standards [Task 3.2]
- Develop the metrological infrastructure for key reactive gases for electrolysers (water vapour and HCl) and for the supply chain (sulphur and ammonia) [Task 3.3]
- Implement metrological guidelines for the onsite calibration and onsite analysis of key contaminants of the supply chain (i.e., H2O) [Task 3.4]

Met4H2 Task 3.2 Traceability - Improving measurement quality and calibration for water vapour amount fraction

Demonstrate equivalence between water vapour gas standards and new and innovative portable standards:

- A3.2.1 – Transportable precision humidity generator & high-pressure frost-point generator
- A3.2.3 – Plan and protocol for Inter-laboratory comparison
- A3.2.4 – Inter-laboratory comparison of water vapour realisations
- A3.2.5 – Report on the results of the interlaboratory comparison

Principle of an inter-laboratory comparison

A demonstration of the capabilities of measurement standards and their associated uncertainties.

Transfer standard instruments are circulated between participants who realise a set of reference values from an agreed protocol using their standards.

Measurement errors are reported to the pilot by participant laboratories with their associated uncertainties.

Initial, mid-point and final measurements at the pilot laboratory enable evaluation of any drift in the transfer standard instruments.

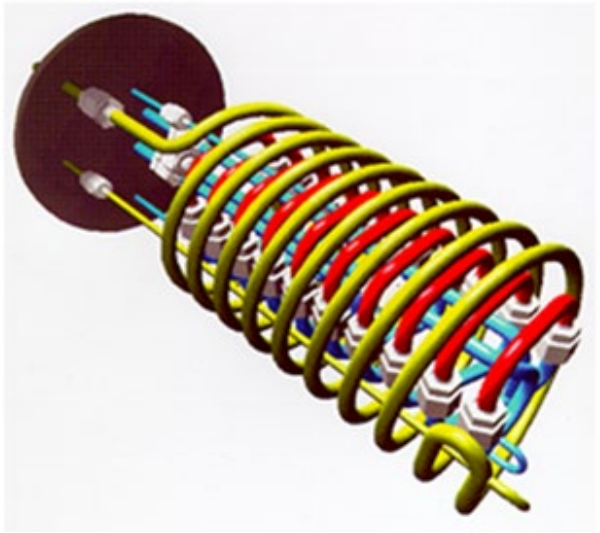
Figure 1 Overview of the comparison schedule

In this work we look to compare water vapour realisations in hydrogen at three European National Measurement Institutes.

Existing NPL standard

- Multi-gas, Multi-pressure Primary Standard Humidity Generator

- Humidity calibrations in “industrial” conditions.
- Non-air gases (e.g methane, nitrogen, CO_2, argon, hydrogen)
- Pressures up to 3 MPa (30 bar)



- Hybrid generator able to calibrate in single pressure dew point mode from -60 ºC to +15 ºC
  ($0.5\ \mu mol\ mol^{-1} < x < 50\ \mu mol\ mol^{-1}$)

- Ability to mix gases using array of mass flow controllers

A3.2.1 VSL standard development

- VSL – Modifications to the High-Pressure Dewpoint Generator

Modifications

- VCR face-seal fittings or AbT fittings (assembly by torque).
- Welded tubing.
- Atex H_2 compatible pressure meters.
- Auxiliary optical table to accommodate various instruments.

For safety

- Pneumatic shut-off valve.
- Proportional release valve.
- LEL detector.
- Check valves.
- 300 $m^3.hr^{-1}$ extraction of exhaust sample gas.

Dew point temperature:
-80 ºC to +20 ºC

Amount fraction:
(0.01 µmol mol-1 < x < 2000 µmol mol-1).

Operating pressure:
0.1 MPa to 6 MPa

A3.2.1 INRIM standard development

- INRIM developed and validated a Transportable precision humidity generator (TPHG)

TECHNICAL CHARACTERISTICS:

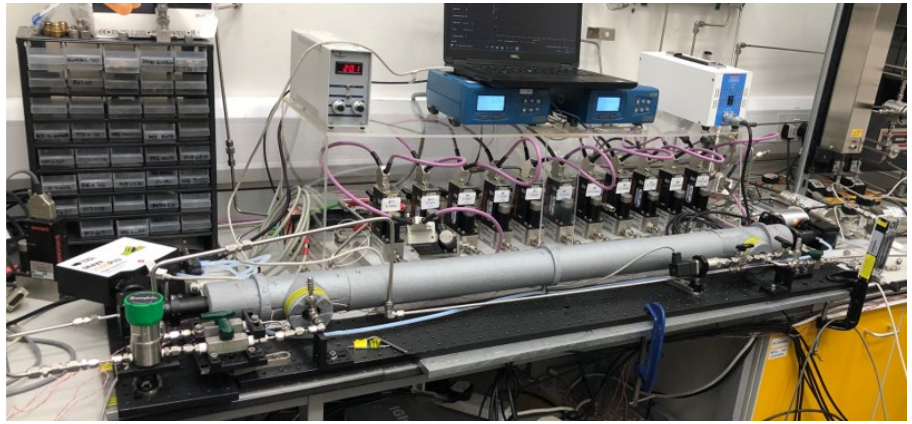
- **Frost point temperature:**
  -55 ° C < T_{fp} < -10 ° C at pressure
- **Water vapor amount fraction:**
  0.5 µmol mol^{-1} < x_w < 50 µmol mol^{-1}
- Pressure: 0.1 MPa < P < 5.5 MPa; tested up to 3 MPa
- Target Uncertainty: 3 % < $u_r(x_w)$ < 5 %

Transfer standard instruments used during inter-laboratory comparison

A C.O.S dew-point temperature measurement principle instrument: MBW 373HPLX high-pressure chilled mirror hygrometer

A C.O.S water vapour amount fraction measurement principle instrument: Tiger Optics SPARK water vapour spectrometer

A research prototype spectrometer: far-UV water vapour spectrometer developed by DTU



A3.2.3 Inter-laboratory comparison - Protocol details

NPL, INRIM, VSL, DTU, POLITO Plan an inter-laboratory comparison of water vapour realisations and measurements in hydrogen in the range of amount fractions between nominally 0.5 µmol mol^{-1} and 50 µmol mol^{-1}.

Water vapour ranges, operating pressures, and gas species compatibilities all considerations in agreeing comparison values.

MET4H$_2$

Metrology for the hydrogen supply chain
Report number Met4H2-A3.2.3

Inter-laboratory comparison of standards for trace water in hydrogen over the nominal range -60 °C to -15 °C frost-point temperature (0.5 µmol mol^{-1} to 50 µmol mol^{-1})

Inter-laboratory comparison protocol

Table 1 List of the transfer standard hygrometers.

Manufacturer	Model	Serial number	Measurement principle	Operating range	Inlet pressure range / MPa	Compatible gas species
MBW	373 LX-HP	14-0610	Chilled-mirror condensation	-60 °C to +20 °C	0.1 to 3	Air, N_2, H_2
Tiger Optics	F7700 -ATM	6159-145-0	CRDS water vapour spectrometer	0 – 1750 µmol mol^{-1}	0.2 to 0.96	Air, N_2, H_2
DTU	Proto-type	n/a	Far-UV spectroscopy	1 - 300 µmol mol^{-1}	0.1 to 4 (H_2) 0.1 to 10 (N_2)	N_2, H_2

Figure 1 Overview of the comparison schedule

Table 2 Measurement values at 0.2 MPa test pressure:

Nominal Frost-point temperature / °C	Nominal equivalent water vapour amount fraction / µmol mol^{-1}
-60.7	5
-52.3	15
-42.3	50

Table 3 Measurement values at 3 MPa test pressure:

Nominal Frost-point temperature / °C	Nominal equivalent water vapour amount fraction / µmol mol^{-1}
-59.0	0.5
-40.0	5
-17.3	50

Inter-laboratory comparison of water vapour realisations

- **A3.2.4 –NPL, INRIM, VSL, DTU, POLITO** Using the protocol defined in A3.2.3, NPL, DTU, INRIM, POLITO and VSL performed an inter-laboratory comparison of the different trace water in hydrogen standards developed by the participants.

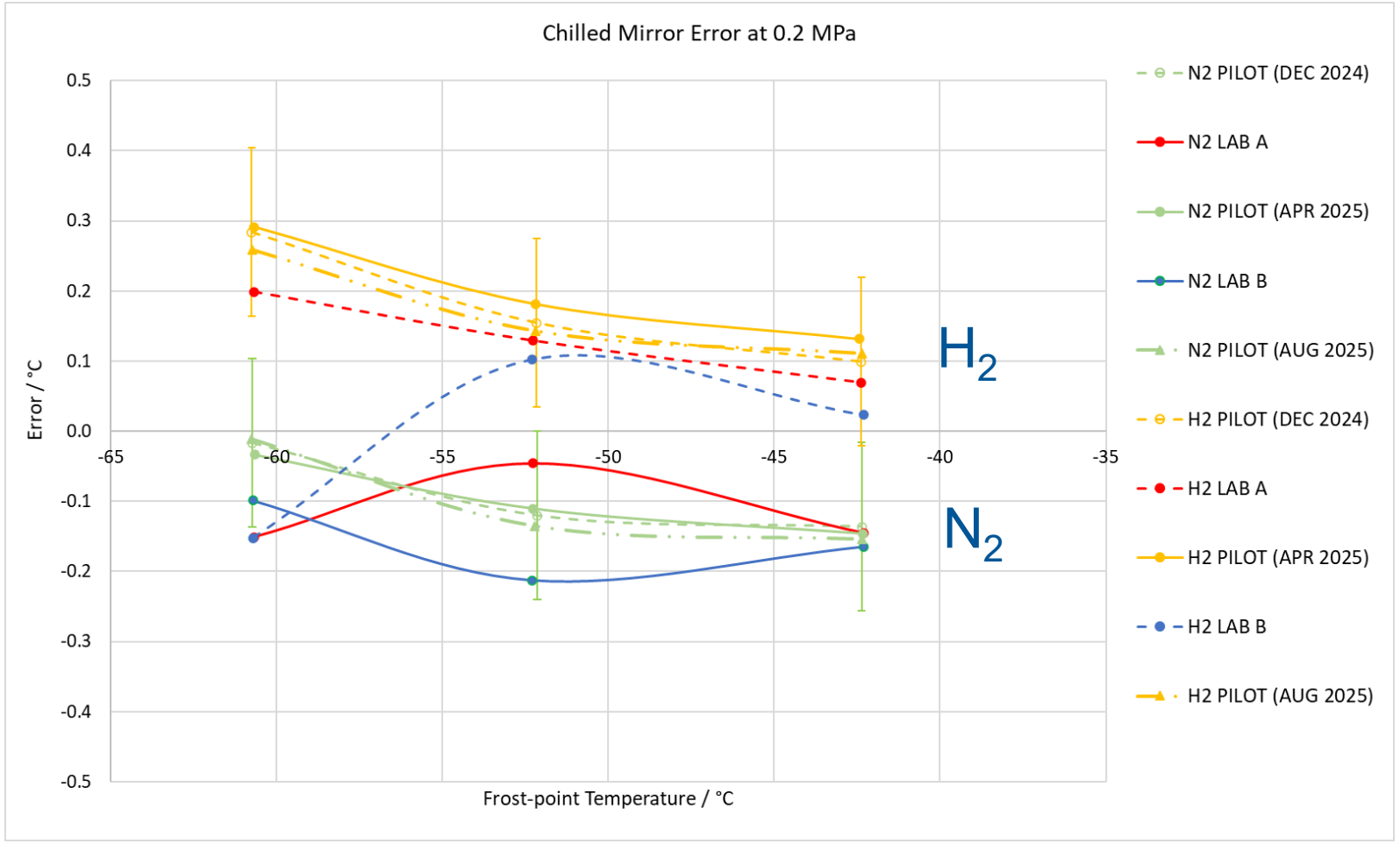
- Final measurements completed at NPL just last week.

ILC Artifacts: CRDS, UV spectrometer, CMH

Nominal Frost-point temperature / °C	Nominal equivalent water vapour amount fraction / µmol mol^{-1}	Test pressure / MPa
-60.7	5	0.2
-59.0	0.5	3
-52.3	15	0.2
-42.3	50	0.2
-40.0	5	3
-17.3	50	3

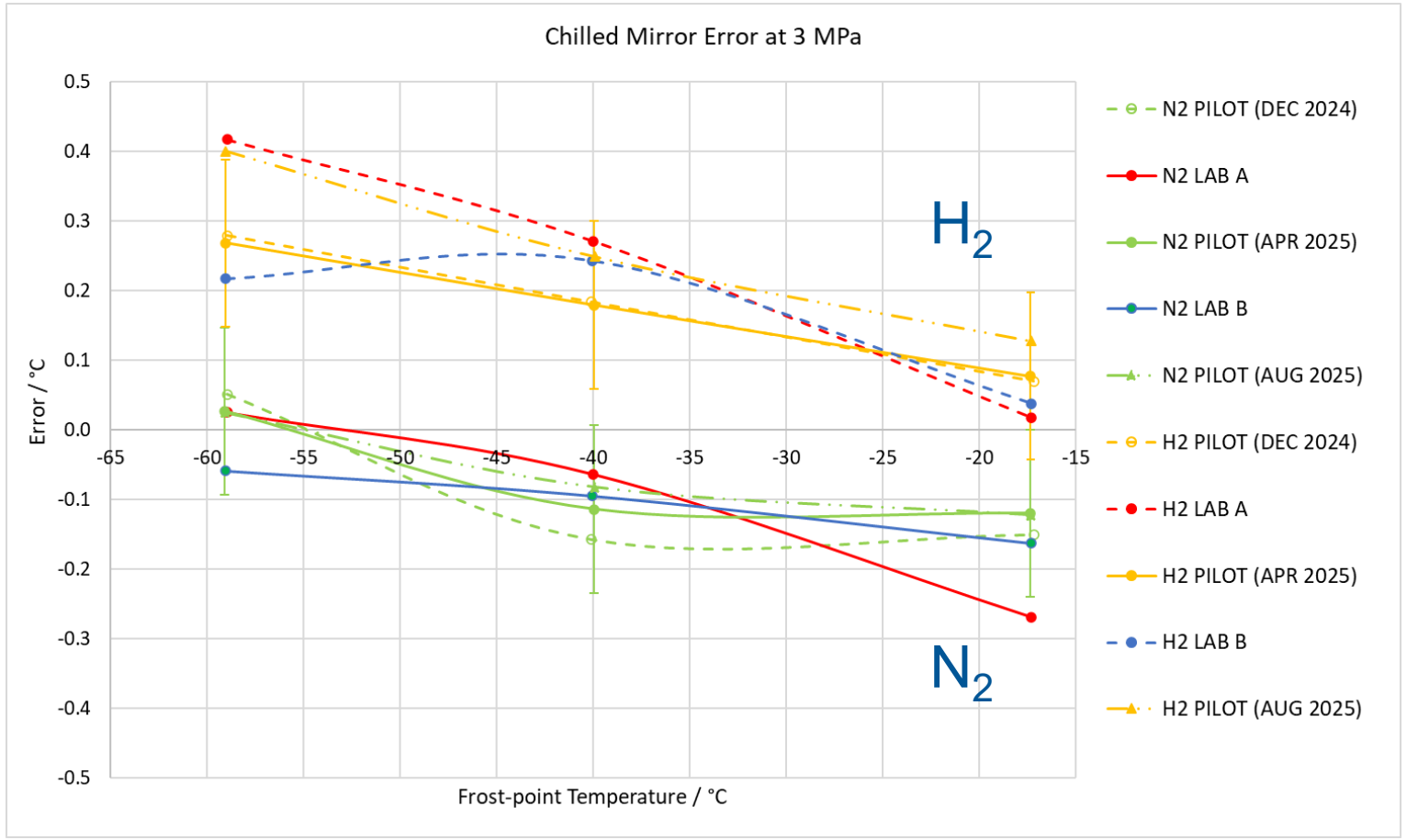
Carrier gas: Nitrogen and hydrogen.

Single-pressure dew-point temperature comparison results at 0.2 MPa



- CMH over-read more in hydrogen compared to nitrogen background gas at all labs.
- In both hydrogen and nitrogen, participants mainly agreed within NPL uncertainties (k = 2 error bars shown) except LAB B in hydrogen at -60 ºC.

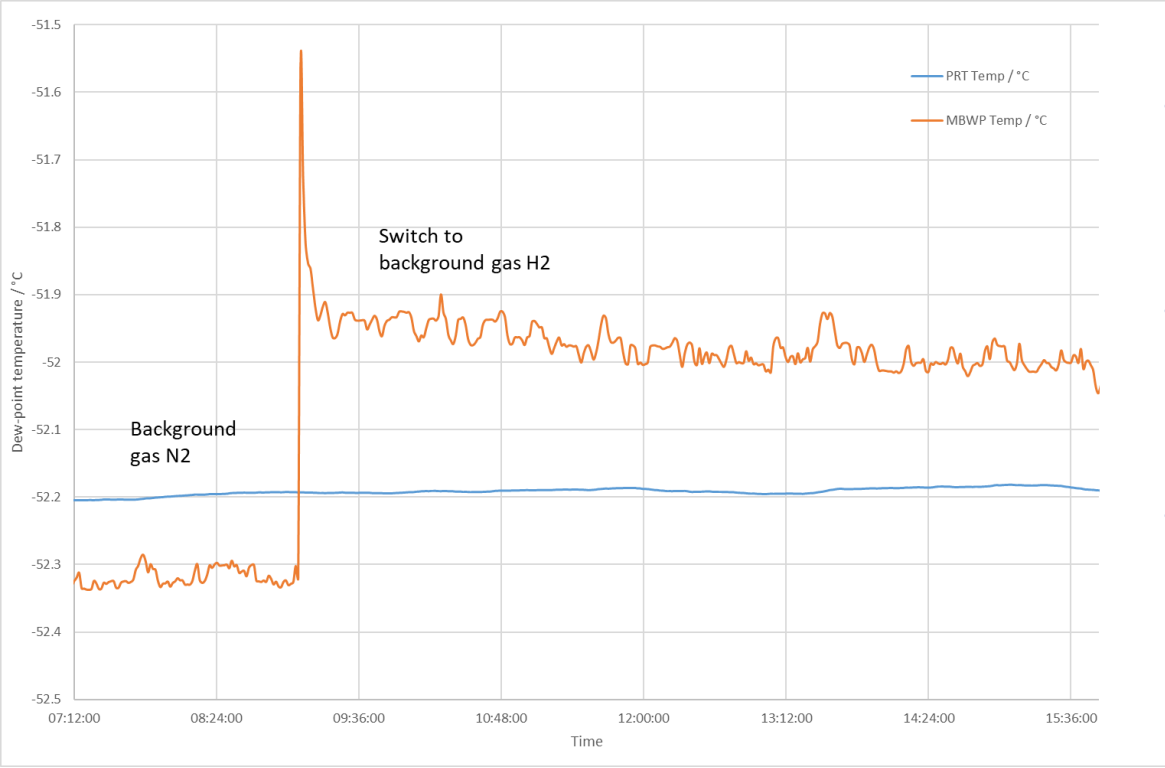
Single-pressure dew-point temperature comparison results at 3 MPa



- CMH over-read more in hydrogen compared to nitrogen background gas at all labs.
- In both hydrogen and nitrogen, participants mainly agreed within NPL uncertainties (shown) – except some scatter seen at -60 ºC.

Conclusions – Chilled Mirror results

- This CMH over-read in hydrogen compared to nitrogen background gas at all labs.
- Consistent error change in hydrogen for all participants meant results still useable measurements for ILC purposes.
- Response of CMH to change to hydrogen background gas can take many hours to stabilise at trace moisture values.



- Some participants could operate in hydrogen overnight, others just during hours when staff present – a different error would result if left longer.
- CMH error appears to have drifted to over-reading in hydrogen over the duration of the ILC according to pilot final repeat results.
- Transfer standard uncertainty contributions to be evaluated and applied to equivalence analysis.

Reference dew-point temperature to amount fraction value conversion considerations

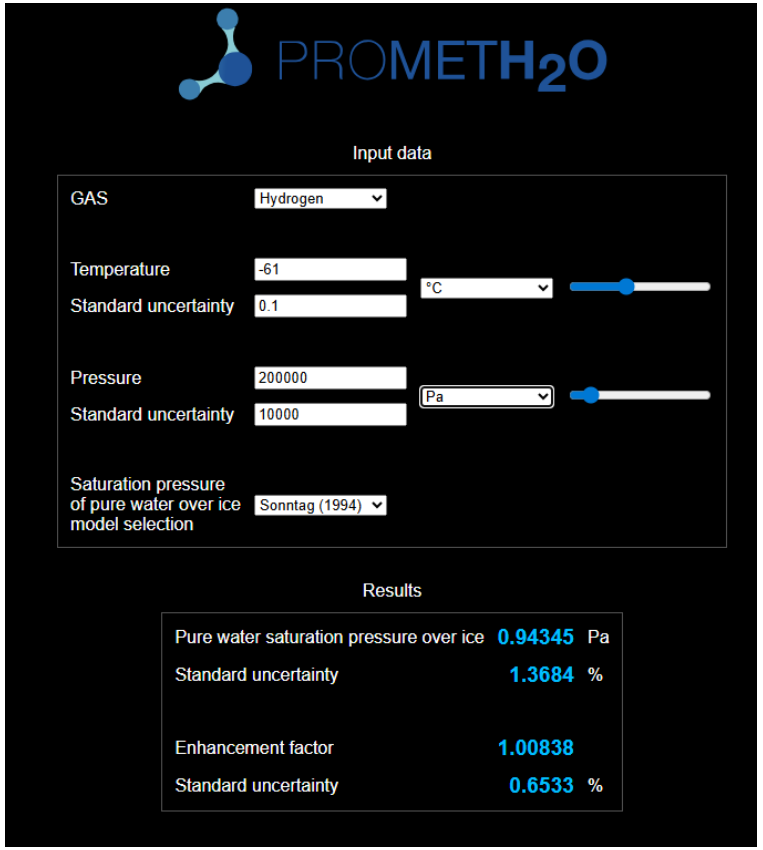
MET4H2

NPL National Physical Laboratory

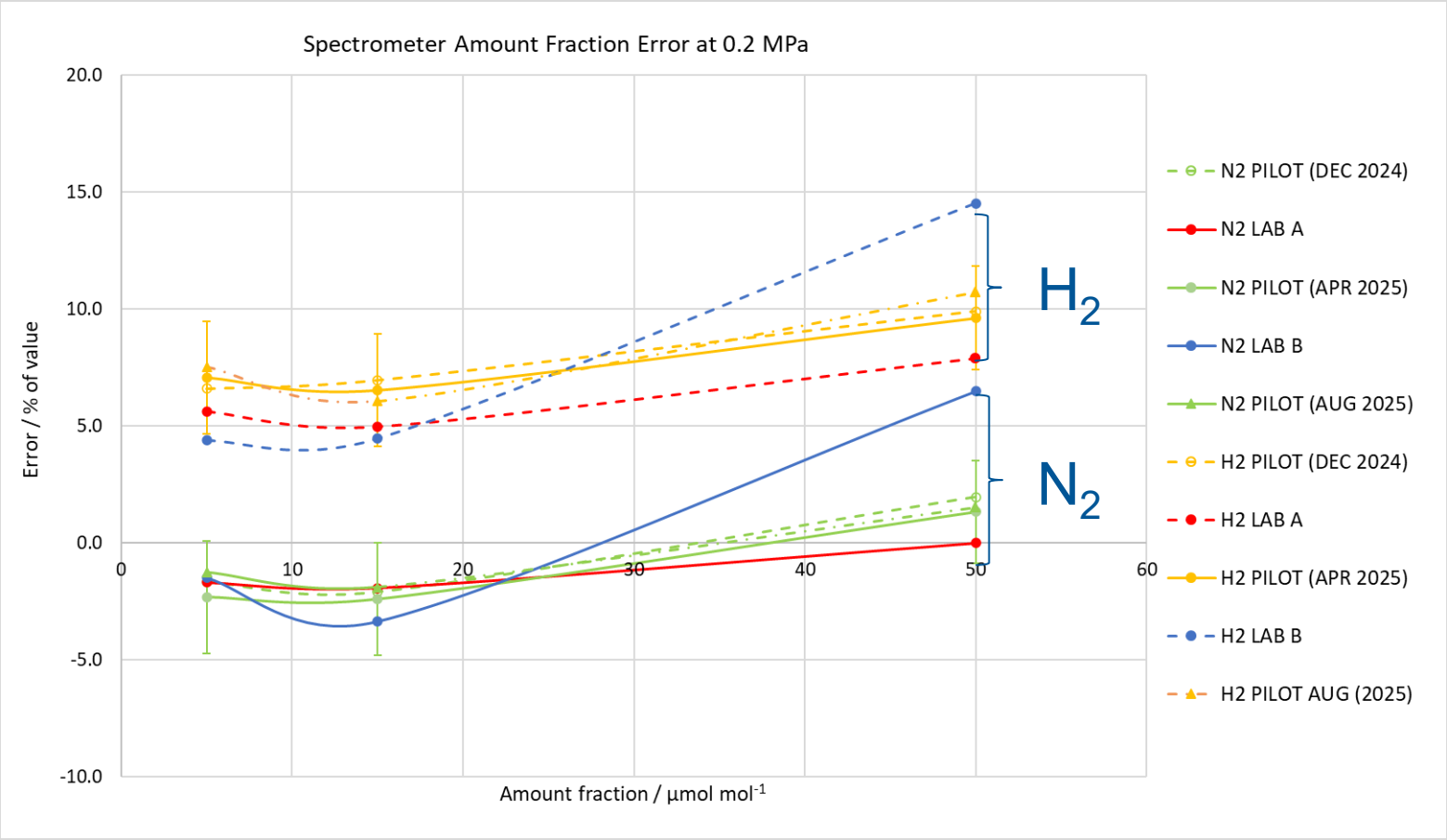
- When calculating amount fraction of water vapour (x) from dew-point temperature (t_d) or vice versa, the **water vapour enhancement factor** (f) is needed in the calculations.

$$x = \frac{f(P, t_d)e(t_d)}{P}$$

- By this factor the deviation of a real gas mixture from pure water vapour is compensated.
- Widely accepted data for WVEF exists for air, but only emerging for other gas species.
- Agreed in ILC for pilot to apply consistent WVEF f values to calculate x values from all participants measurements of t_d and P.
- f-calculator from ProMetH2O EMPIR project used to calculate 0.2 MPa values. (Use limited to 1 MPa)
- www.prometh2o.unicas.it/
- NPL experimental data from MefHySto EMPIR project used for estimates of f at 3 MPa.

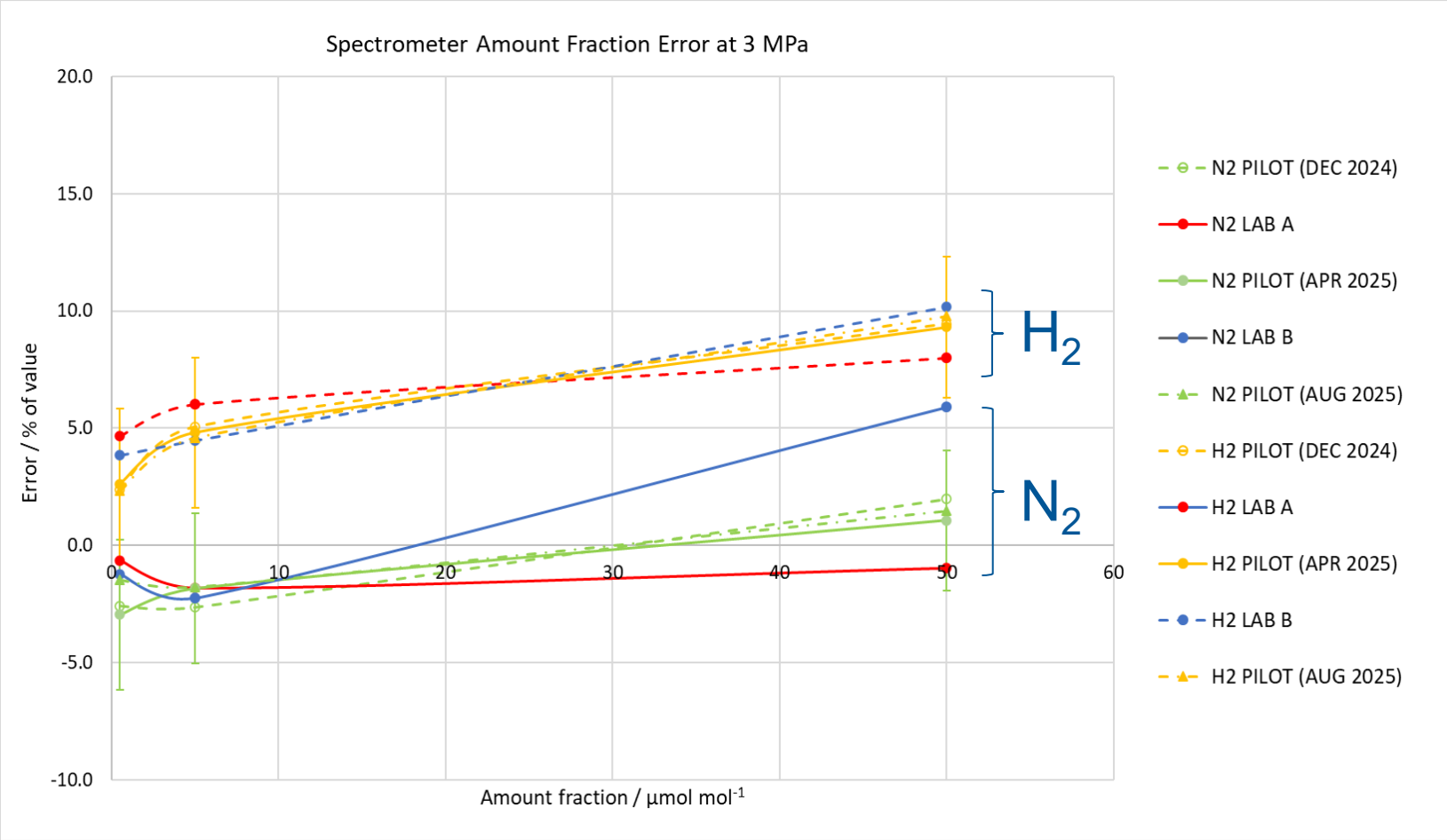


Amount fraction Spectrometer comparison results at 0.2 MPa



- Spectrometer over-read more in hydrogen compared to nitrogen background gas at all labs.
- In both hydrogen and nitrogen, participants mainly agreed within NPL uncertainties (shown) except LAB B at 50 µmol mol^{-1}.

Amount fraction Spectrometer comparison results at 3 MPa



- Spectrometer over-read more in hydrogen compared to nitrogen background gas at all labs.
- In hydrogen participants agreed within NPL uncertainties (shown), in nitrogen agreement again ok except LAB B at 50 µmol mol^{-1} in nitrogen.

Conclusions – Spectrometer results

- Conversion of reference frost point to amount fraction would be affected by choice of water vapour enhancement factor – pilot applied same WVEF calculation to conversion of each participant's results.
- Hydrogen values for spectrometer appear to be over-reading compared to measurements of nitrogen at same water contents.
- This error is not due to the operator using an incorrect background gas "mode" as it is known that the error due to this is much larger than that observed.
- Not possible at this stage to distinguish if this is measurement error due to background gas change in generator, choice of WVEF equation used to calculate reference values or instrument error background gas dependence.
- Consistent error change in hydrogen for all participants meant still useable measurements for ILC purposes.
- Transfer standard uncertainty contributions still to be evaluated and applied to equivalence analysis.

- DTU spectrometer results being analysed and D5 report to be issued by end of month.

Equivalence reporting template: Water Vapour spectrometer

1. Results: amount fraction (using water vapour spectrometer)

1.1 Saturator pressure: 0.2 MPa

Table 1.1.1. Amount fraction: 5 mol mol^{-1}

Gas: N_2

	INRIM		NPL		VSL	
INRIM						
NPL						
VSL						

Gas: H_2

	INRIM		NPL		VSL	
INRIM						
NPL						
VSL						

Table 1.1.2. Amount fraction: 15 mol mol^{-1}

Gas: N_2

	INRIM		NPL		VSL	
INRIM						
NPL						
VSL						

Gas: H_2

	INRIM		NPL		VSL	
INRIM						
NPL						
VSL						

Table 1.1.3. Amount fraction: 50 mol mol^{-1}

Gas: N_2

	INRIM		NPL		VSL	
INRIM						
NPL						
VSL						

Gas: H_2

	INRIM		NPL		VSL	
INRIM						
NPL						
VSL						

1.2 Saturator pressure: 3 MPa

Table 1.2.1. Amount fraction: 0.5 mol mol^{-1}

Gas: N_2

	INRIM		NPL		VSL	
INRIM						
NPL						
VSL						

Gas: H_2

	INRIM		NPL		VSL	
INRIM						
NPL						
VSL						

Table 1.2.2. Amount fraction: 5 mol mol^{-1}

Gas: N_2

	INRIM		NPL		VSL	
INRIM						
NPL						
VSL						

Gas: H_2

	INRIM		NPL		VSL	
INRIM						
NPL						
VSL						

Table 1.2.3. Amount fraction: 50 mol mol^{-1}

Gas: N_2

	INRIM		NPL		VSL	
INRIM						
NPL						
VSL						

Gas: H_2

	INRIM		NPL		VSL	
INRIM						
NPL						
VSL						

Equivalence reporting template: Chilled Mirror hygrometer

2. Results: frost point (using cooled-mirror hygrometer)

2.1 Saturator pressure: 0.2 MPa

Table 2.1.1 Saturator temperature (frost point at 0.2 MPa): -60.7 °C

Gas: N_2

	INRIM	NPL	VSL
INRIM			
NPL			
VSL			

Gas: H_2

	INRIM	NPL	VSL
INRIM			
NPL			
VSL			

Table 2.1.2. Saturator temperature (frost point at 0.2 MPa): -52.3 °C

Gas: N_2

	INRIM	NPL	VSL
INRIM			
NPL			
VSL			

Gas: H_2

	INRIM	NPL	VSL
INRIM			
NPL			
VSL			

Table 2.1.3 Saturator temperature (frost point at 0.2 MPa): -42.3 °C

Gas: N_2

	INRIM	NPL	VSL
INRIM			
NPL			
VSL			

Gas: H_2

	INRIM	NPL	VSL
INRIM			
NPL			
VSL			

2.2 Saturator pressure: 3 MPa

Table 2.2.1. Saturator temperature (frost point at 3 MPa): --59.0 °C

Gas: N_2

	INRIM	NPL	VSL
INRIM			
NPL			
VSL			

Gas: H_2

	INRIM	NPL	VSL
INRIM			
NPL			
VSL			

Table 2.2.2. Saturator temperature (frost point at 3 MPa): -40.0 °C

Gas: N_2

	INRIM	NPL	VSL
INRIM			
NPL			
VSL			

Gas: H_2

	INRIM	NPL	VSL
INRIM			
NPL			
VSL			

Table 2.2.3. Saturator temperature (frost point at 3 MPa): -17.3 °C

Gas: N_2

	INRIM	NPL	VSL
INRIM			
NPL			
VSL			

Gas: H_2

	INRIM	NPL	VSL
INRIM			
NPL			
VSL			

Recommendations for future improvements

- Spend longer characterising transfer standards to better understand response time.
- If no overnight operation possible ensure only faster responding instruments used.
- Consider scope at planning stage – if evaluating equivalences, many equivalence tables might be needed:
  - No. of tables = measured quantities x pressures x gas species x measured values
- Participants may choose their own conversions (enhancement factors) or this may be standardised – decide which is relevant.
- Consider required inlet pressure if selecting a spectrometer for use. Not all can be operated at nominally atmospheric inlet pressure, only selected models.
- Consider which humidity quantity is the most meaningful for the comparison based on the capabilities of the participants.

Deliverable of WP3

D5: Report on the results of the intercomparison on trace water in hydrogen standards over the nominal range from 0.5 µmol/mol to 50 µmol/mol with conclusions on the recommendations for future improvements

NPL, INRIM, VSL, DTU, POLITO – M36 Sep 2025

- Last ILC measurements made in early September 2025.
- Final analysis and draft of report in progress for publication by the end of the month.

Summary

- Need for water vapour measurement in hydrogen
- How task meets aims of the project
- Principle of an ILC
- Protocol details
- Standards involved in the ILC
- Dew-point temperature and amount fraction value considerations
- Results
- Conclusions / Future Recommendations

Thank you!

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www.npl.co.uk/temperature-humidity

EUROPEAN PARTNERSHIP Co-funded by the European Union METROLOGY PARTNERSHIP EURAMET

MET4H2

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www.inrim.it

Metrologically-traceable quality monitoring in the H_2 supply chain

and recommendations for improving ISO 19880-8 and ISO 21087

Vito Fernicola on behalf of Met4H2 Partners

Hydrogen quality control tools in Met4H2

Developing metrological tools to ensure reliable and traceable measurements necessary to apply appropriate quality control on hydrogen throughout the supply chain to support the transition into green hydrogen

- Provide a good practice guide and new sampling system for industry in order to sample hydrogen gas representatively
- Demonstrate equivalence between water vapour gas standards and new and innovative portable standards
- Develop the metrological infrastructure for key reactive gases for electrolysers (water vapour and HCl) and for the supply chain (sulphur and ammonia)
- Implement metrological guidelines for the onsite calibration and onsite analysis of key contaminants of the supply chain (i.e., H2O)

Focus of this presentation

Good practice guide focused on traceable measurement, online analysis, on-site calibration and validation using reference standards and offline measurements relevant to the hydrogen supply chain:

i. Traceable quality monitoring in alkaline electrolyser

ii. Traceable quality monitoring in hydrogen distribution

iii. Lesson learnt, recommendations and inputs to ISO19880-8 and ISO 21087

What this piece of work delivered?

Intercomparison on trace water in hydrogen standards over the nominal range from 0.5 µmol/mol to 50 µmol/mol with conclusions on the recommendations for future improvements

NPL, INRIM, VSL, DTU, POLITO

Good practice guide on metrologically traceable quality monitoring in the hydrogen supply chain, including offline measurements and onsite calibration, and recommendations for future improvements of ISO 19880-8 and ISO 21087

INRIM, BAM, CEM, DFM, NPL, PTB, VSL, VTT, DTU, ENVIPARK, Nippon Gases, POLITO

Sampling strategies and requirements for H_2 analysis

MET4H2

MET4H2

Review of sampling strategy and requirements for hydrogen quality analysis
Report number Met4H2 – A3.1.1 and A3.1.2

Task	Activity	Reporting date
3.1	A3.1.1 and A3.1.2	XX
Title: Review of sampling strategy and requirements for hydrogen quality analysis		
Authors: Ziyin Chen (NPL), Thomas Bacquart (NPL), Vito C Fernicola (INRIM), Davide Trapani (ENVIPARK), Stefano Boggio (NIPPON GASES), Pasquale Colacino (NIPPON GASES)		Corresponding author
Contributing partners: NPL (UK), INRIM (IT), ENVIPARK (IT), NIPPON GASES (IT)		
Key words: Sampling requirements, sampling system, gas cylinders		
Notice: This work was funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them. The contents of this report have been obtained using best scientific practices and have been peer-reviewed prior to release. Nevertheless, the material is provided "as is", without any kind of warranty regarding correctness, completeness, or fitness-for-purpose.		
Acknowledgement: The project Met4H2 21GRD05 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.		
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Feedback: The consortium welcomes feedback. Please send your comments, suggestions or other feedback to the project coordinator, Dr. Adriaan van der Veen (VSL), avdveen@vsl.nl.		

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Table 1 Requirement of the sampling points in industry

No	Scenario	pressure	Humidity	Temperature	Sampling frequency	Sampling duration	Safety	Volume	Key compounds	Venting option
1	Alkaline electrolyser	5 bar	N/A	N/A	Continuous monitoring	During electrolyser operation	According to the classification provided in the electrolyser user manual	• Hydrogen: 10.66 m3/h (in nominal conditions) • Oxygen: 5.33 m3/h (in nominal conditions)	• Hydrogen concentration in the oxygen stream • Oxygen concentration in the hydrogen stream • Traces of electrolyte (i.e., NaOH) • Humidity	N/A
2	SMR before PSA	< 30 bar (normally around 15 bar)	N/A	Ambient (max 38°C)	N/A	N/A	ATEX zone 2	N/A	N/A	N/A
3	SMR after PSA	< 30 bar (normally around 15 bar)	≤ 5 ppm	Ambient (max 38°C)	1/day	10 min	ATEX zone 2	2.5 l/min	O2, H2O, CO2, N2, CO, CO2, CH4 (THC)	Yes, through the line in the lab
4	(SMR + PSA) to Storage/Pipeline/compressors	14 bar	≤ 5 ppm	Ambient	1/day (each line)	10 min	ATEX zone 2	2.5 l/min	O2, H2O, CO2, N2, CO, CO2, CH4 (THC)	Yes, through the line in the lab
5	H2 from compressors (bundles, cylinders and Tube trailers)	200 bar	≤ 5 ppm	Ambient	1/day	10 min	ATEX zone 2	2.5 l/min	O2, H2O, CO2, N2, CO, CO2, CH4 (THC)	Yes, through the line in the lab

For example 1, 2, 3 and 4, a system without pressure regulation may be suitable if components are within pressure rating
For example 5, the system require pressure regulation as gas cylinder are rated below

NPL National Physical Laboratory

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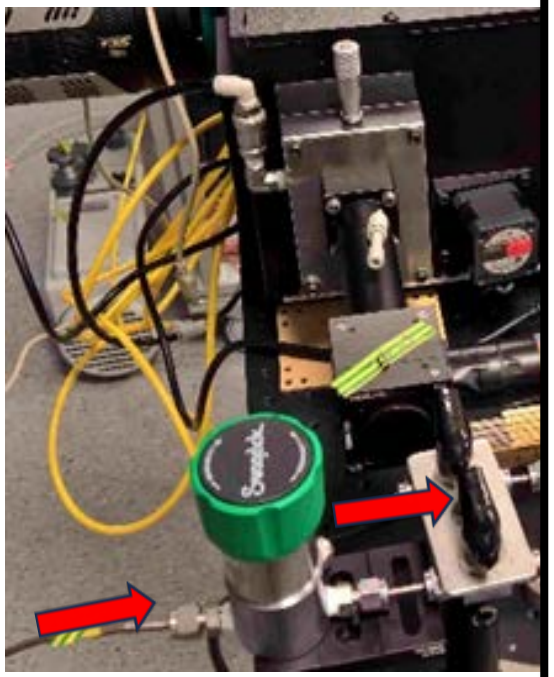
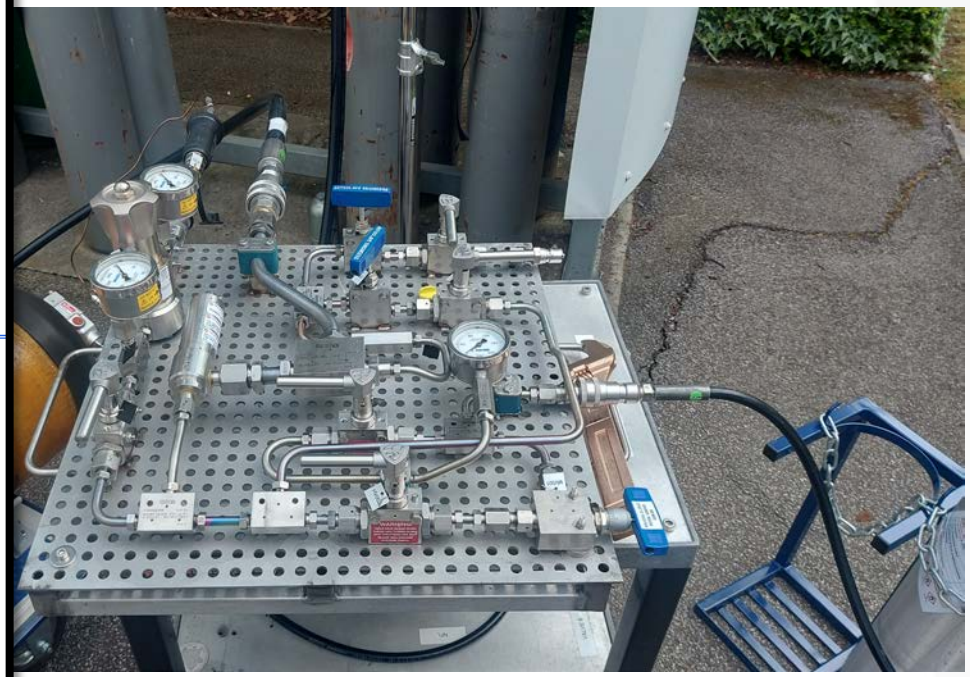
Hydrogen sampling systems

DTU sampling system: up t

ling system: 10 -to- 875 bar





MET4H2

Hydrogen gas quality - Good practice guide and recommendations for hydrogen gas sampling online and offline
Met4H2-A3.1.5

Task	Activity	Reporting date
3.1	3.1.5	XXX.2025

Title

Good practice guide and recommendations for hydrogen gas sampling online and offline

Authors	Corresponding author
Fangyu Zhang (NPL), Shirin Khaki (NPL), Linga Reddy Enakonda (NPL), Hannah Kerr (NPL), Abigail S. O. Morris (NPL), Thomas Bacquart (NPL), Vito C. Fernicola (INRIM), Rugiada Cuccaro (INRIM), Rezvaneh Nobakht (INRIM), Alexander Fateev (DTU), Ilaria Schiavi (Envipark), Stefano Boggio (Nippon Gases), Simone Mandarino (Nippon Gases), Luca Augello (Nippon Gases), Luca Berardino (POLITO), Gabriele Restaldo (SAGAT), Matthias Richter (BAM)	Fangyu Zhang

Contributing partners

NPL (UK), INRIM (IT), DTU (DK), Envipark (IT), Nippon Gases (IT), POLITO (IT), SAGAT (IT), BAM (DE)

Key words

Sampling, hydrogen gas quality, hydrogen distribution, alkaline electrolyser

Notice

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Acknowledgement

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Feedback

The consortium welcomes feedback. Please send your comments, suggestions or other feedback to the project coordinator, Dr. Adriaan van der Veen (VSL), avdveen@vsl.nl.

DTU

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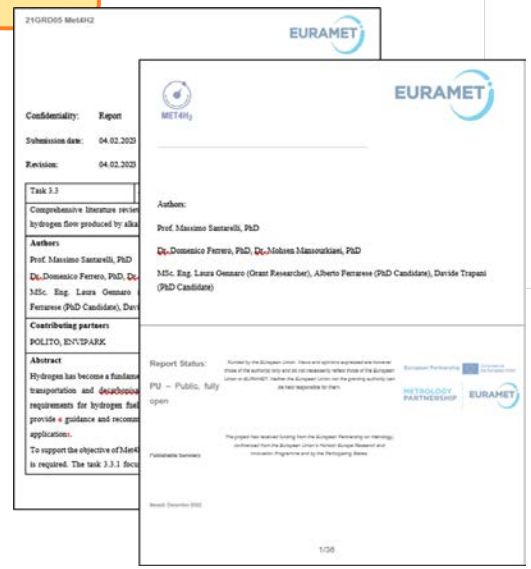
Survey of key reactive gases in electrolysers and the supply chain

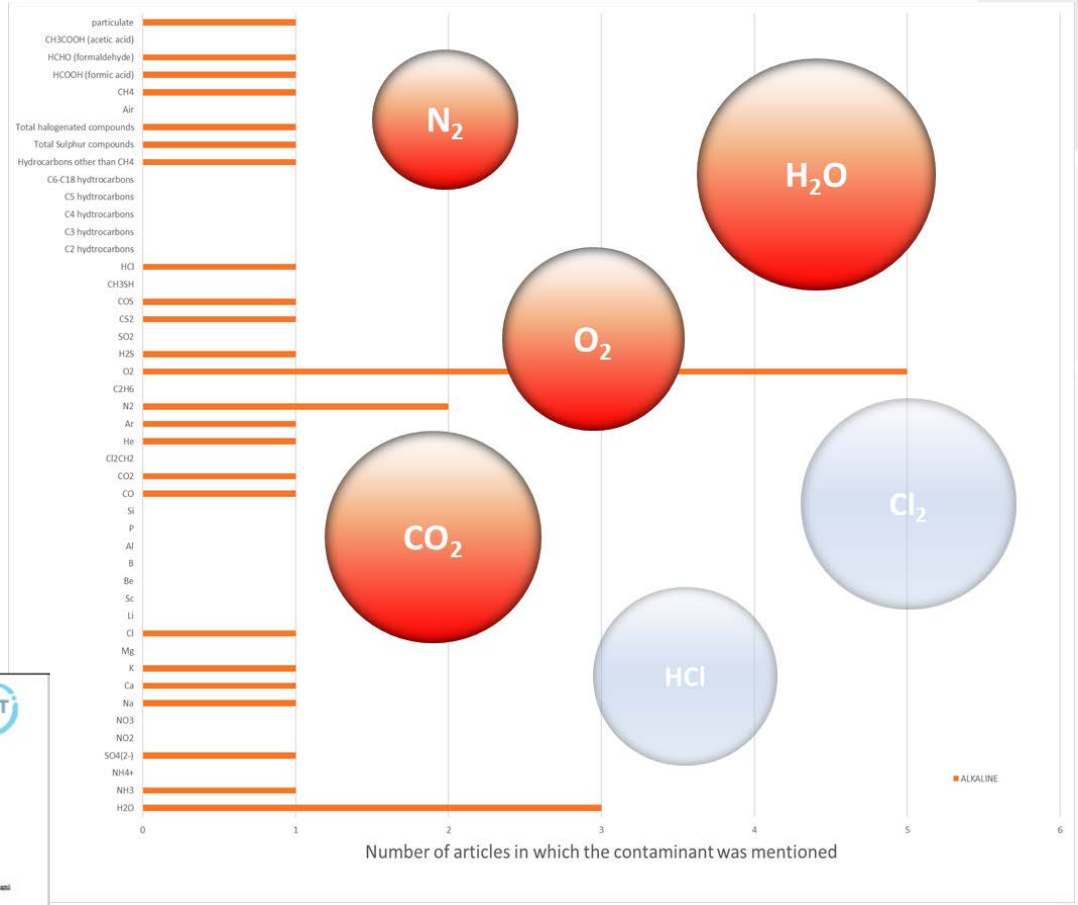
Literature review

Data obtained from the literature review were **not enough to build a real scale for the probability classes of occurence** of different type of contaminants in H_2

Even before considering the possibility of performing an experimental campaign**, it's possible to suggest that the class of events producing considerable amounts of H_2O, O_2, N_2 (non-necessarily over the thresholds) could be very likely,** since the frequency with which they are looked for in the studied articles is significantly higher with respect to the other contaminants.

For **other kind of contaminants** for which a particular interest in the consortium and in the task was expressed **(e.g. HCl, Cl_2) nothing certain can be affirmed without experimental data**. Their absence among the contaminants detected reflects indeed only a lack of articles searching for them and not an effective evidence of detection of no-traces of them.





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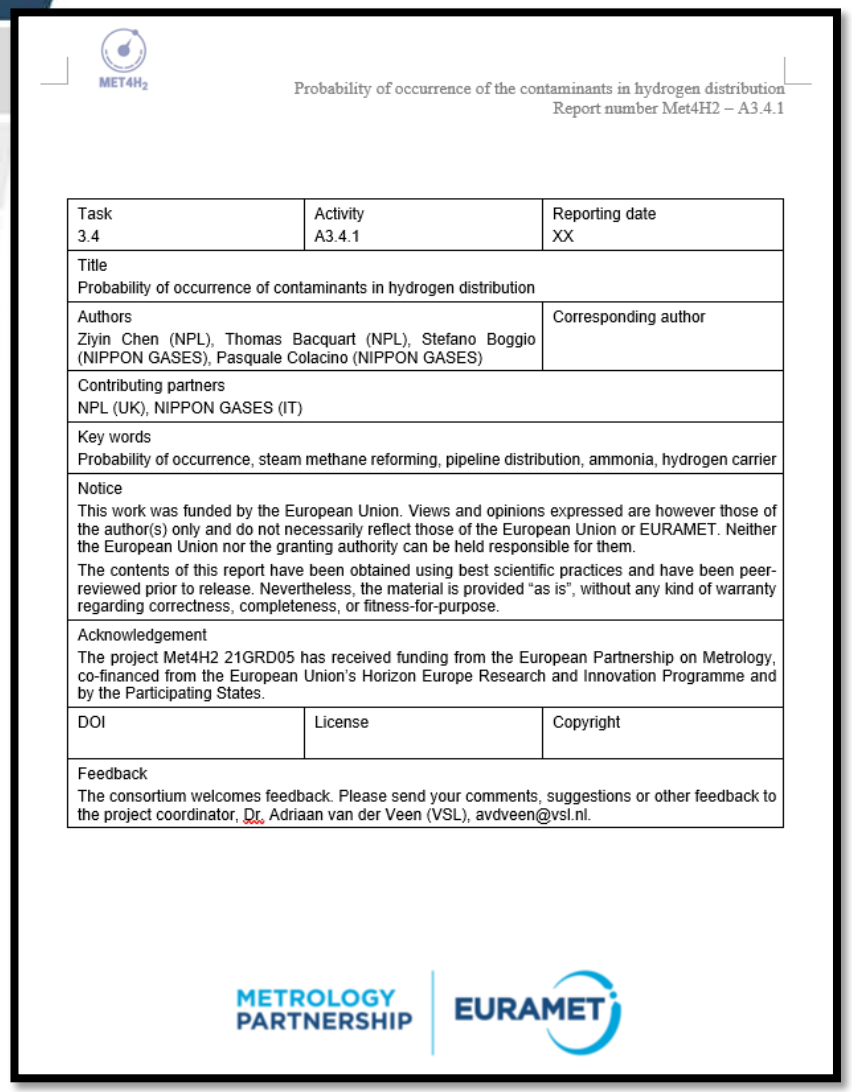
Contaminants occurrence assessment



MET4H2

Probability of occurrence of the contaminants in hydrogen distribution
Report number Met4H2 – A3.4.1

Task	Activity	Reporting date
3.4	A3.4.1	XX

Title
Probability of occurrence of contaminants in hydrogen distribution

Authors
Ziyin Chen (NPL), Thomas Bacquart (NPL), Stefano Boggio (NIPPON GASES), Pasquale Colacino (NIPPON GASES)

Corresponding author

Contributing partners
NPL (UK), NIPPON GASES (IT)

Key words
Probability of occurrence, steam methane reforming, pipeline distribution, ammonia, hydrogen carrier

Notice
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Acknowledgement
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Feedback
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Contaminants	Threshold in ISO 14687:2019 (µmol/mol)	Probability of occurrence of contaminants in SMR	Probability of occurrence of contaminants in pipeline		Probability of occurrence of contaminants in transport hydrogen as ammonia
			Repurposed network	Dedicated hydrogen pipeline	
Inert gas: N2	300	Possible (3)	Frequent (4)	Very rare (1)	Possible (3)
Inert gas: Ar	300	Very unlikely (0)	Very unlikely (0)	Very unlikely (0)	Very unlikely (0)
Oxygen	5	Rare (2)	Rare (2)	Very rare (1)	Very rare (1)
Carbon dioxide	2	Very unlikely (0)	Very unlikely (0)	Very unlikely (0)	Very unlikely (0)
Carbon monoxide	0.2	Rare (2)	Very unlikely (0)	Very unlikely (0)	Very unlikely (0)
Methane	100	Very rare (1)	Very unlikely (0)	Very unlikely (0)	Very unlikely (0)
Water	5	Possible (3)	UD	Rare (2)	Rare (2)
Total Sulphur compounds	0.004	Very unlikely (0)	Frequent (4)	Very unlikely (0)	Very unlikely (0)
Ammonia	0.1	Very unlikely (0)	Very unlikely (0)	Very unlikely (0)	Possible (3)
Total Hydrocarbons (excluding CH4)	2	Rare (2)	Frequent (4)	Very unlikely (0)	Very rare (1)
Formaldehyde	0.2	Very unlikely (0)	Very unlikely (0)	Very unlikely (0)	Very unlikely (0)
Formic acid	0.2	Very unlikely (0)	Very unlikely (0)	Very unlikely (0)	Very unlikely (0)
Halogenated compounds	0.05	Very unlikely (0)	Very rare (1)	Very rare (1)	Very unlikely (0)
Helium	300	Very unlikely (0)	Very unlikely (0)	Very unlikely (0)	Very unlikely (0)

The work "*Monitoring of hydrogen purity in the hydrogen supply chain: metrological approach from contaminants occurrence assessment to online monitoring*" was presented in The World Hydrogen Energy Conference, 2024, Cancun.

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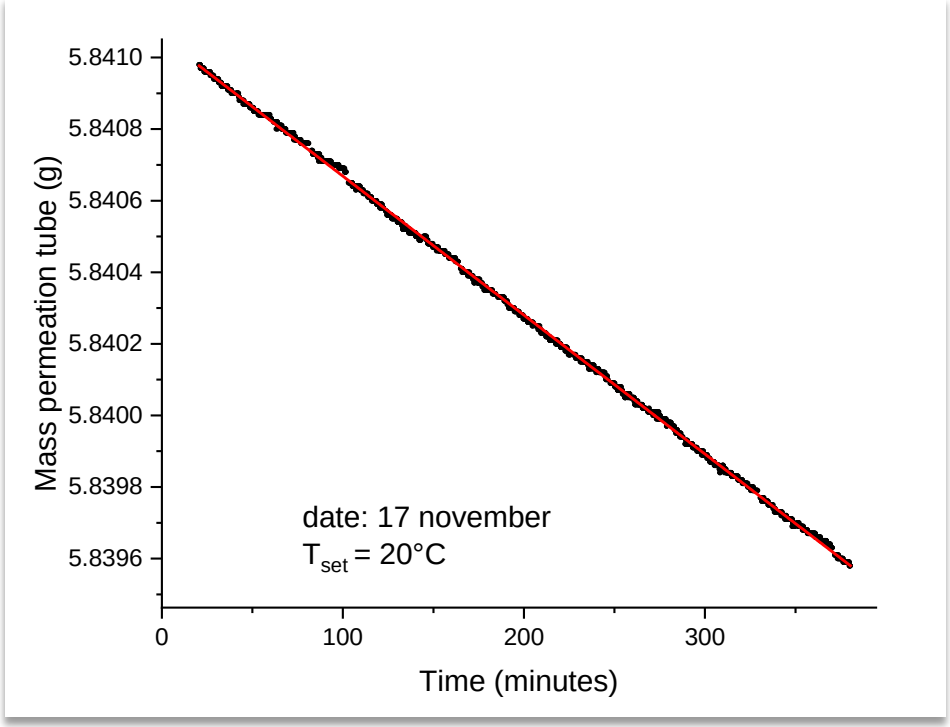
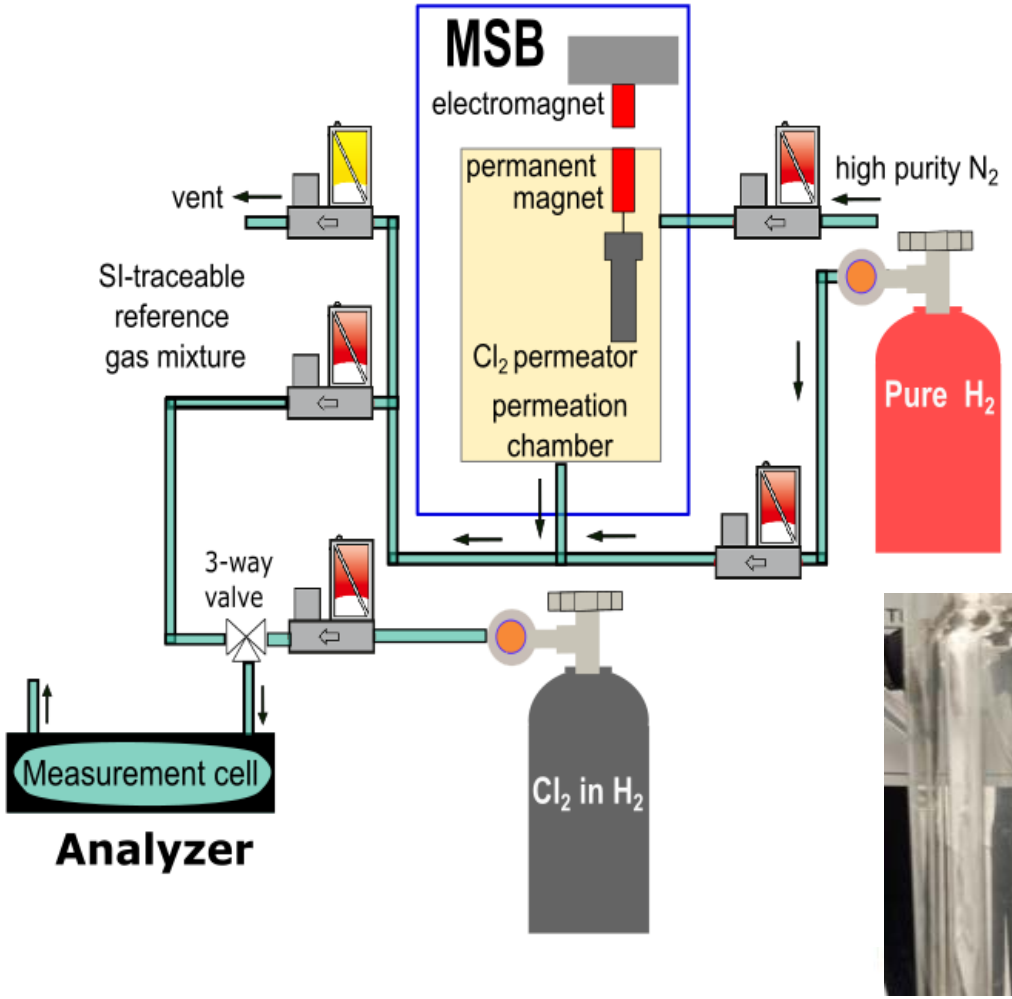
Developing the measurement infrastructure …

Reference gas mixtures: Cl_2 in N_2 or H_2

Cl_2 permeation (permeation rate 3.9-to-7.5 µg/min) used to certify the prepared static standards (static mixtures were –10% compared to permeation).

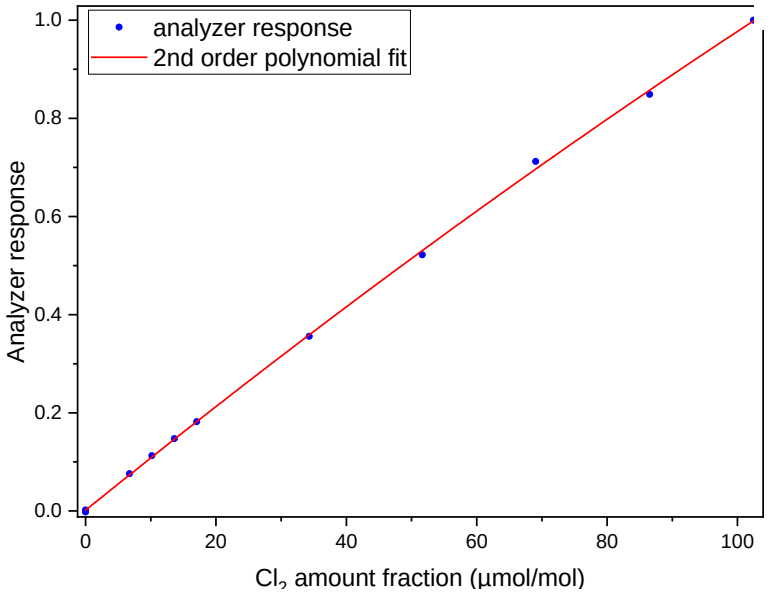


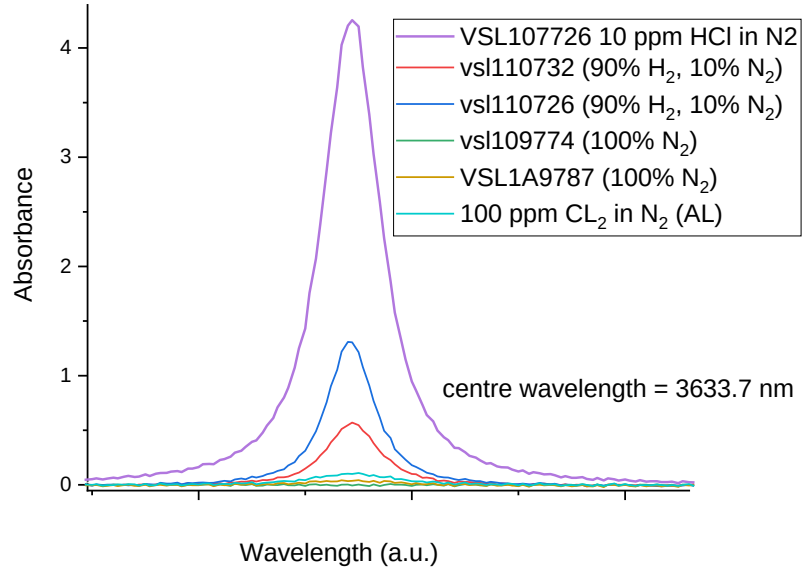


Reference gas mixtures: Cl_2 in N_2 or H_2

- Obtained 104 µmol/mol Cl_2 in N_2 (50 L). Dynamic dilutions were analysed using cavity-enhanced spectroscopy.
- Prepared 2 mixtures of Cl_2 in N_2 and 2 mixtures of Cl_2 in H_2 (10 L cylinders, Aculife IV).
- Stability study completed. N_2 mixtures relatively stable, H_2 mixtures decreasing.
- HCl formed (in particular in the H_2 matrix, up to 5 µmol/mol)

$$H_2 + Cl_2 \rightarrow 2\,HCl$$

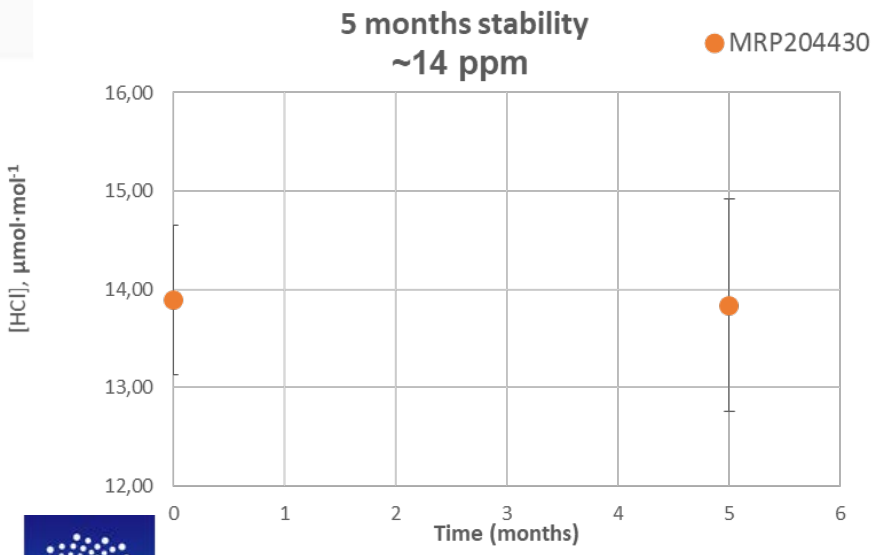


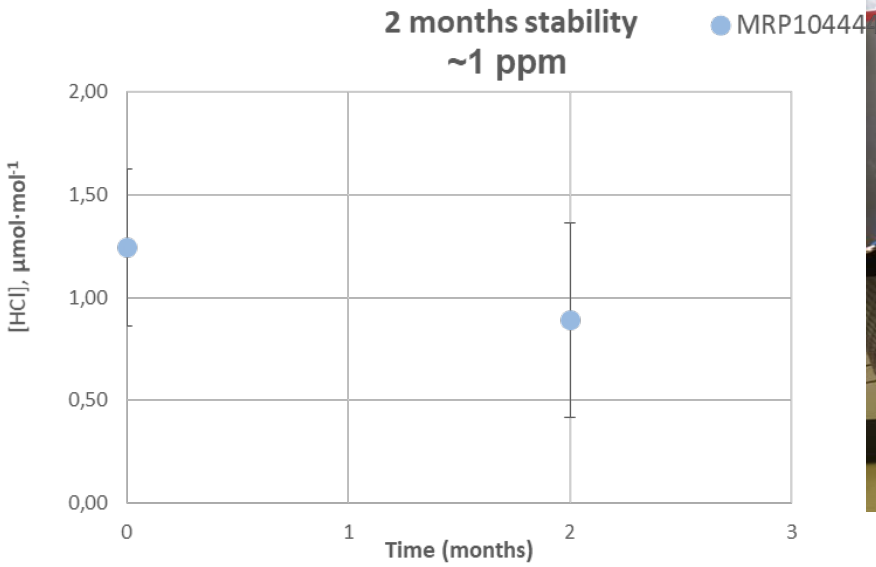


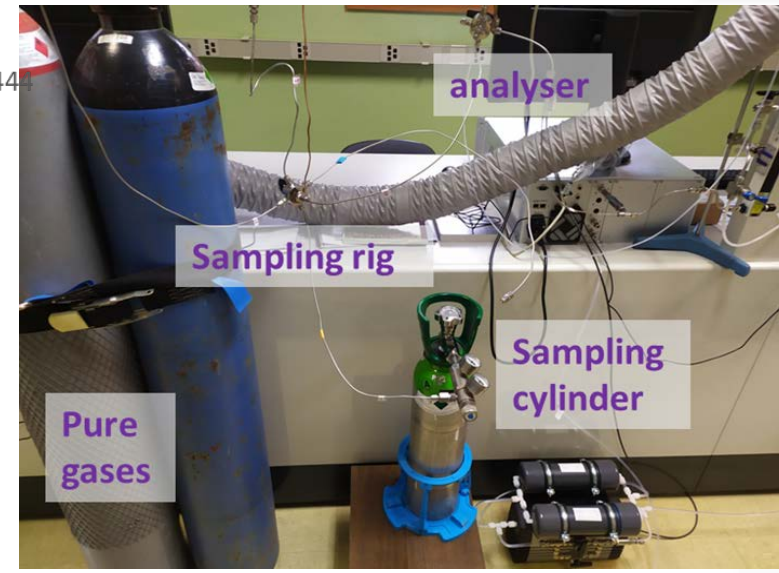
Reference gas mixtures: HCl in H_2

Stability study

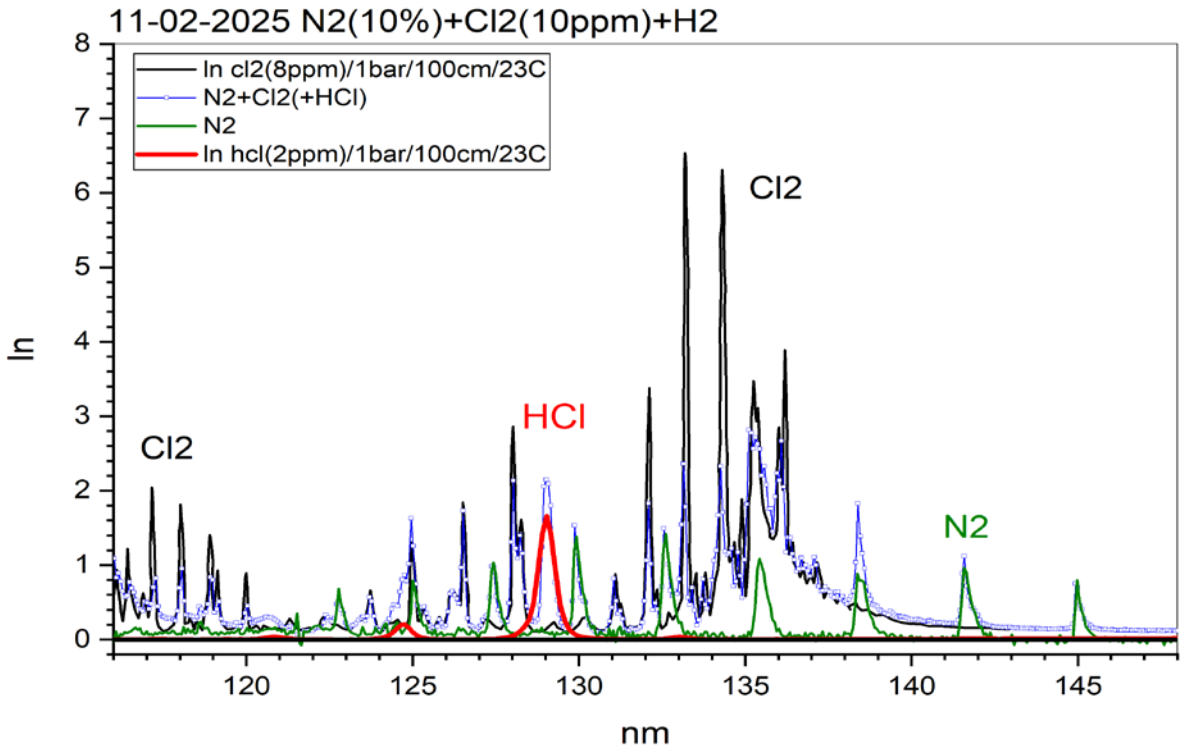
- A key challenge in PRO-CEAS spectroscopic analysis is the **high gas consumption** during measurements which makes it challenging to undertake long-term stability studies.
- 5 L aluminium alloy cylinders with ACULIFE® IV passivation.



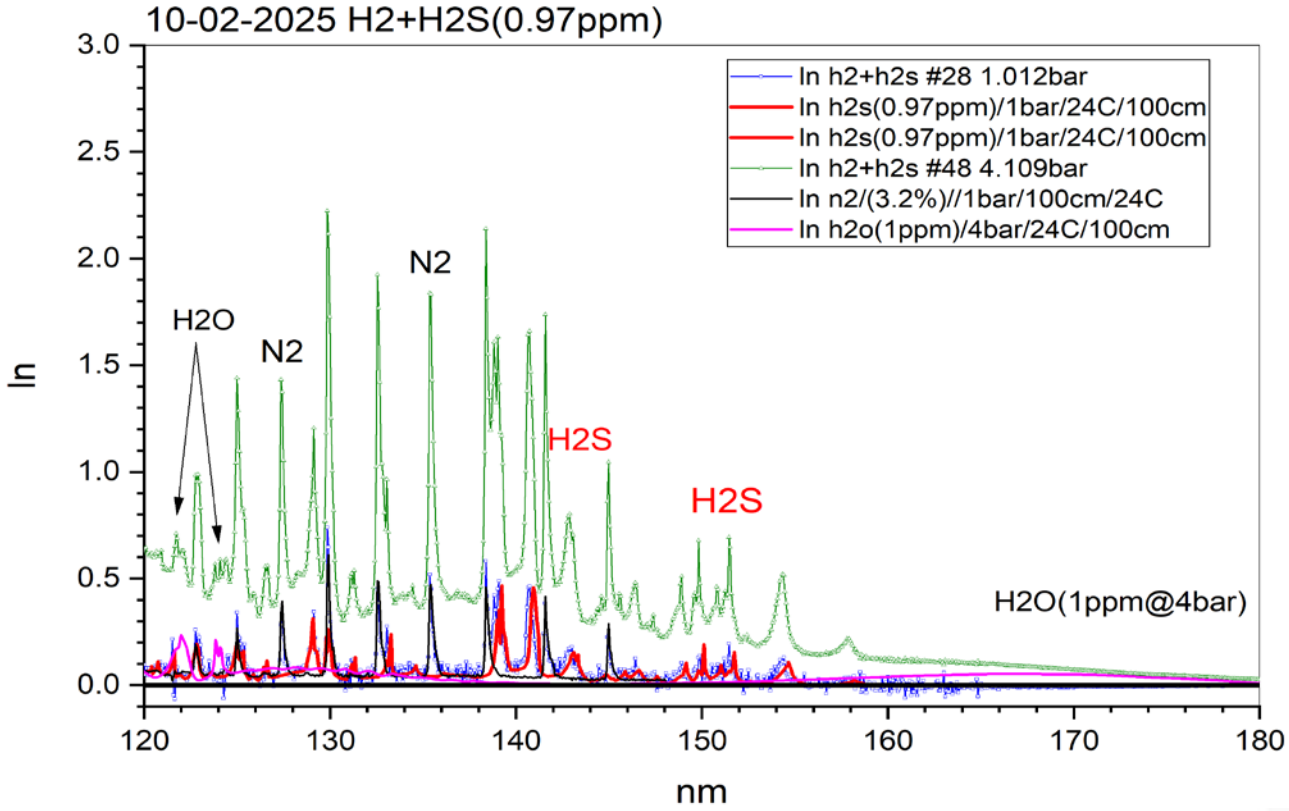




Multicomponent gas analyser (HCl, H_2S, H_2O and CO_2 in H_2)

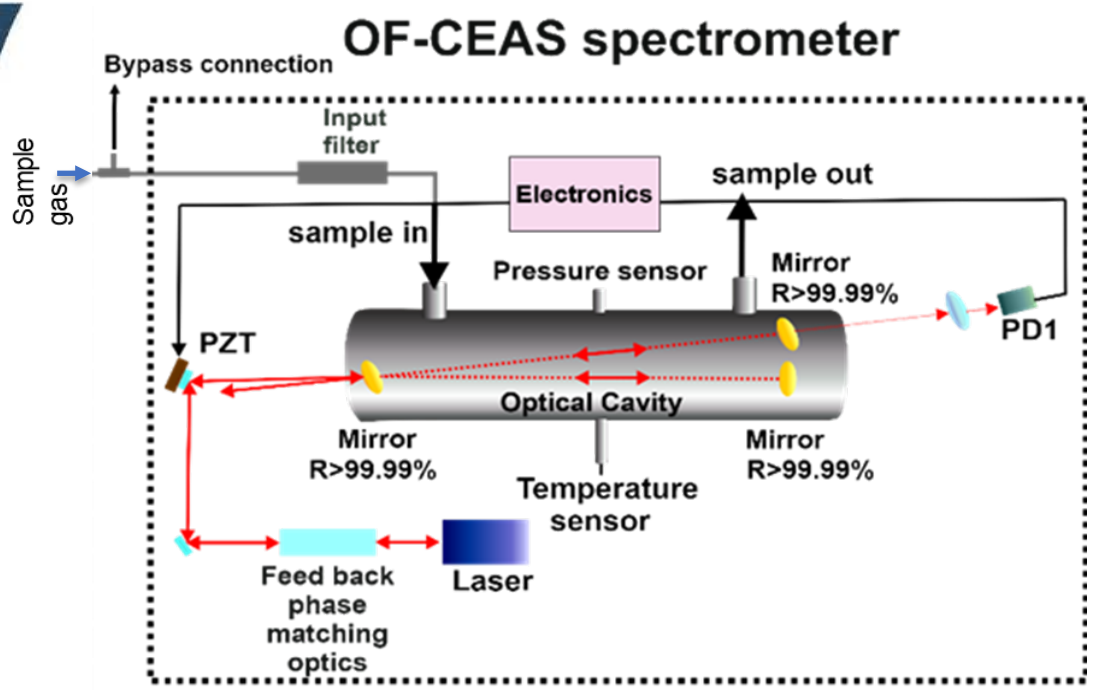


- Exp. data: absorption spectrum in H2+Cl2+N2+HCl: **blue**
- HCl(2ppm) modelled spectrum: **red**
- Cl2(8ppm) modelled spectrum: **black**
- N2 reference: **olive**

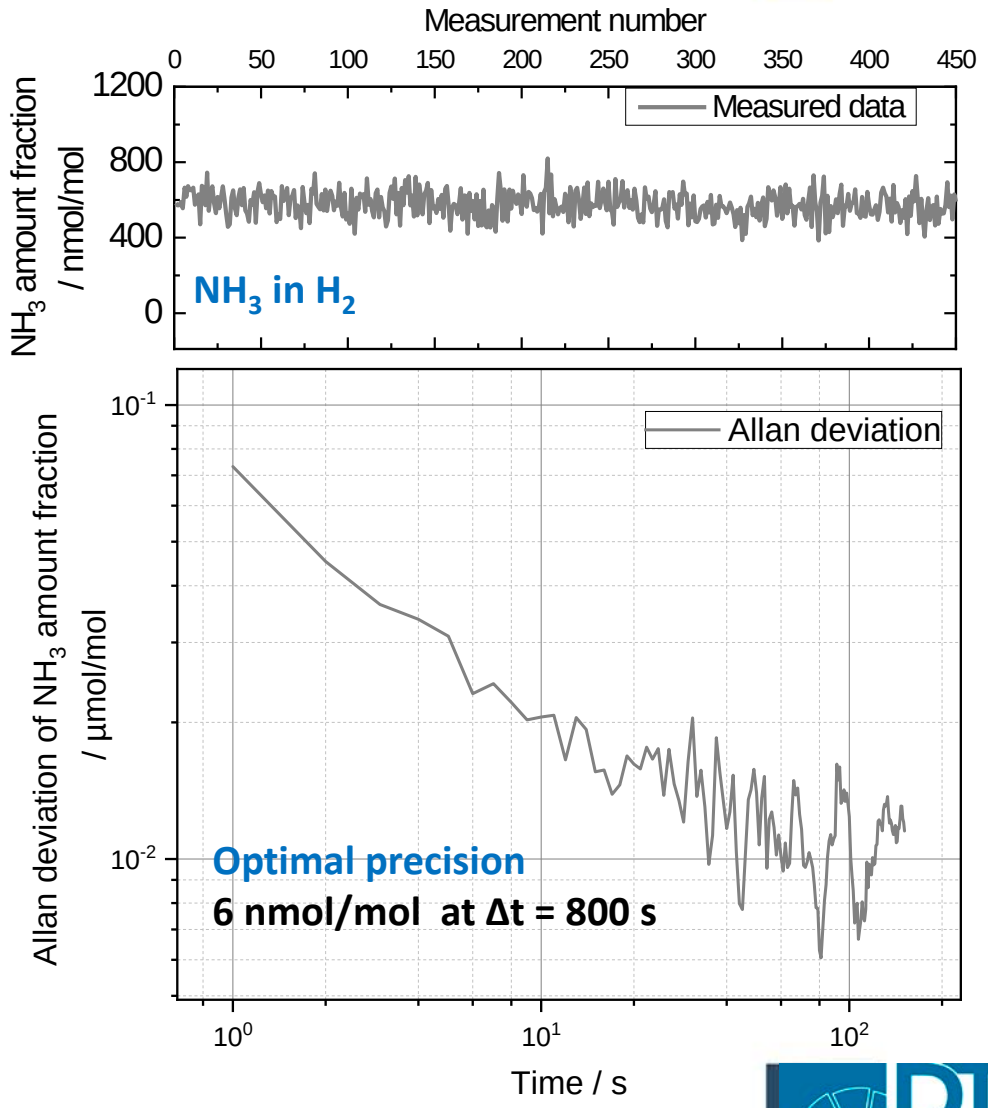


- Exp. data: absorption spectrum in H2+H2S(0.97ppm) at 1 bar: **blue**
- H2S(0.97ppm) modelled spectrum at 1 bar: **red**
- N2(3.2%) modelled spectrum at 1 bar : **black**
- Exp. Data: absorption spectrum in H2+H2S(0.97ppm) at **4 bar**: **olive**

Measurements of NH_3 in H_2



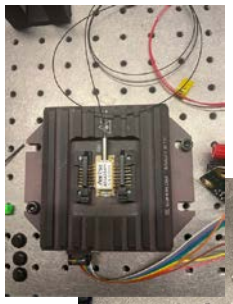
- Spectroscopic method based on Optical-feedback cavity enhanced absorption spectroscopy (OF-CEAS)
- Measurement are performed without prior calibration of the instrument
- Target amount fraction range: **6 - 1000 nmol/mol**
- Combined uncertainty: **5 %**



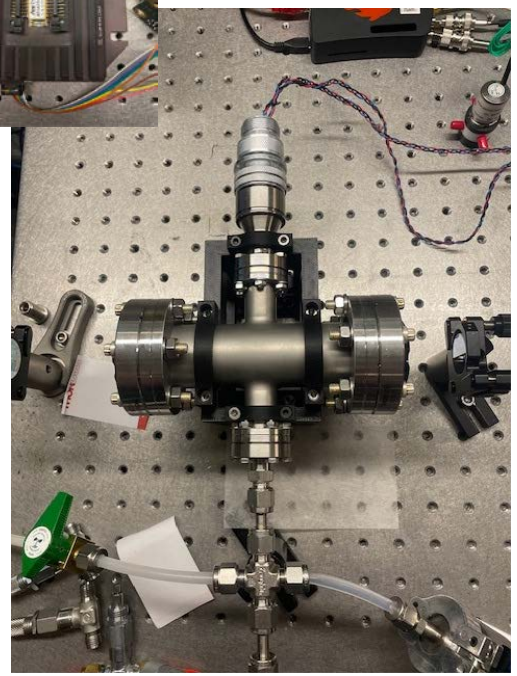
Photoacoustic method development for NH_3

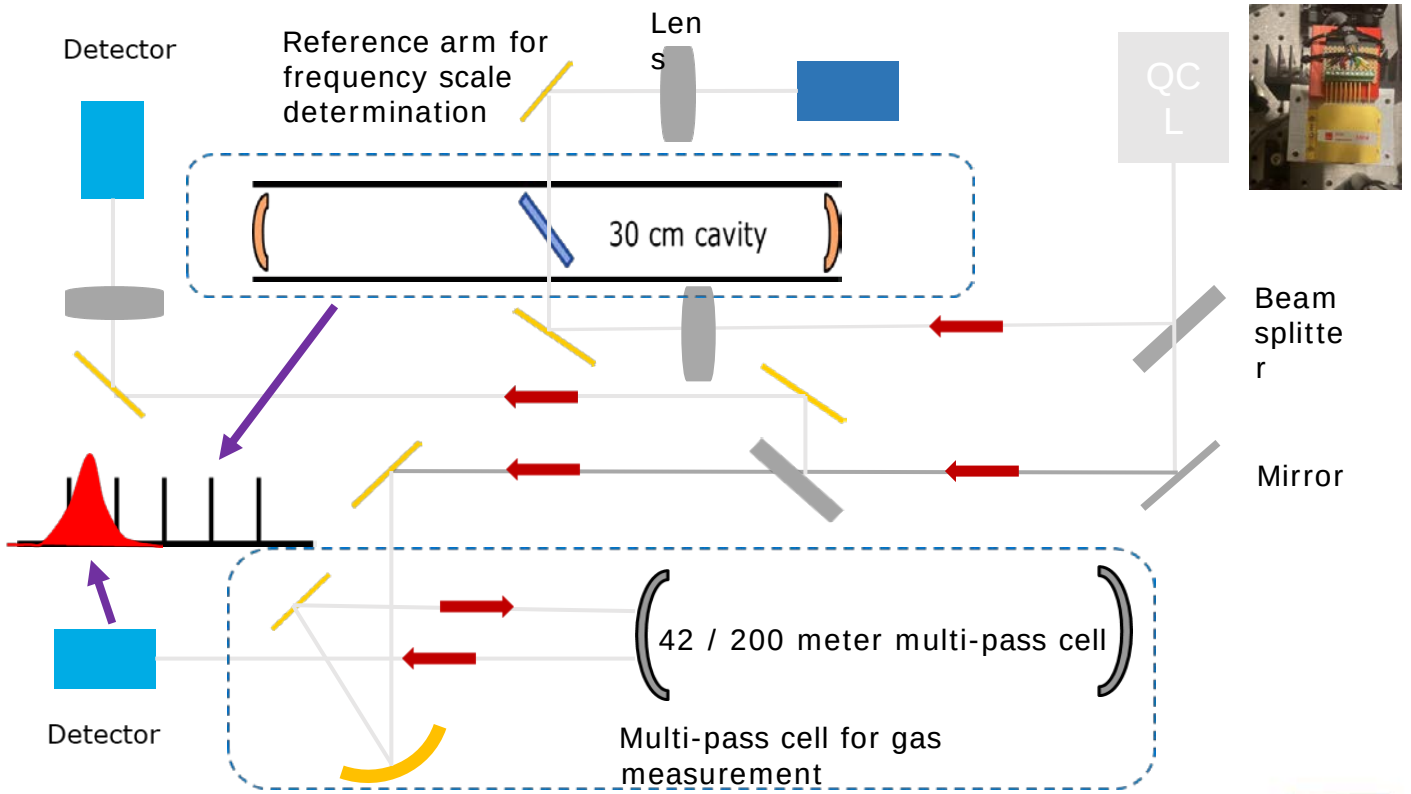
Gas calibration free method.
Accurate knowledge of molecular line strength, temperature, pressure and absorption path length required.

Butterfly
DFB laser



Compact
photoacoustic
cell cell





Providing traceability to water vapour measurements in H_2

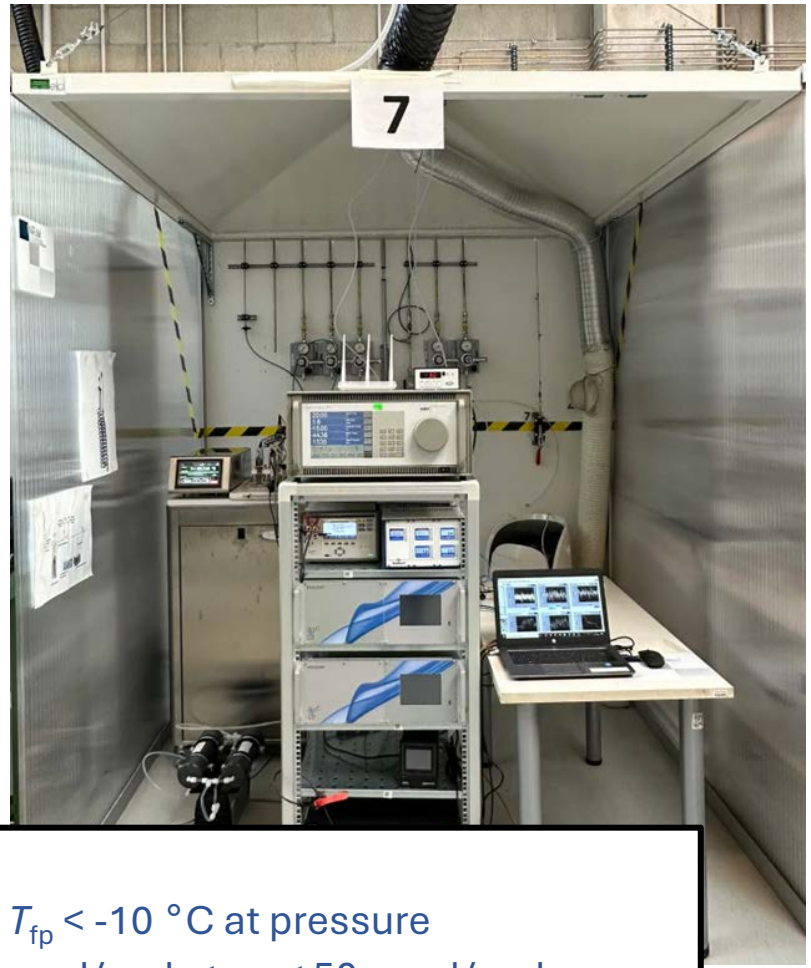
- Transportable precision humidity generator and high-pressure frost-point generator
- Novel methods for water vapour cylinder production
- Inter-laboratory comparison of water vapour realisations
- Demonstrate the equivalence between water vapour gas standards and new and innovative portable standards

INRIM Transportable Precision Humidity Generator for H_2

MET4H2

Design

System in operation



Heat exchanger and saturator

TECHNICAL CHARACTERISTICS:

- Frost point temperature: -55 °C < T_{fp} < -10 °C at pressure
- Water vapor amount fraction: 0.5 µmol/mol < x_w < 50 µmol/mol
- Pressure: 0.1 MPa < P < 5.5 MPa; tested up to 3 MPa
- Target Uncertainty: 3 % < $u_r(x_w)$ < 5 %

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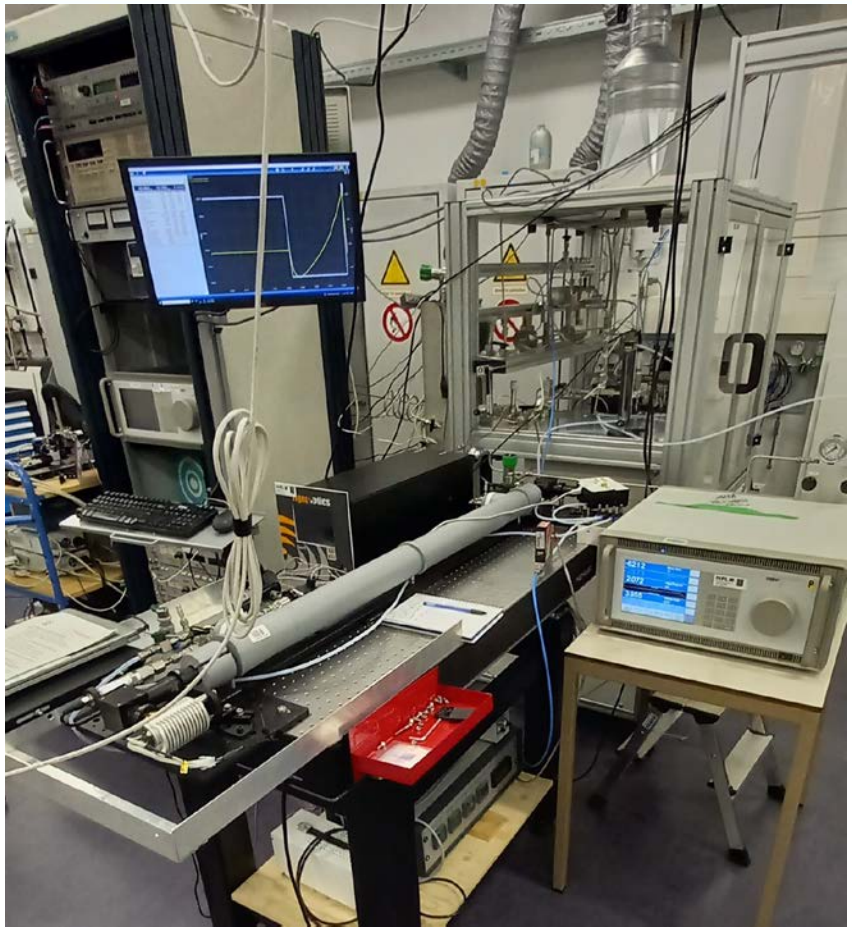
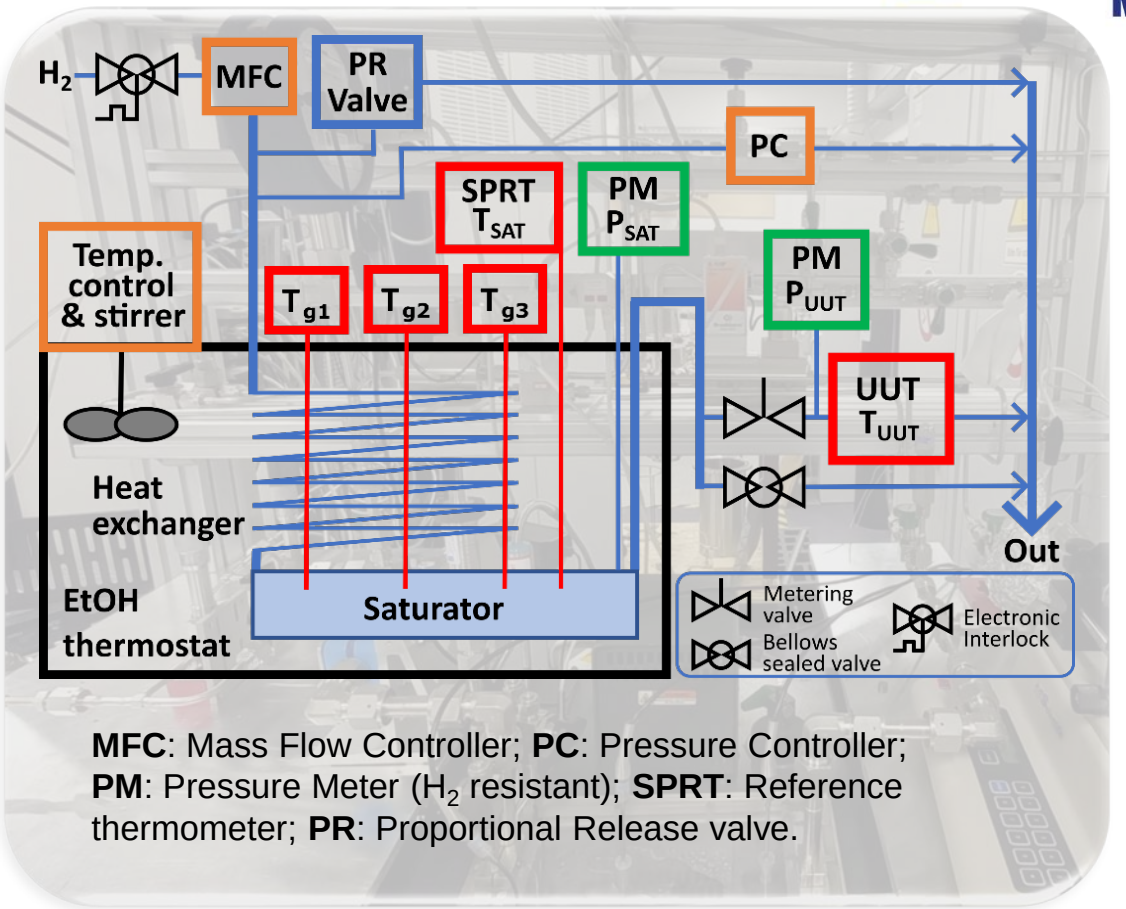
VSL High-Pressure Dewpoint Generator



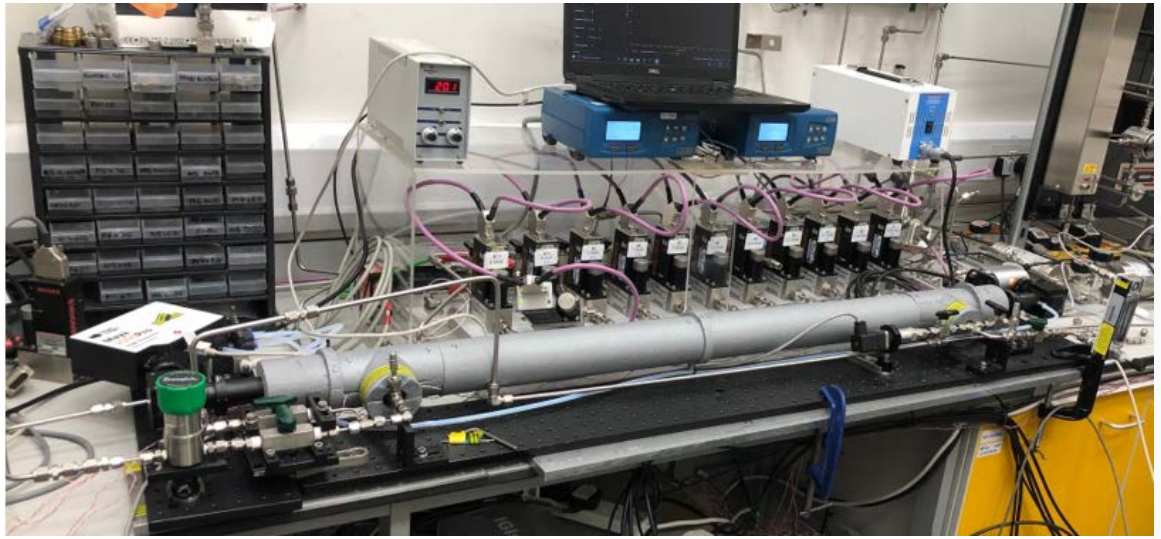


MFC: Mass Flow Controller; **PC**: Pressure Controller; **PM**: Pressure Meter (H_2 resistant); **SPRT**: Reference thermometer; **PR**: Proportional Release valve.

TECHNICAL CHARACTERISTICS:

- Frost point temperature: -80 °C < T_{fp} < +20 °C at pressure
- Water vapor amount fraction: 0.5 µmol/mol < x_w < 100 µmol/mol
- Pressure: 0.1 MPa < P < 6 MPa; tested up to 6 MPa
- Target Uncertainty: 3 % < $u_r(x_w)$ < 5 %

NPL Multi-gas, multi-pressure primary standard humidity generator

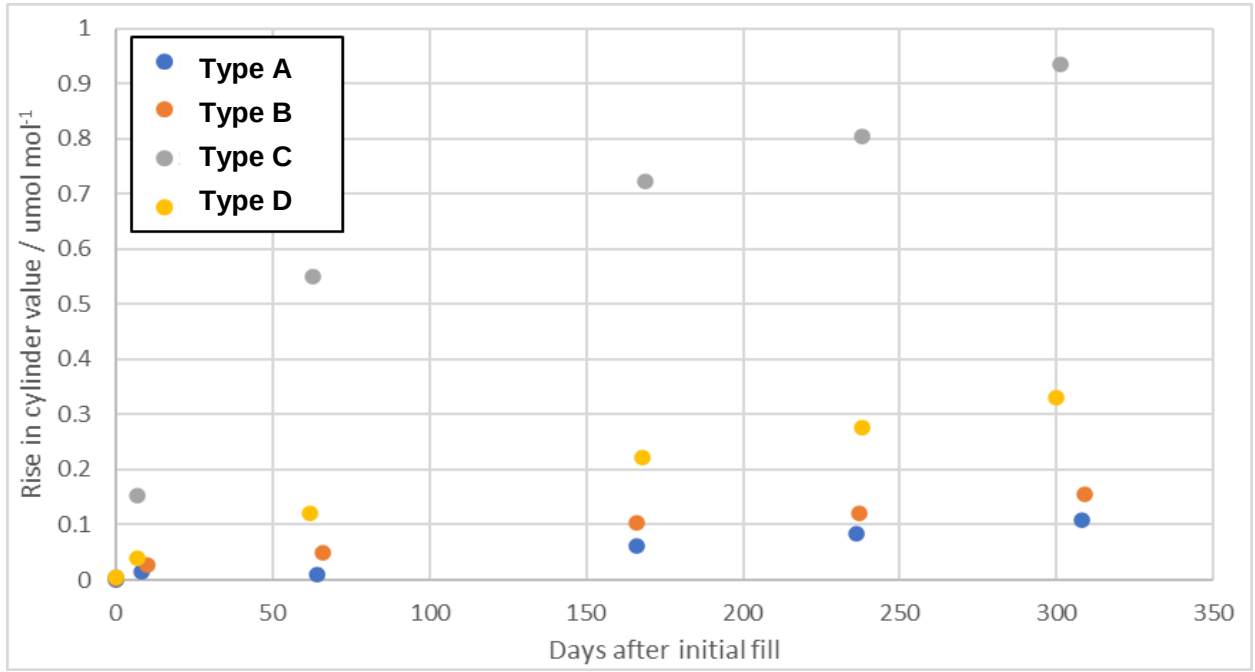


TECHNICAL CHARACTERISTICS:

- Frost point temperature: -60 °C < T_{fp} < +15 °C at pressure
- Water vapor amount fraction: 0.5 µmol/mol < x_w < 0.5 %
- Pressure: 0.1 MPa < P < 3 MPa; tested up to 3 MPa

Novel method of H_2O reference cylinder production

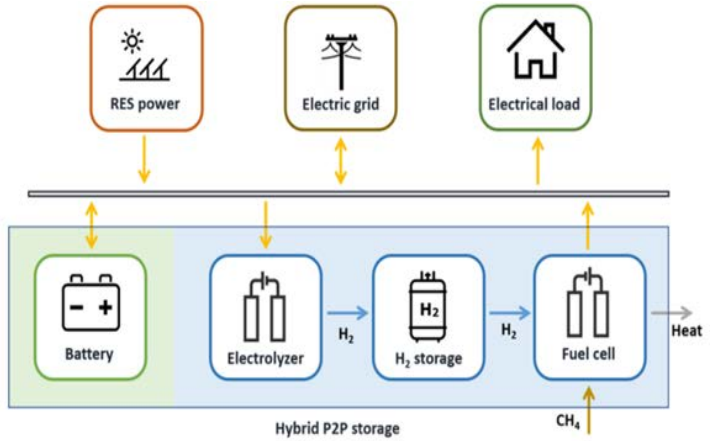
- Novel method transfers NPL Multi-gas, Multi-pressure Primary Standard Humidity Generator traceability to binary H_2O gas mixtures in cylinders.
- NPL evaluated the accuracy and stability of different surface coatings of cylinders over 10 months in project lifetime



Industrial demonstration - round 1

The demonstration was carried out on a 6-kW electrolyser installed at Torino Airport.

Online/onsite monitoring of AEM electrolyser at the Torino Airport



Alkaline Exchange Membrane (AEM) electrolyser was made available by the Airport Authority (SAGAT) who is a project collaborator. The electrolyser is part of a demonstration plant developed within the Horizon 2020 Project TULIPS

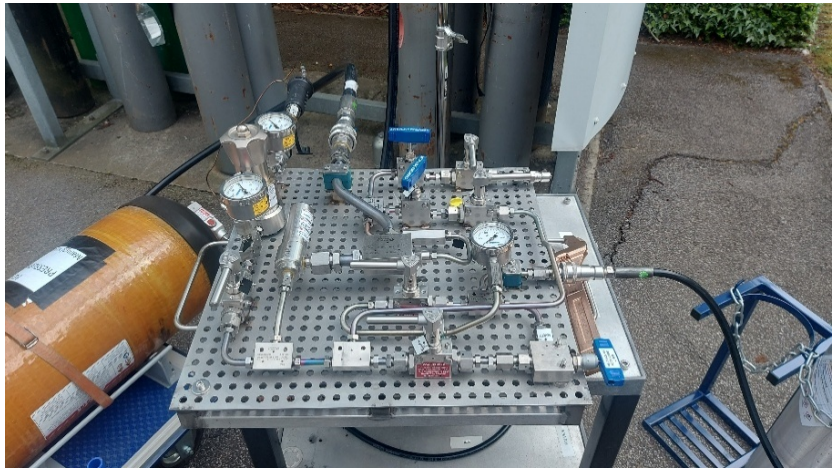
Onsite measurements were carried out at a hydrogen production location at the Torino Airport. The activities performed by INRIM and NPL:

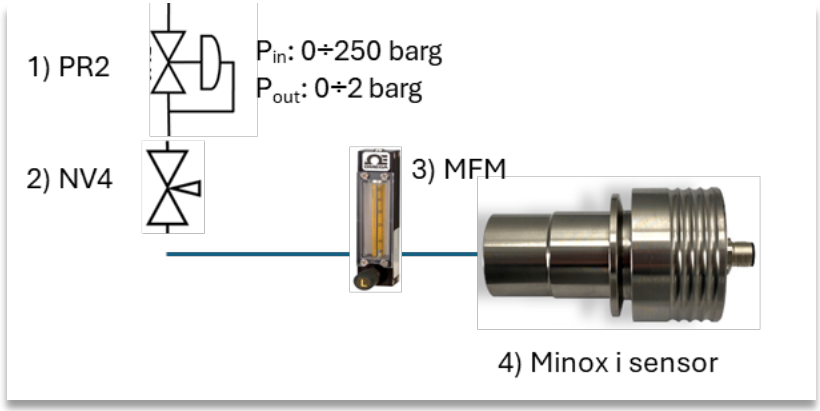
- **Gas sampling**
- **Online measurements** concerning the content of oxygen and water vapour in the hydrogen stream.

ENVIPARK, POLITO, INRIM and NPL identified the best sampling points in the section of tubing just before the mixing skid and receiving hydrogen from either the storage or directly from the electrolyser.

Instruments and sensors selection

- Instruments were selected for the onsite demonstration at Turin Airport:
  - Sampling system (NPL)
  - O2 sensor (NPL)
  - Humidity sensor (INRIM)





Industrial demonstration - round 1

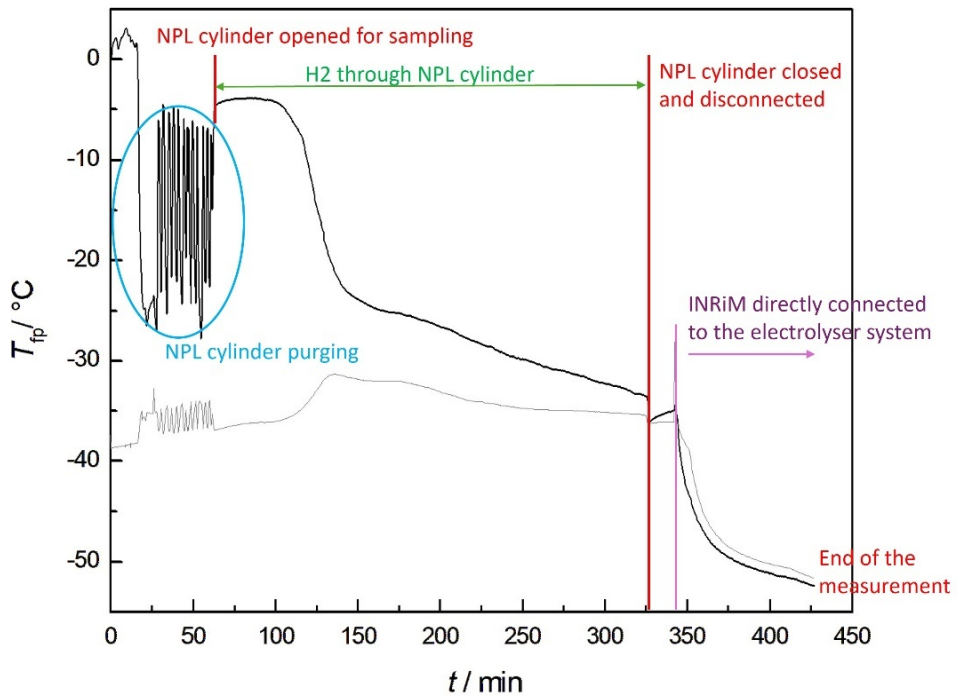
ENAPTER Alkaline Exchange Membrane (AEM) electrolyser

ENAPTER
PSA drier

Industrial demonstration - round 1 results

- Sensor calibration (POLITO, NPL, INRIM)
- Online and onsite monitoring and calibration of an electrolyser(NPL, INRIM, ENVIPARK, POLITO, SAGAT)
- Sampling (NPL)
- Offline measurements (NPL, VSL)

Online measurements (humidity)



. *Michell sensor* *SHAW sensor*

Offline measurements

Compound	Alkaline electrolyser sample 1 (D923897)	Alkaline electrolyser sample 2 (D923893)	ISO 14687:2019 Grade D
	Measured amount fraction and uncertainty (k = 2) [µmol/mol]		Maximum amount fraction [µmol/mol]
Total non-methane hydrocarbons	0.0166 ± 0.0036	0.041 ± 0.007	2
CH_4	<0.005	<0.005	100
CO_2	0.060 ± 0.006	0.0192 ± 0.0025	2
He	<3.5	<3.5	300
H_2O	23.8 ± 1.4	11.5 ± 0.7	5
NH_3	<0.010	<0.010	0.1
HCOOH	0.0212 ± 0.0022	0.0084 ± 0.0019	0.2
HCHO	< 0.010	< 0.010	0.2
Total sulphur compounds	< 0.0010	< 0.0010	0.004
CO	<0.015	<0.015	0.2
N_2	10.42 ± 0.55	2.38 ± 0.23	300
Ar	0.096 ± 0.020	0.049 ± 0.010	300
O_2	11.2 ± 0.7	7.07 ± 0.44	5
Total halogenated compounds	< 0.017	< 0.016	0.05

Industrial demonstration - round 2

The demonstration was carried out at the Nippon Gases plant in San Salvo - Italy

Online and onsite monitoring at a hydrogen production plant

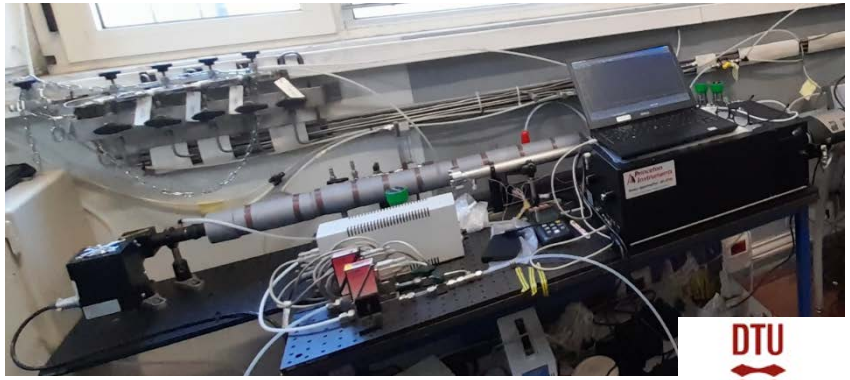
The San Salvo plant produces ultra-high purity hydrogen from natural gas through catalytic reforming and shift conversion. Impurities are removed via a single absorption system, and the hydrogen is purified using PSA before being distributed or stored. Steam is generated by recovering excess heat, and the final product is compressed into mobile containers. Quality is ensured through continuous analysis.

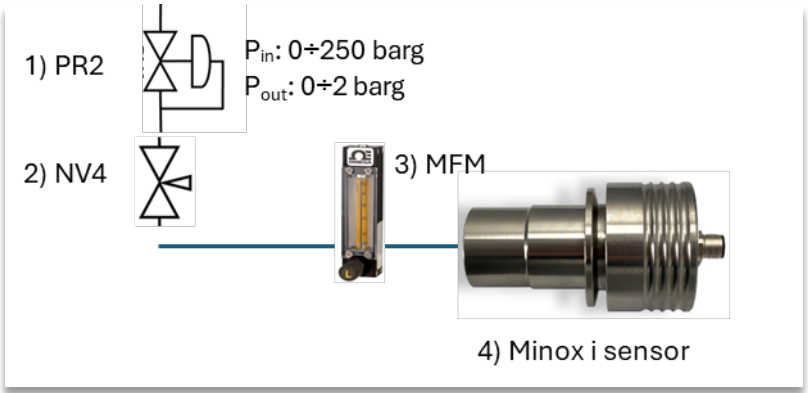
- **Setup Definition**: Connection layout and sampling points were defined.
- **Risk Assessment**: Conducted in relation to plant operations and project activities.
- **System Modifications**: Nippon Gases technicians implemented the required changes.

Instruments and sensors selection

Instruments are selected for the onsite demonstration @ Nippon Gases:

- Sampling system (NPL)
- O2 sensor (NPL)
- Humidity sensor (INRIM)
- Multi-component analyser (DTU)
- Calibration gas (NPL, CEM)





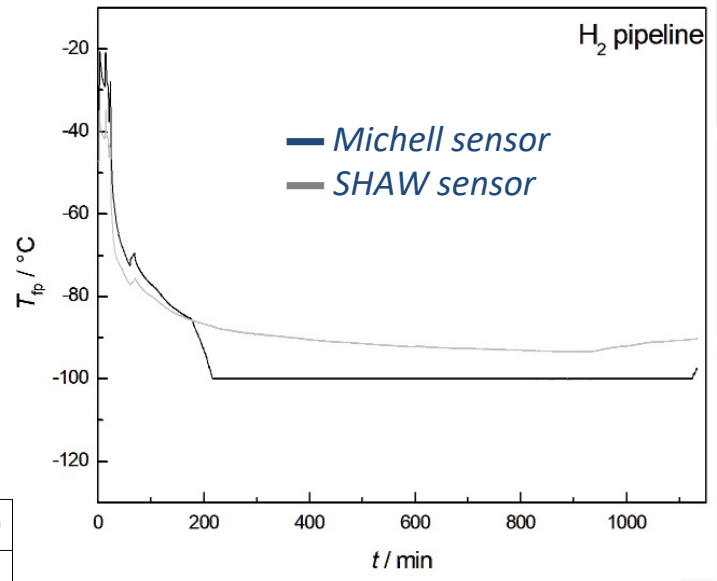
Industrial demonstration - round 2

- Online and onsite monitoring and calibration at SMR and pipeline @ Nippon Gases (Nippon Gases, NPL, INRIM, DTU)
- Sampling (NPL)
- Offline measurements (NPL, BAM, PTB) – samples were analysed in NPL and current with BAM and PTB

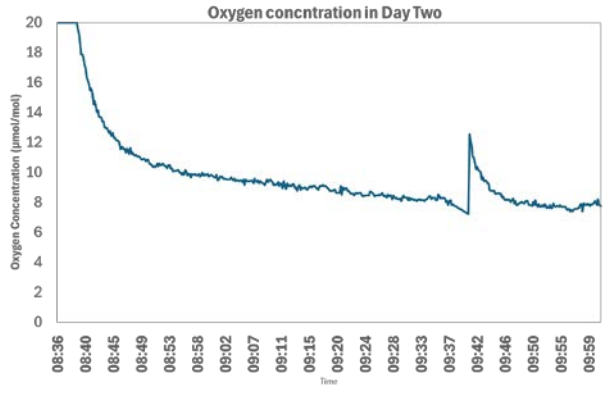
Offline measurement

Compound	Pipeline sample 1 (D923901)	Pipeline sample 2 (D923900)	SMR sample 1 (D819918)	SMR sample 2 (D819919)	ISO 14687:2019 Grade D
	Measured amount fraction and uncertainty (k = 2) [µmol/mol]				Maximum amount fraction [µmol/mol]
Total non methane hydrocarbons	<0.021	<0.021	<0.021	<0.021	2
CH_4	<0.006	<0.006	<0.006	<0.006	100
CO_2	0.0254 ± 0.0027	0.0308 ± 0.0033	<0.008	<0.008	2
CO	<0.009	<0.009	<0.009	<0.009	0.2
He	101 ± 6	96.8 ± 4.9	100 ± 6	100 ± 6	300
H_2O	44.9 ± 2.7	21.7 ± 1.3	13.4 ± 0.8	7.57 ± 0.45	5
NH_3	< 0.005	< 0.005	< 0.005	< 0.005	0.1
HCOOH	0.0084 ± 0.0020	0.0084 ± 0.0021	<0.008	<0.008	0.2
HCHO	< 0.010	< 0.010	< 0.010	< 0.010	0.2
Total sulphur compounds	<0.0007	<0.0007	<0.0007	<0.0007	0.004
N_2	1.63 ± 0.09	3.32 ± 0.18	0.40 ± 0.08	2.20 ± 0.12	300
Ar	0.169 ± 0.017	0.159 ± 0.020	0.163 ± 0.018	0.166 ± 0.017	300
O_2	0.451 ± 0.040	0.181 ± 0.042	0.185 ± 0.042	0.173 ± 0.042	5
Total halogenated compounds	<0.017	<0.018	<0.025	<0.019	0.05

Online measurement (humidity)



Online measurement (Oxygen)



Lessons learnt and recommendations

Reference materials and analytical methods for the determination of impurities in H_2

1. Preparation of gravimetric and dynamic primary reference gas standards
   - Matrix/balance gases must be of the highest available **purity**
   - Inner surfaces of gas cylinders and tubing **treated/coated** to avoid adsorption
   - MFC must be **calibrated** to the respective matrix gases
2. Analysis of impurities
   - For sulphur analysis, **SCD detector** is recommended
   - GC carrier gas and dilution gas for the preparation of standards must be **checked in advance** for possible interferences

Sampling procedure and online hydrogen quality monitoring

3. Sampling procedure
   - Carefully **plan the sampling operation**, including location for sampling system, hydrogen venting and staff training
   - Sampling kit and its procedure should be **validated** (e.g. leaks), documented and properly applied
   - **Purging** and the effect of insufficient purging should be considered
4. Humidity measurements
   - Minimise the length of the **sampling line** to sensors/analysers and carefully check for leaks.
   - **Wait enough** time for the humidity sensors to reach a consistent, reading (e.g., several hours for sub-ppm water vapour measurement).
   - Install humidity sensors on **independent sampling lines.**

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Inputs to ISO19880-8 and ISO 21087

Recommendations to ISO 19880-8

- Water and oxygen are impurities potentially over the threshold when hydrogen is produced by alkaline electrolysis. Installation of online devices to monitor H2O and O2 in hydrogen gas sourced from alkaline electrolysers is suggested to HRS
- Validation of the performance of sensors/analysers prior to their deployment on site
- Make scheduled calibrations for sensors and online analysers against known standards, especially before critical measurements or any process changes.

Recommendations to ISO 21087

- Carefully identify the purging requirement of the sampling device
- Identify methods to check for sufficient purging to remove moisture and air out of the sampling kit and cylinder, to ensure consistent measurement and operational safety.

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MET4H2

Best practices in the evaluation of the measurement uncertainty of quantities relevant to fiscal measurements along the hydrogen supply chain

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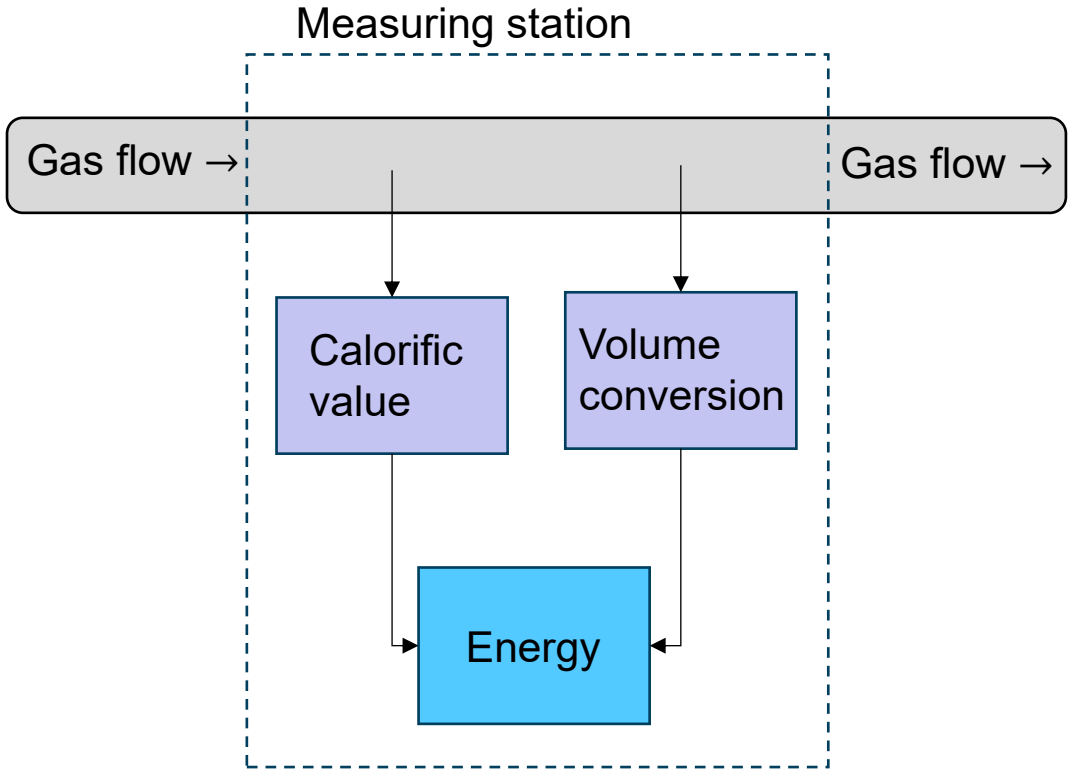
UNIVERSITY OF LJUBLJANA | FS Faculty of Mechanical Engineering

Can we keep using the current gas infrastructure once H2 joins the game?

A measuring station for fiscal metering often consists of

- Flow meter measuring the volume flow rate of the gas
- Gas chromatograph (GC) measuring the gas composition



The energy is then computed as

$$E = V \cdot H$$

V is the normal volume

H is the calorific value

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How to calculate the uncertainty is also part of the infrastructure!

Standards for the energy determination (ISO 15112, OIML R140) assume independence of measurement results

$$E_{tot} = \sum E_t = \sum V_t H_t$$

$$u^2\,(E_{\mathrm{tot}}) = \sum u^2\,(E_t) = \sum E_i^2 (u_{\mathrm{rel}}^2(V_t) + u_{\mathrm{rel}}^2(H_t))$$

This assumption might lead to costly errors once hydrogen is introduced in the gas grid

Improvements investigated in Met4H2:

1. Correlations due to the instrumentation
2. Temporal correlations in subsequent measurements due to the continuous underlying process
3. Error introduced by the numerical approximation

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Improvements developed in the project

1. **Correlations due to the instrumentation**
2. Temporal correlations in subsequent measurements
3. Error introduced by the numerical approximation

1. Instrumental uncertainty induce correlations

Instruments at a metering station (e.g., flow meter, pressure sensor, etc …) take tons of data every day

These data are all equally affected by, e.g., calibration uncertainty, installation effects, and repeatability

Therefore, the measurement results are mutually correlated, and these uncertainty sources should be included in the covariance

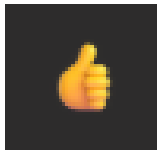
Correlation coefficients are generally large (0.7 or greater)

1. Furthermore, the same measurement result can be used to compute multiple quantities

$$V_0 = V(p,T)\frac{pT_0Z_0}{p_0TZ} = V(p,T)\cdot K$$

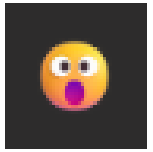
V (V_0) is the volume at actual (standard reference) conditions

p (p_0) is the pressure at actual (standard reference) conditions



T (T_0) is the temperature at actual (standard reference) conditions

Z (Z_0) is the compressibility factor at actual (standard reference) conditions



1. The compressibility factor at actual and at reference conditions are calculated assuming the same composition

The measured gas composition cause correlation between the two compressibility factors

The uncertainty in the gas composition should be propagated forward keeping in mind that the composition is subject to a natural constraint

Z is calculated using an appropriate equation of state (e.g., GERG-2008)

Z_0 is calculated using ISO 6976

1. The uncertainty associated with the composition to Z can be calculated numerically

Assume the following gas composition

Component	x cmol mol^{-1}	$u(x)$ cmol mol^{-1}
Nitrogen	3,280	0,022
Carbon dioxide	2,421	0,019
Methane	84,335	0,111
Ethane	6,587	0,044
Propane	3,378	0,110

Construct a matrix such that for each column $j = 1, \ldots, N-1$ the first j elements are

$$Q = \begin{bmatrix} -0{,}70711 & -0{,}40825 & -0{,}28868 & -0{,}22361 \\ 0{,}70711 & -0{,}40825 & -0{,}28868 & -0{,}22361 \\ 0 & 0{,}81650 & -0{,}28868 & -0{,}22361 \\ 0 & 0 & 0{,}86603 & -0{,}22361 \\ 0 & 0 & 0 & 0{,}89443 \end{bmatrix}$$

$$\frac{\quad j \quad}{\sqrt{j(j+1)}}$$

and the other elements are zero

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1. The uncertainty associated with the composition to Z can be calculated numerically

$$b_j = \frac{f\left(\boldsymbol{x}_0 + h\boldsymbol{q}_j\right) - f\left(\boldsymbol{x}_0\right)}{h} \qquad j = 1, \ldots, N-1$$

where

- f is a validated implementation of the equation of state (e.g., TREND)
- $\boldsymbol{x}_0$ is the measured composition
- $\boldsymbol{q}_j$ is the *j*-th column from the previously generated matrix
- h is set equal to 1 % of the smallest amount fraction

The sensitivity coefficients are given by

$$\boldsymbol{c}^{\boldsymbol{T}} = \boldsymbol{b}\boldsymbol{Q}^{\boldsymbol{T}}$$

1. Including the correlations leads to an increase of about 30 % in the uncertainty of the conversion factor K

The correlation coefficient between Z and Z_0 is 0,011 for this composition

The compressibility factor is correlated also with temperature and pressure (this can be calculated with the standard numerical approach of the GUM)

Combining the relative uncertainties with the covariances lead to $u_{rel}(K) = 0{,}13\ \%$ which is 30 % larger than the case without covariances

Note. In case of energy calculations, the compressibility factor is correlated also with the calorific value!

Improvements developed in the project

1. Correlations due to the instrumentation

2. **Temporal correlations in subsequent measurements**

3. Error introduced by the numerical approximation

2. We developed a procedure to evaluate dependencies in time series using auto-regressive moving average (ARMA) models

Phenomena such as the injection or withdrawal of gas may cause dependencies between subsequent measurements of the same quantity

Such dependencies should be analysed by means of a suitable time series model (e.g., ARMA models, wavelets, …)

ARMA models are suitable to describe statistically stationary time series and assume that the error terms of the model behave like white noise

These *autocorrelations* are different from the instrumental correlations!

2. Time series analysis: some useful statistical tools

AR: autoregressive; expresses the current value as a linear combination of a finite number of past values of the same variable

MA: moving average; describes the dependence of the current value on the current and past values of another variable

ARMA: autoregressive moving average

ACF: autocorrelation function; measures the correlation between observations at different distances apart

PACF: partial ACF; computes the correlation between two variables with the linear effect on a third variable removed

(Statistically) weakly stationary series: i) finite variance process with constant mean; ii) the auto-covariance depends only on the distance between two data points

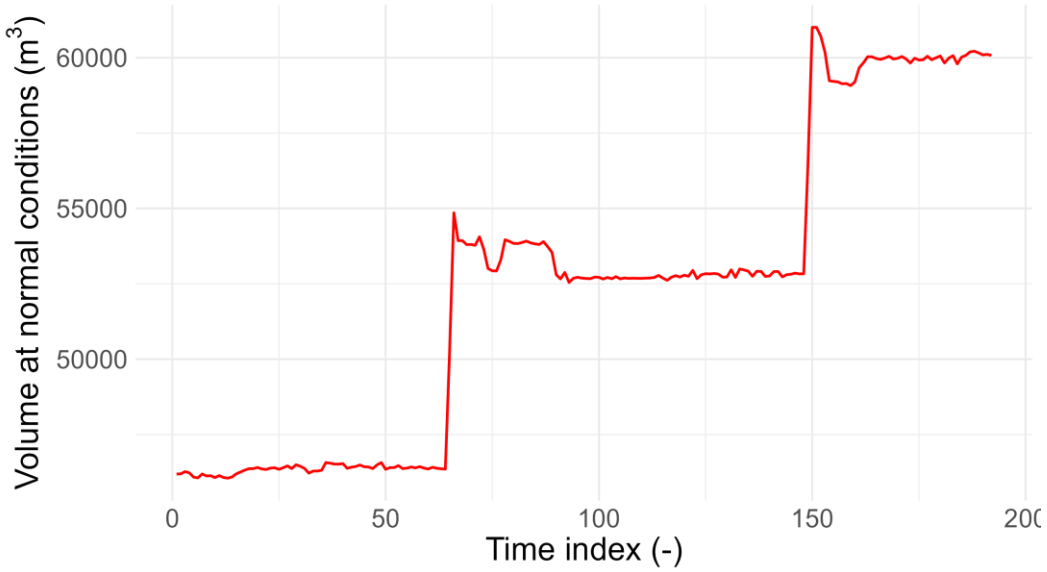
2. Before using a time series model, you should check the properties of your data

1. Look for missing data or for anomalous values

2. Plot the empirical probability distribution function

3. Are the data normally distributed? → Shapiro test

4. Is the time series stationary? → Augmented Dickey Fuller test



Example of recorded volume data.

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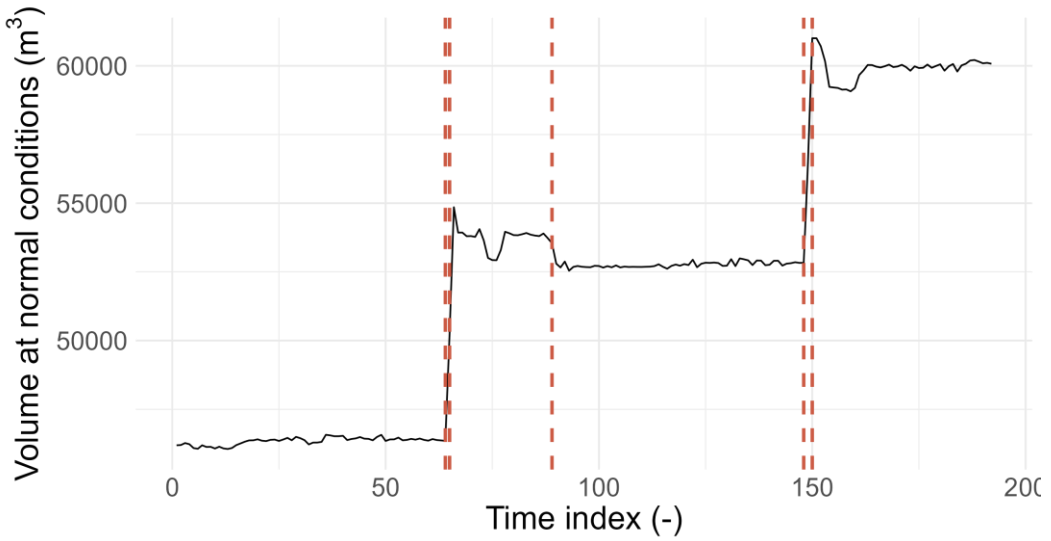
2. If your data do not meet the requirements, you might want to restrict your analysis to a sub-series

Change point methods:

- BinSeg (binary segmentation)
  - Approximate method
  - Indicated to detect significant jumps
- PELT (Pruned Exact Linear Time)
  - Exact method
  - Detects also more subtle changes



Example of segmentation results using BinSeg.

You should still check the properties of the selected subseries before proceeding with the analysis!

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2. Remember the physics behind your data when selecting a mathematical representation of your data

Tools to select an ARMA model:

1. ACF and PACF
2. Prop
   proc
3. Selection criteria such as Akaike's Information Criterion or Bayesian Information Criterion

Beware! Fitting a model does not imply that your model is a good representation of your data!

Example of stationary subseries of the calorific value data, its ACF and PACF. In this case, an AR(2) model is the best candidate.

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2. The evaluation of uncertainty using time series analysis does **not** include the instrumental measurement uncertainty

The law of propagation of uncertainty (LPU) for correlated input quantities

$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u(x_i, x_j)$$

$$E_{tot} = \sum_{t=1}^{N} E_t = \sum_{t=1}^{N} V_t H_t$$

Serial correlations influence only the uncertainty obtained by the statistical data analysis

Correlations due to, e.g., instrumentation are treated separately (see 1.)

2. The serial correlation increases the estimated type A uncertainty by circa 50 %

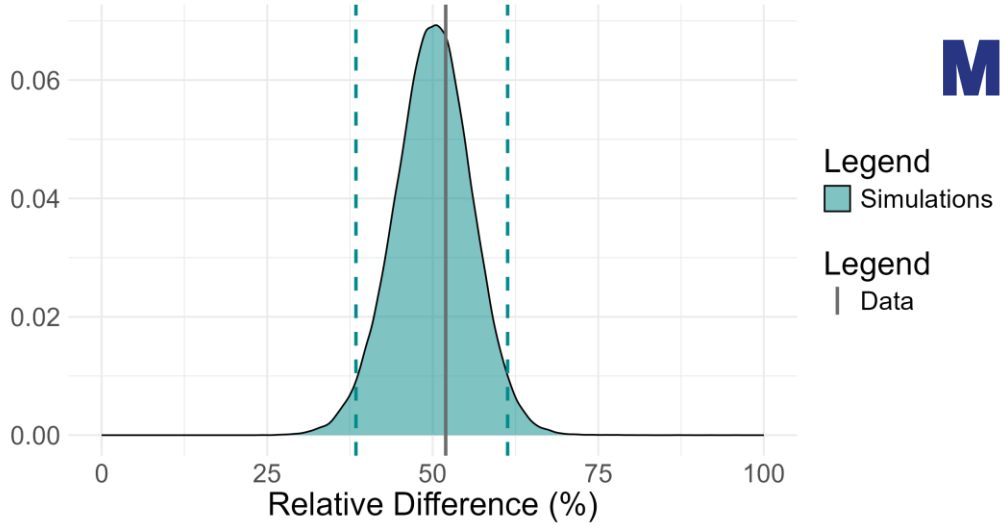
Relative difference calculated on simulated data

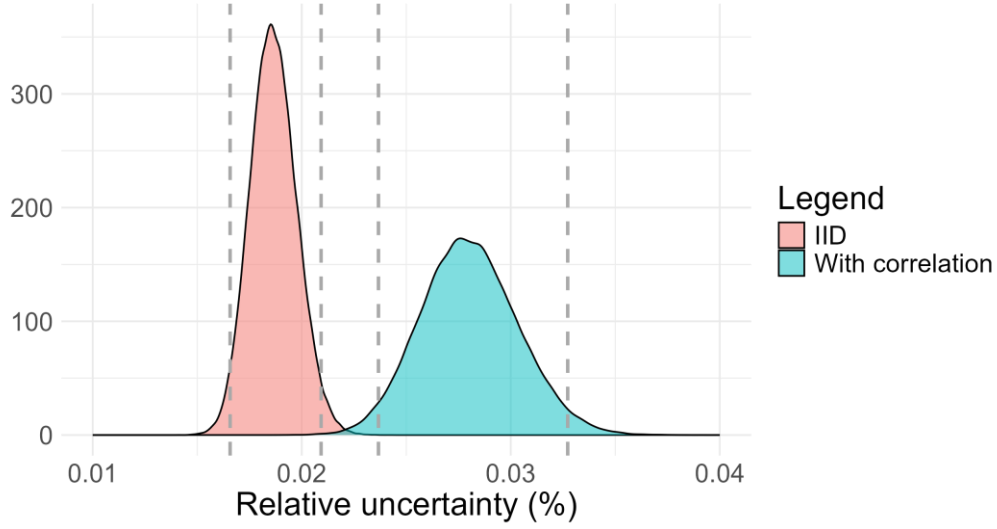
$$\frac{u_{\mathrm{cor}}(E_{\mathrm{tot}}) - u_{\mathrm{iid}}(E_{\mathrm{tot}})}{u_{\mathrm{iid}}(E_{\mathrm{tot}})} \cdot 100\%$$

Relative uncertainty $x \in \{cor, iid\}$

$$u_{x,\mathrm{rel}}(E_{\mathrm{tot}}) = \frac{u_x(E_{\mathrm{tot}})}{E_{\mathrm{tot}}} \cdot 100\%$$

Including the serial correlation increases the uncertainty typically by 50 %





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Improvements developed in the project

1. Correlations due to the instrumentation

2. Temporal correlations in subsequent measurements

3. **Error introduced by the numerical approximation**

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3. We developed a method to determine the numerical approximation error by separating the signal's components

The uncertainty of aggregated quantities (e.g., average, total) depends both on the numerical procedure and on the observed quantities over time

Usually observed quantities have both a deterministic and a random component that change simultaneously

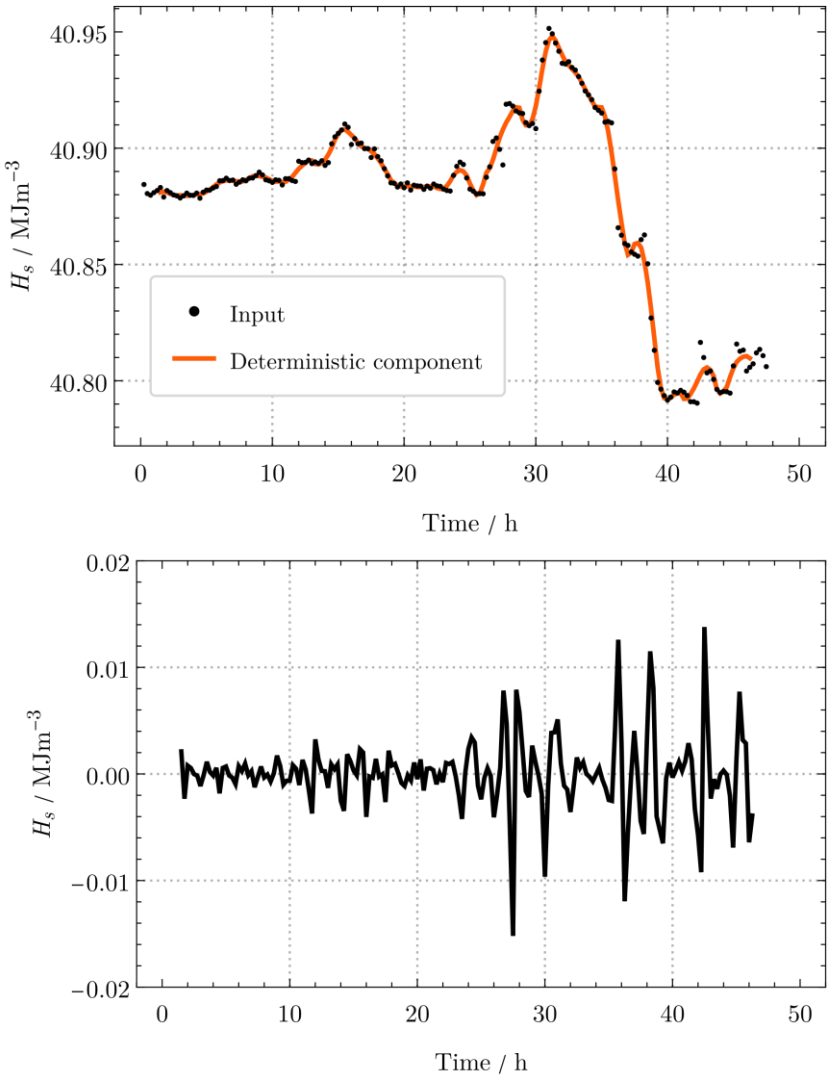
Time domain filtering techniques can be used to separate these components, since they generally act on different time scales

3. Separation of the deterministic and random components

Savitzky-Golay filtering: moving average method based on least squares polynomial fitting

Parameters:

- Order of the smoothing polynomial
  - Try to avoid over- and under-fitting
- Number of samples in the smoothing window



Example of signal separation into deterministic and random components.

3. The uncertainty related to the numerical integration of the deterministic signal is estimated using the decimation method

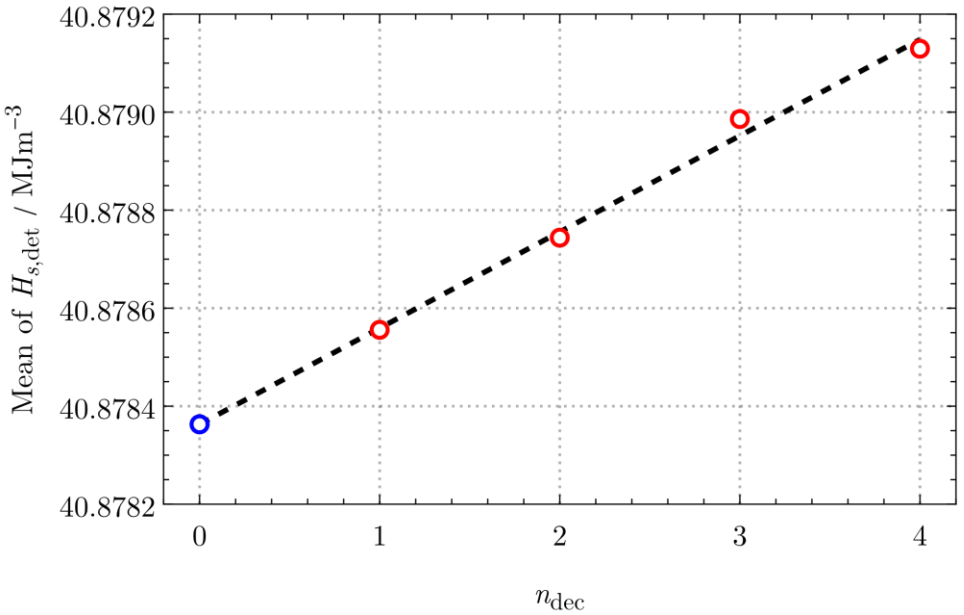
Decimation by a factor m means that only every m^{th} sample is taken

Calculate the desired quantity q for different decimation factors

Estimate by least squares

$$q(m) = a \cdot m + b$$

$q(m = 0) = b$ is the reference value



Example of the application of the decimation method.

3. The uncertainty related to the numerical integration of the deterministic signal is estimated using the decimation method

The numerical integration error is

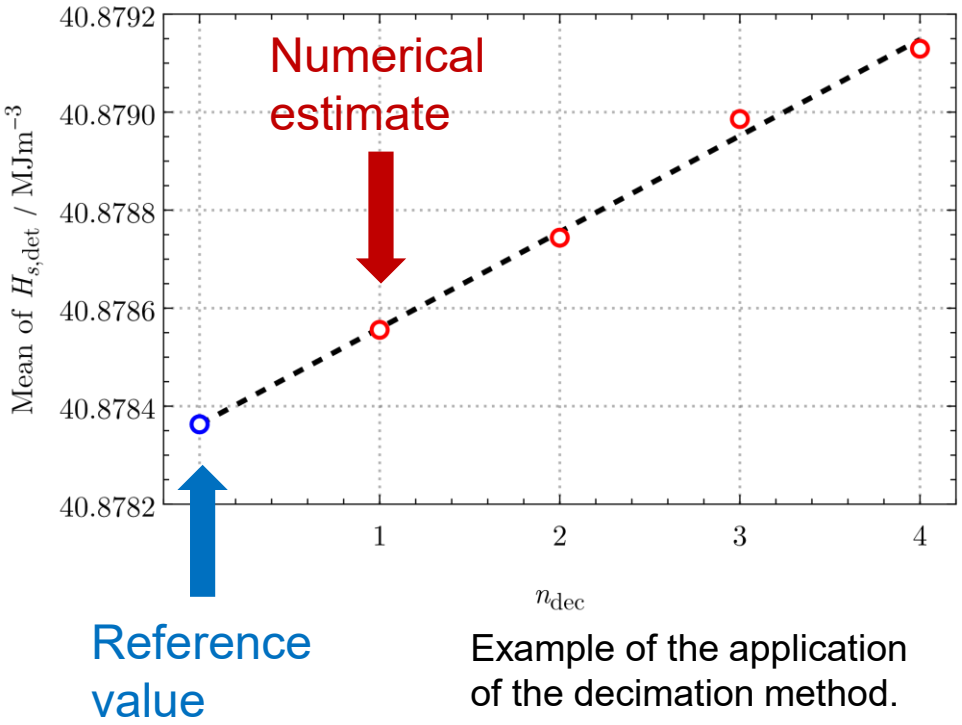
$$e_{det} = q(1) - q(0) = 0{,}19 \text{ kJ/m}^3$$

with associated uncertainty

$$u(e_{det}) = s\big(q(0)\big) = 0{,}035 \text{ kJ/m}^3$$

Combined, they give

$$u_{det} = \sqrt{\left(\frac{e_{det}}{\sqrt{3}}\right)^2 + u^2(e_{det})} = 0{,}12 \text{ kJ/m}^3$$



Example of the application of the decimation method.

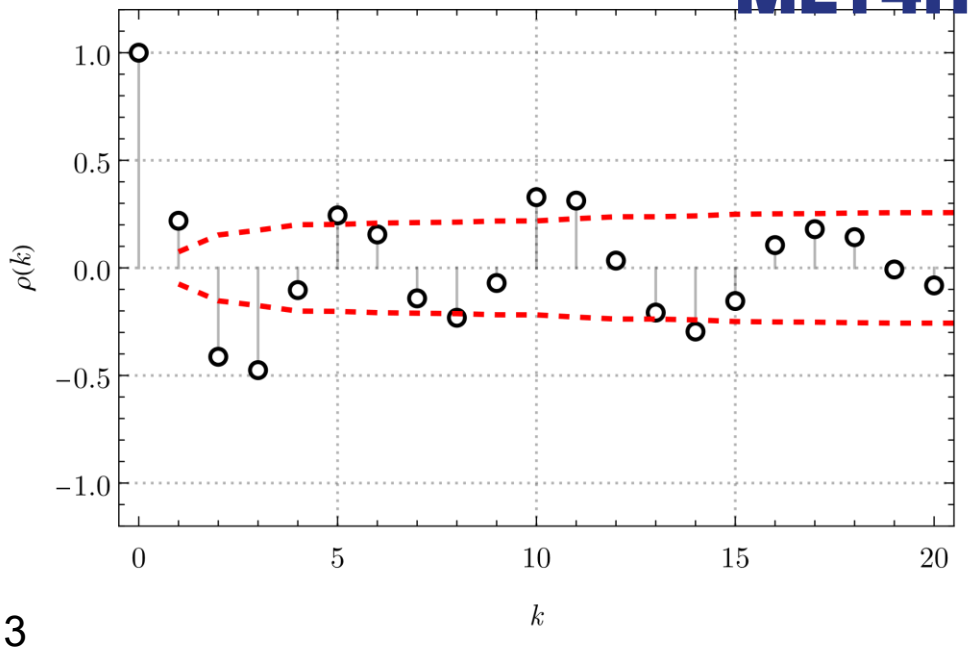
3. The uncertainty related to the numerical integration of the random signal is estimated by statistical analysis

Without correlation

$$u_{ran}^{(uncor)} = \frac{s(q_{ran,i})}{\sqrt{N}} = 0{,}25 \text{ kJ/m}^3$$

With correlation

$$u_{ran}^{(cor)} = \frac{s(q_{ran,i})}{\sqrt{N}} \sqrt{1 + \frac{2\sum_{k=1}^{N_{cor}} (N_{ran}-1)\rho(k)}{N_{ran}}} = 0{,}30 \text{ kJ/m}^3$$



Example ACF of the random component.

The number of auto-correlation to be considered could be determined as the smallest l for which $\rho(l) > 0$ and $\rho(l+1) < 0$. In this case $l = 1$.

3. The uncertainty evaluated by separating the two components is almost 10 times smaller!

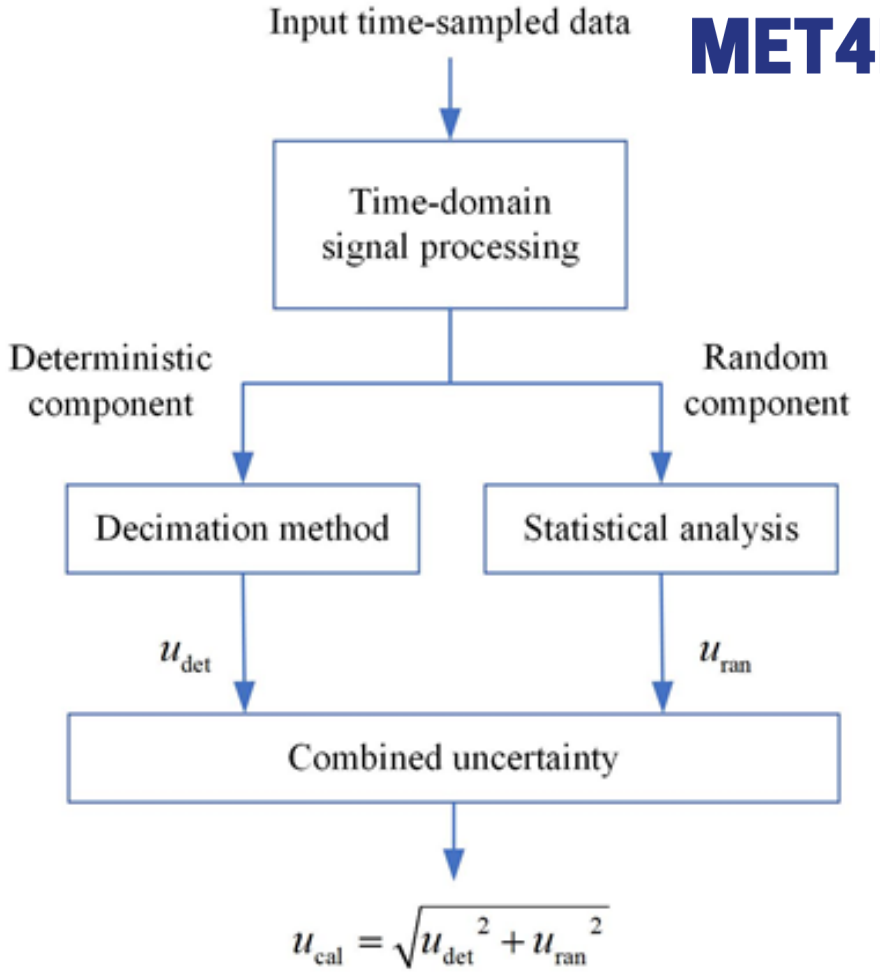
The uncertainties of the two components are combined using the LPU:

$$u_c^{(uncor)} = \sqrt{u_{det}^2 + u_{ran}^{(uncor)^2}} = 0{,}28 \text{ kJ/m}^3$$

$$u_c^{(cor)} = \sqrt{u_{det}^2 + u_{ran}^{(cor)^2}} = 0{,}32 \text{ kJ/m}^3$$

Without separate evaluation

$$u_c = \frac{s(q_i)}{\sqrt{N}} = 2{,}94 \text{ kJ/m}^3$$



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Conclusions

1. Correlations due to the instrumentation
   - Inclusion of the instrumental correlation leads to an increase of 30 % in the uncertainty associated to the volume conversion factor

2. Temporal correlations in subsequent measurements
   - Including the serial correlation leads to an increase of circa 50 % in the type A uncertainty of the total energy

3. Error introduced by the numerical approximation
   - Separation into deterministic and random component leads to an uncertainty 10 times smaller for the average calorific value

Useful references

ISO 15112 Natural gas – Energy determination. ISO, International Organization for Standardization

EN 1776 Gas infrastructure – Gas measuring systems – Functional requirements. CEN, European Committee for Standardization

OIML R 140 Measuring systems for gaseous fuel. OIML, International Organization for Legal Metrology

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A. M. H. van der Veen et al. *Best practices in the evaluation of the measurement uncertainty of quantities relevant to fiscal measurements along the hydrogen supply chain.* (2025)

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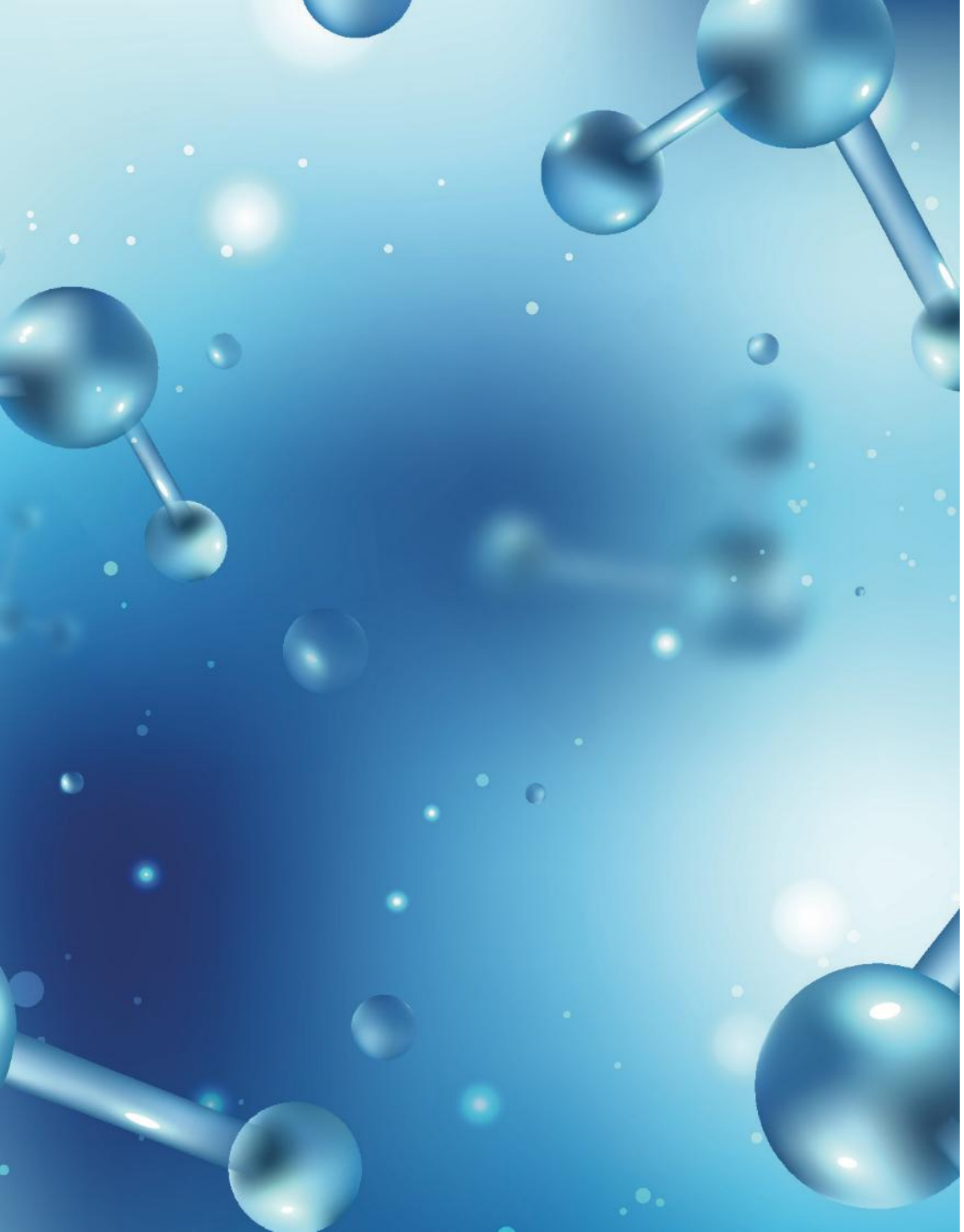

METERING UNCERTAINTY FOR CUSTODY TRANSFER OF HYDROGEN FOR TRANSPORT, HEAT, AND STORAGE

M36 Workshop,
September, 2025

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EXAMPLES OF METERING UNCERTAINTY EVALUATIONS ACROSS VARIOUS SEGMENTS OF THE HYDROGEN SUPPLY CHAIN

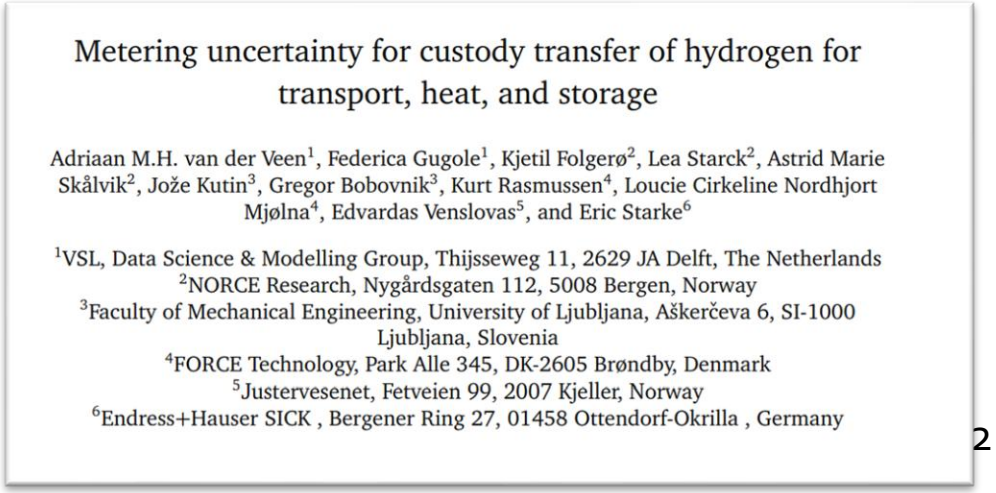
Objective

- Demonstrate how the methods described in the best-practice guide from Met4H2 can be implemented using real-world data
- Illustrate how dependencies between measurement results can be evaluated

Examples

1. Gas grid - Temporal correlations and numerical approximations
2. Industrial supply chain – Monte Carlo based uncertainty analysis
3. Refuelling station – Qualitative analysis

Met4H2 report



Metering uncertainty for custody transfer of hydrogen for transport, heat, and storage

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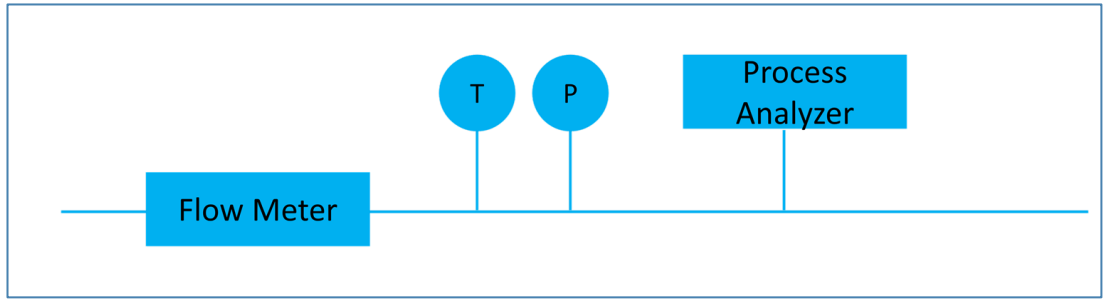
ILLUSTRATIVE EXAMPLE

Synthetic example:
Blend of hydrogen and natural gas



- Energy content calculated from volume flow rate at reference conditions and the calorific value of the gas
- Volume flow rate at reference conditions calculated from the measured volume flow rate using a conversion factor (K)
- Conversion factor depends on gas composition, temperature and pressure
- Calorific value and conversion factor depend on gas quality => correlation

$$\dot{E}_i = \dot{V}_{0i} H_{vi}$$

$$\dot{V}_{0i} = \underbrace{\frac{p_i T_0 Z_{0i}}{p_0 T_i Z_i}}_{K} \dot{V}_i$$

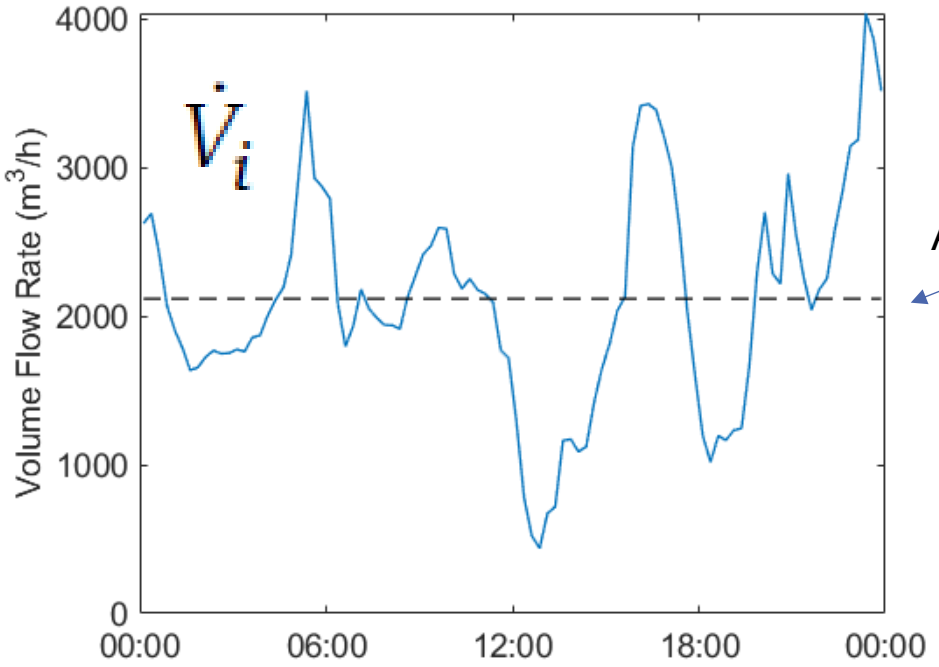
ILLUSTRATIVE EXAMPLE

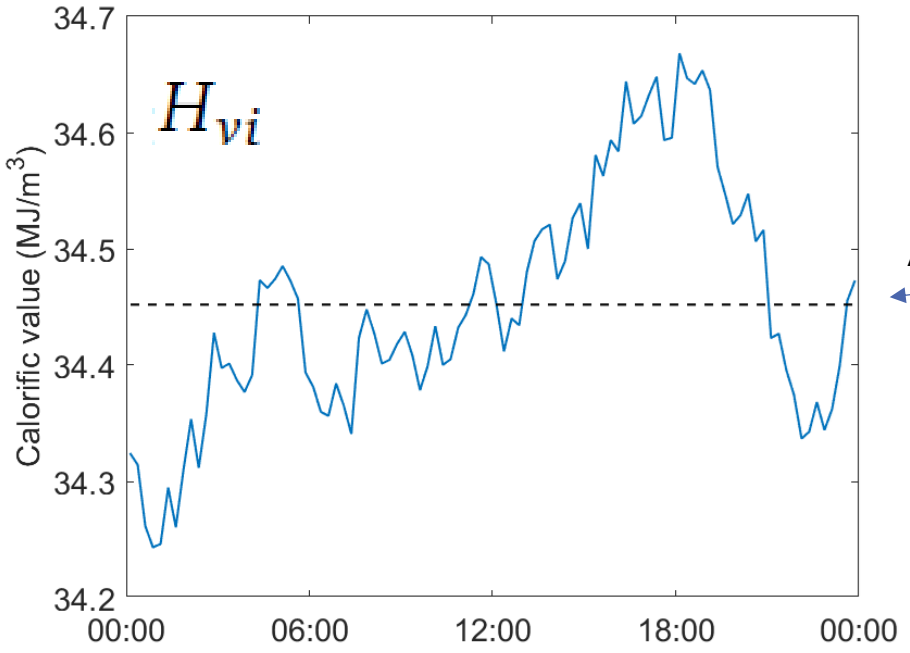
$$\dot{V}_{0i} = \frac{p_i T_0 Z_{0i}}{p_0 T_i Z_i} \dot{V}_i$$

$$\dot{E}_i = \dot{V}_{0i} H_{vi}$$

- **Importance of correlations**
  - Composition influences both Volume conversion and Calorific value

- Uncertainty analysis on daily averages
  - Ignoring correlations between $\overline{\dot{V}_0}$ and $\overline{H_v}$: 0.75 %
  - Including correlations between $\overline{\dot{V}_0}$ and $\overline{H_v}$: 0.89 %

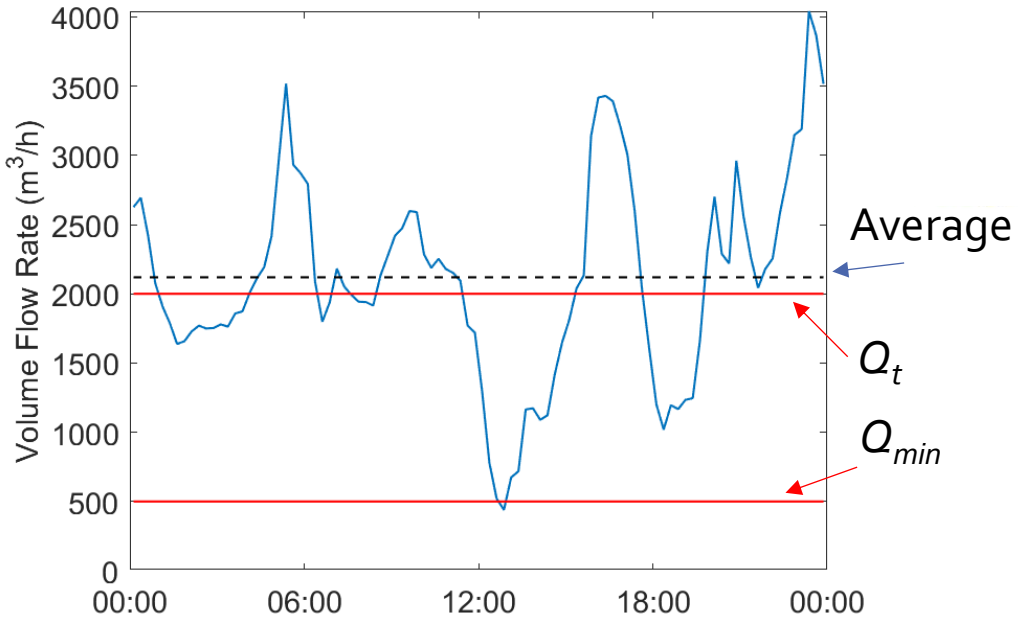




A. M. H. van der Veen, K. Folgerø, F. Gugole "Measurement uncertainty in the totalisation of quantity and energy measurement in gas grids" (Gases) *Gases 2025, 5(2), 7; https://doi.org/10.3390/gases5020007*

ILLUSTRATIVE EXAMPLE

- **Importance of time-resolution**
  - Flow rate is partly below transition rate
    => increased uncertainty
  - Analysis of averaged data vs 15-min interval



- Uncertainty analysis on daily averages
  - Ignoring correlations between Vo and Hv: 0.75 %
  - Including correlations between Vo and Hv: 0.89 %

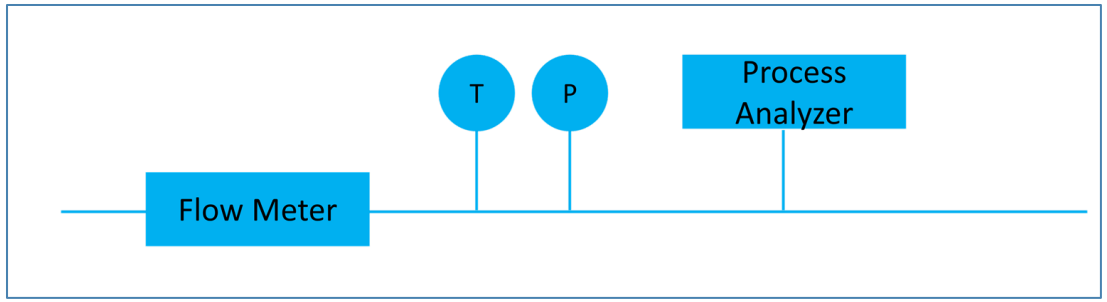
Input variable	Range	Uncertainty
T	293.15 K	0.3 K
p	50 bar	0.1 bar
Q_V	$Q_{V,t} < Q_V < Q_{V,max}$	0.5 %
	$Q_{V,min} < Q_V < Q_{V,t}$	1.0 %
	$Q_V < Q_{V,min}$	2.0 %

- **Uncertainty analysis on 15 min data**
  - Including correlations between Vo and Hv: **0.97 %**
    assuming full correlations between succeeding measurements

Component	x cmol mol^{-1}	$U(x)(k=2)$ cmol mol^{-1}
nitrogen	0.148	0.0025
carbon dioxide	0.0566	0.0032
methane	96.3954	0.2400
ethane	3.0545	0.0250
propane	0.2251	0.0053
iso-butane	0.0356	0.0010
n-butane	0.0315	0.0007
iso-pentane	0.0075	0.0004
n-pentane	0.0043	0.0004
n-hexane	0.0115	0.0010
helium	0.030	0.0025
hydrogen	15.2 - 16.8	0.500

2. INDUSTRIAL SUPPLY: MONTE CARLO BASED UNCERTAINTY ANALYSIS

- Evaluation of uncertainty in
  - Energy flow rate
  - Accumulated energy over a month

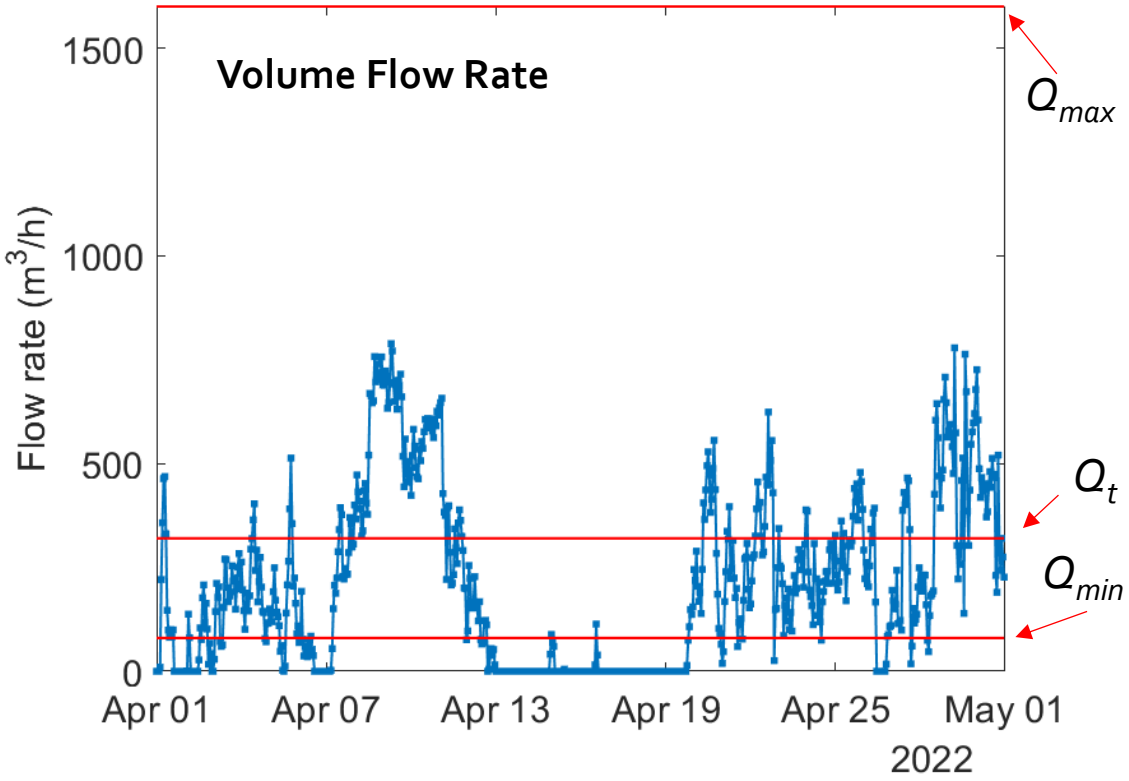


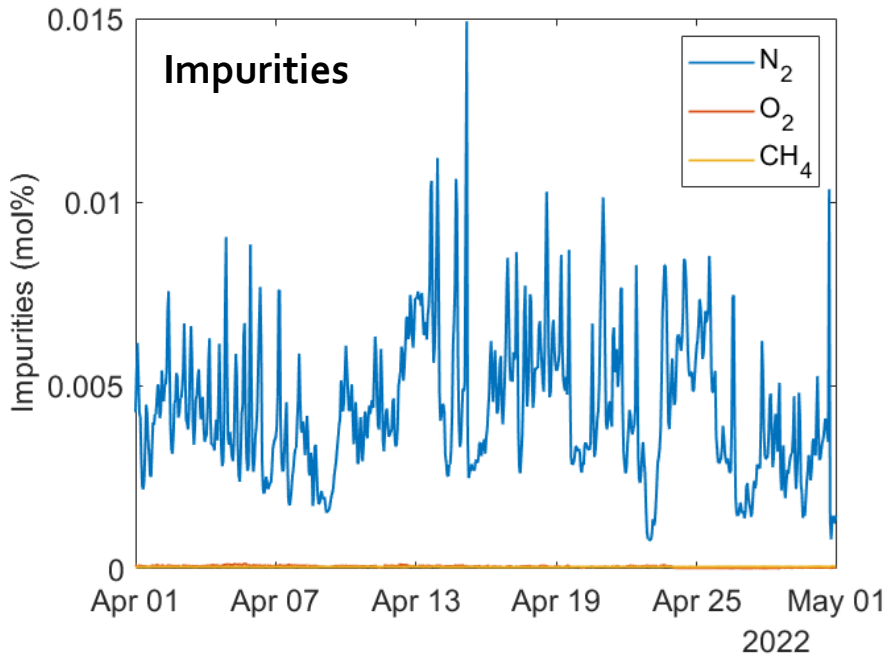
- Experimental data from a metering station at an industrial cluster
  - Volume rate (10" Turbine Meter)
  - Temperature
  - Pressure
  - Composition (Gas Chromatograph)

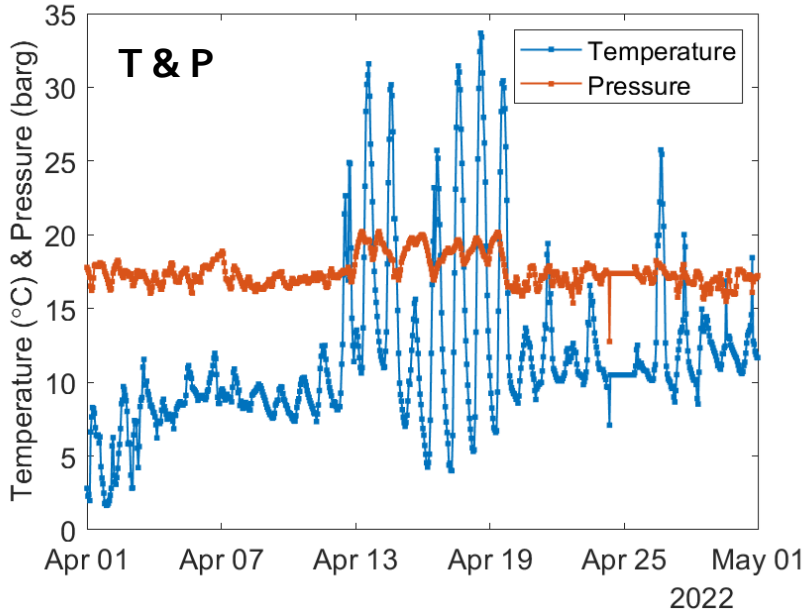
Averaged values over 60-minute intervals

No information about instrumentation, installation conditions, calibration procedures, or maintenance practice
=> *Uncertainty analysis based on typical performances and reasonable assumptions*

EXPERIMENTAL DATA







2. ASSUMPTIONS

- Rough uncertainty assumptions
- Variability within 60-minute interval is not considered
- Hydrogen composition calculated by-difference (no need for normalisation)

Uncertainty assumptions (k=2)

Input variable	Range	Uncertainty
T		0.2 K
p		0.07 bar
Q_V	$320 \leq Q_V \leq 1600$	0.6 %
	$80 \leq Q_V \leq 320$	1.2 %
	$Q_V < 80$	2.4 %
x_{N_2}		0.001 cmol/mol

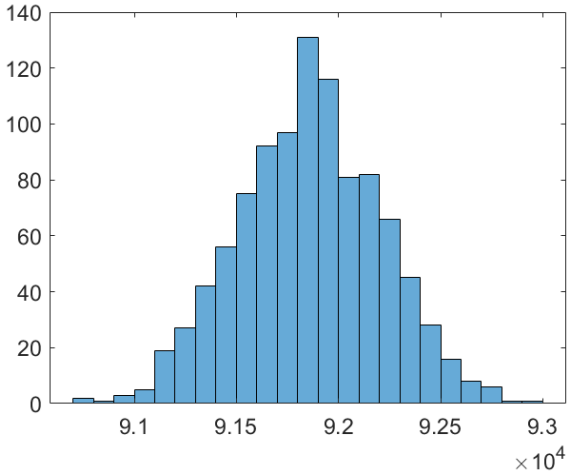
METHOD

- *Aim*: Calculate uncertainty in Energy flow rate
- Monte Carlo method applied
  - Latin hypercube sampling
  - 1000 iterations for each time interval
- Parameters varied according to their input uncertainties /distributions
  - Volume flow rate , Temperature, Pressure, Composition (N2)
- Parameters calculated (for all iterations)
  - Energy flow rate, Z, Z_0, Calorific value, Temperature, Pressure
  - Correlations between Z, Z_0, T, P, H_v inherently present, as all values are derived from identical composition iterations
- Uncertainty calculated from distribution of output-parameters

$$\dot{V}_{0i} = \frac{p_i T_0 Z_{0i}}{p_0 T_i Z_i} \dot{V}_i$$

$$\dot{E}_i = \dot{V}_{0i} H_{vi}$$

$$E(t_N) = \Delta t \sum_{i=1}^{N} \dot{E}_i$$

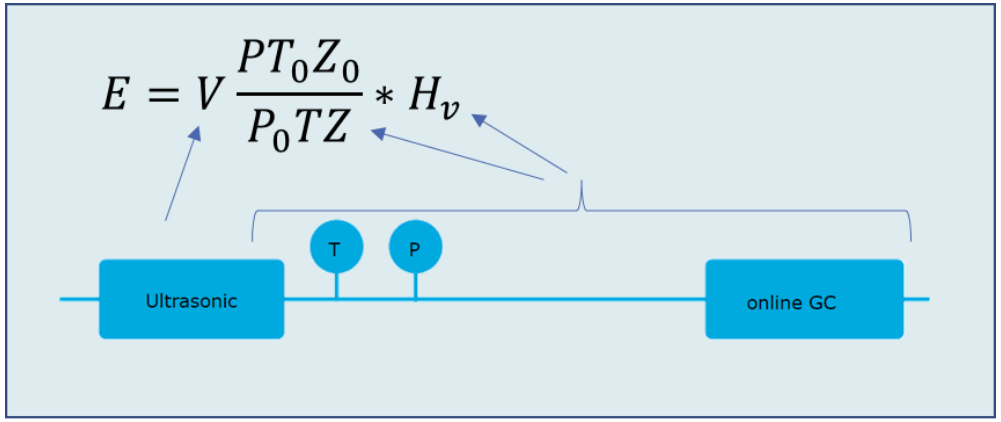


SOFTWARE

Features

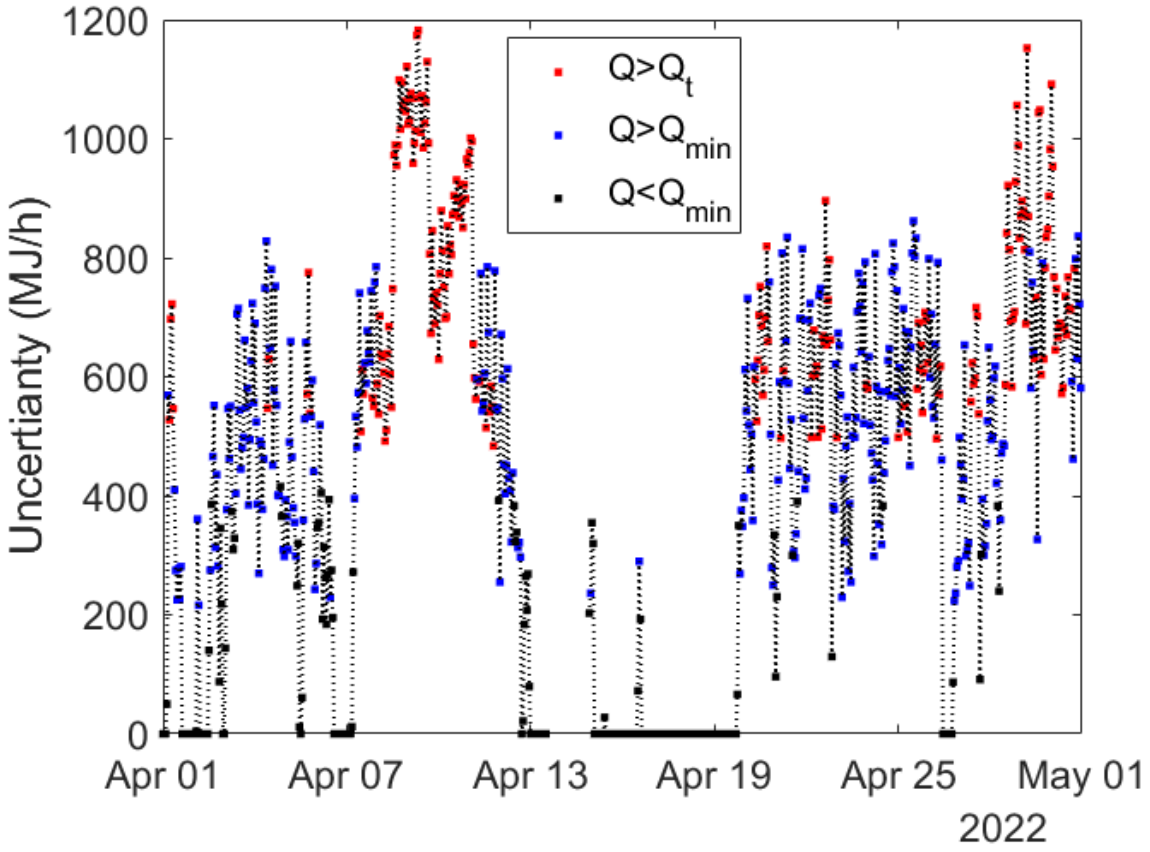
- Framework implemented in Python
- Includes EoS calculations using AGA8 and GERG-2008
  - REFPROP (Trend, CoolProp, pyforfluid)
- Combines Monte-Carlo and analytical calculations
- Modular framework ready for addition of new modules
- Input data provided in spreadsheet-format (Excel)
- Output data in spreadsheet-format (Excel)

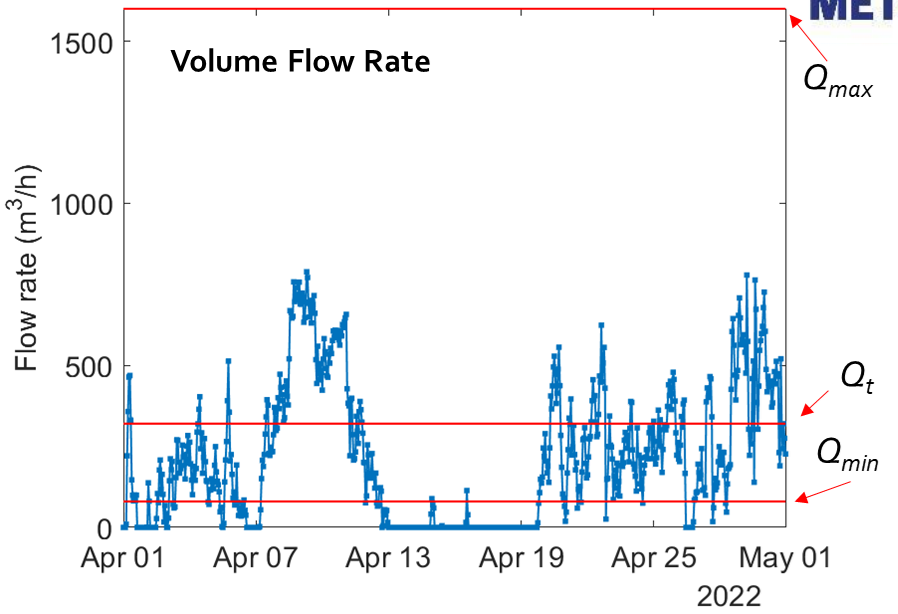
Example: USM metering station



Sheets	Description
Configuration	Metering station configuration
ProcessData	Flow rates, Temperature, Pressure vs time
Composition	Fluid composition vs time
USM_unc	Input data for USM uncertainty analysis
T_unc	Input data for temperature transmitter uncertainty analysis
P_unc	Input data for pressure transmitter uncertainty analysis
Composition_unc	Uncertainty data for composition

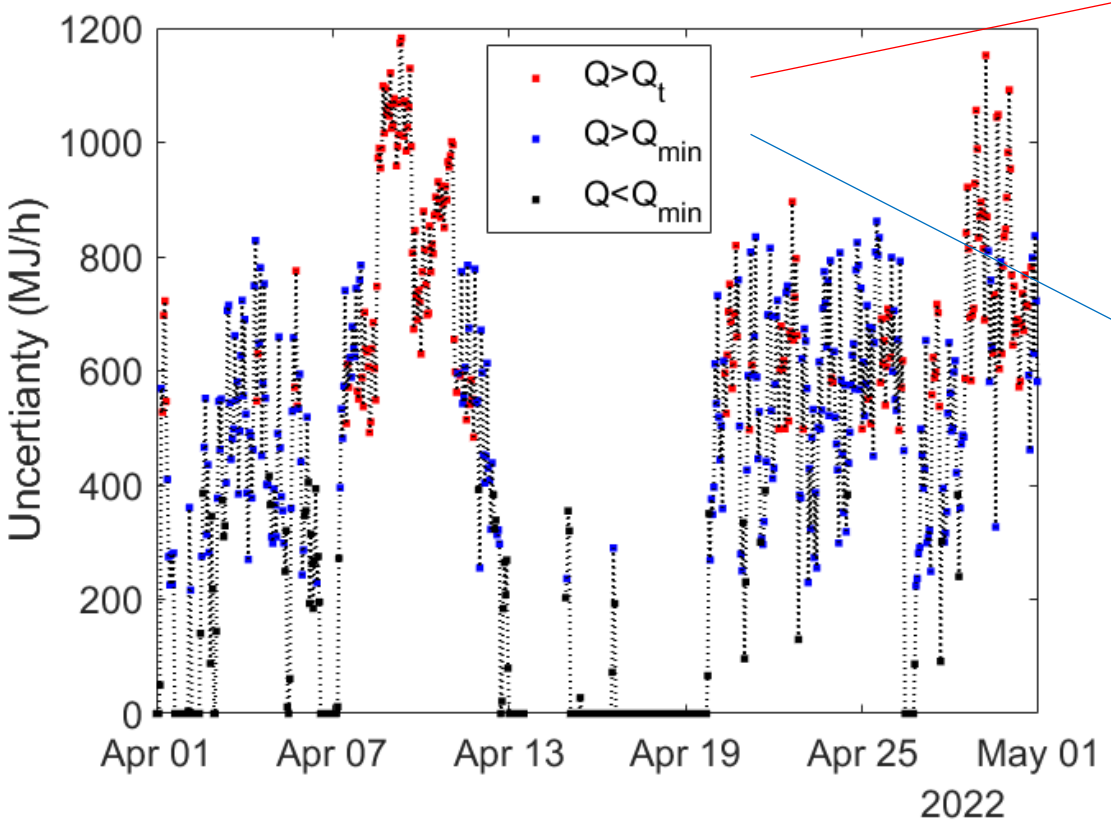
RESULTS:
ENERGY FLOW RATE

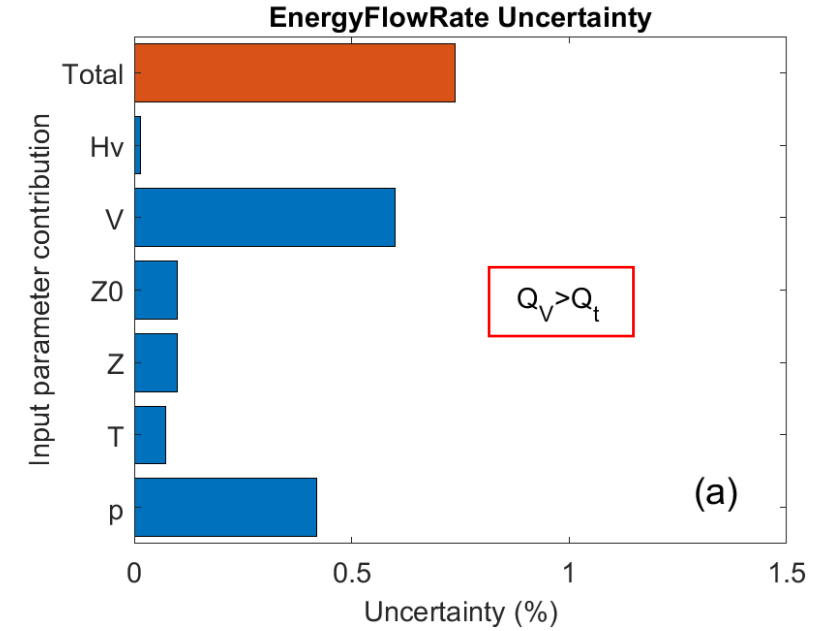


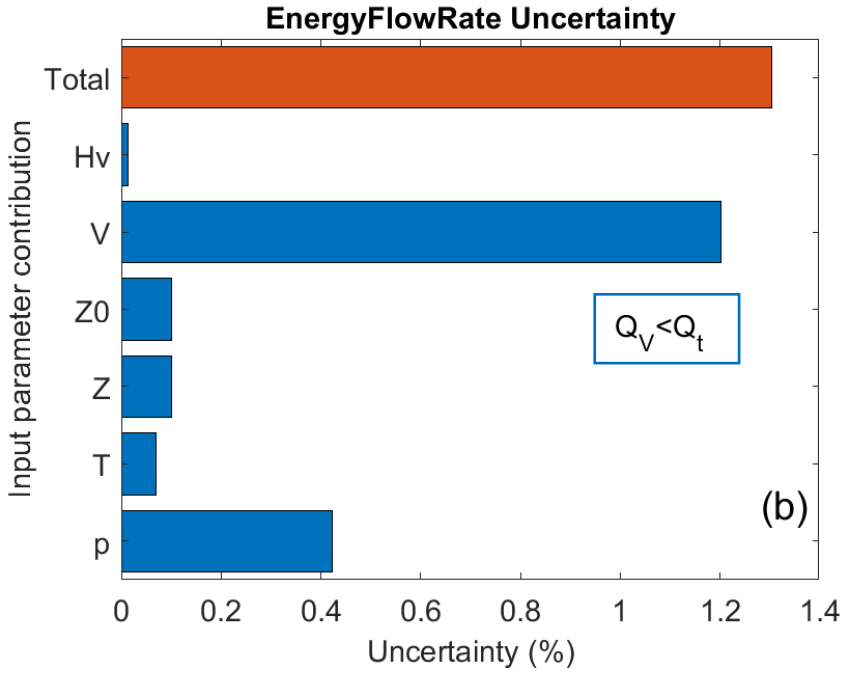


- Temperature
- Pressure
- Composition

RESULTS: ENERGY FLOW RATE







$$\frac{u(E_i)}{E} = \sqrt{(\frac{u(p_i)}{p_i})^2 + (\frac{u(T_i)}{T})^2 + (\frac{u(Z_i)}{Z_i})^2 + (\frac{u(Z_{0i})}{Z_{0i}})^2 + (\frac{u(\dot{V}_i)}{\dot{V}_i})^2 + (\frac{u(H_i)}{H_i})^2 + (\frac{u_{corr,i}}{E})^2}$$

RESULTS: ACCUMULATED ENERGY

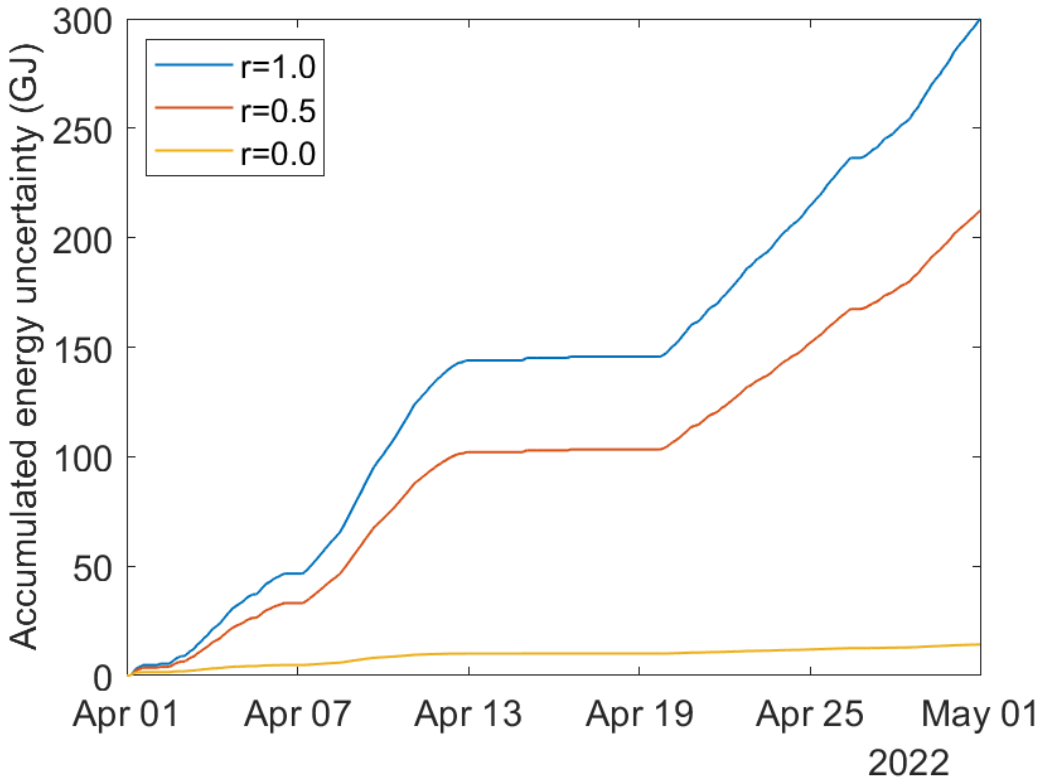
r=1 => $u\left(E(t_N)\right) = \sum_{i=1}^{N} u(E_i)$

r=0 => $u\left(E(t_N)\right) = \sqrt{\sum_{i=1}^{N} u^2(E_i)}$

- Need to include temporal correlations between succeeding measurements

$$u^2(E(t_N)) = \sum_{i=1}^{N} u^2(E_i) + \sum_{i=1}^{N-1} r_{i,i+1} u(E_i) u(E_{i+1})$$

- Non-stationary data makes it difficult to apply ARMA method
- Example illustrates importance of estimating *r*
- *Need for robust methods to calculate serial correlation dynamic measurements*



3. REFUELLING STATION: QUALITATIVE ANALYSIS

Filling Type	Typical Pressure	Vehicle Type	Hydrogen Capacity	Refuelling Duration
H35	350 bar	Heavy-duty (buses, trucks)	>10 kg	10–15 minutes
H70	700 bar	Light-duty (cars)	4–7 kg	3–5 minutes

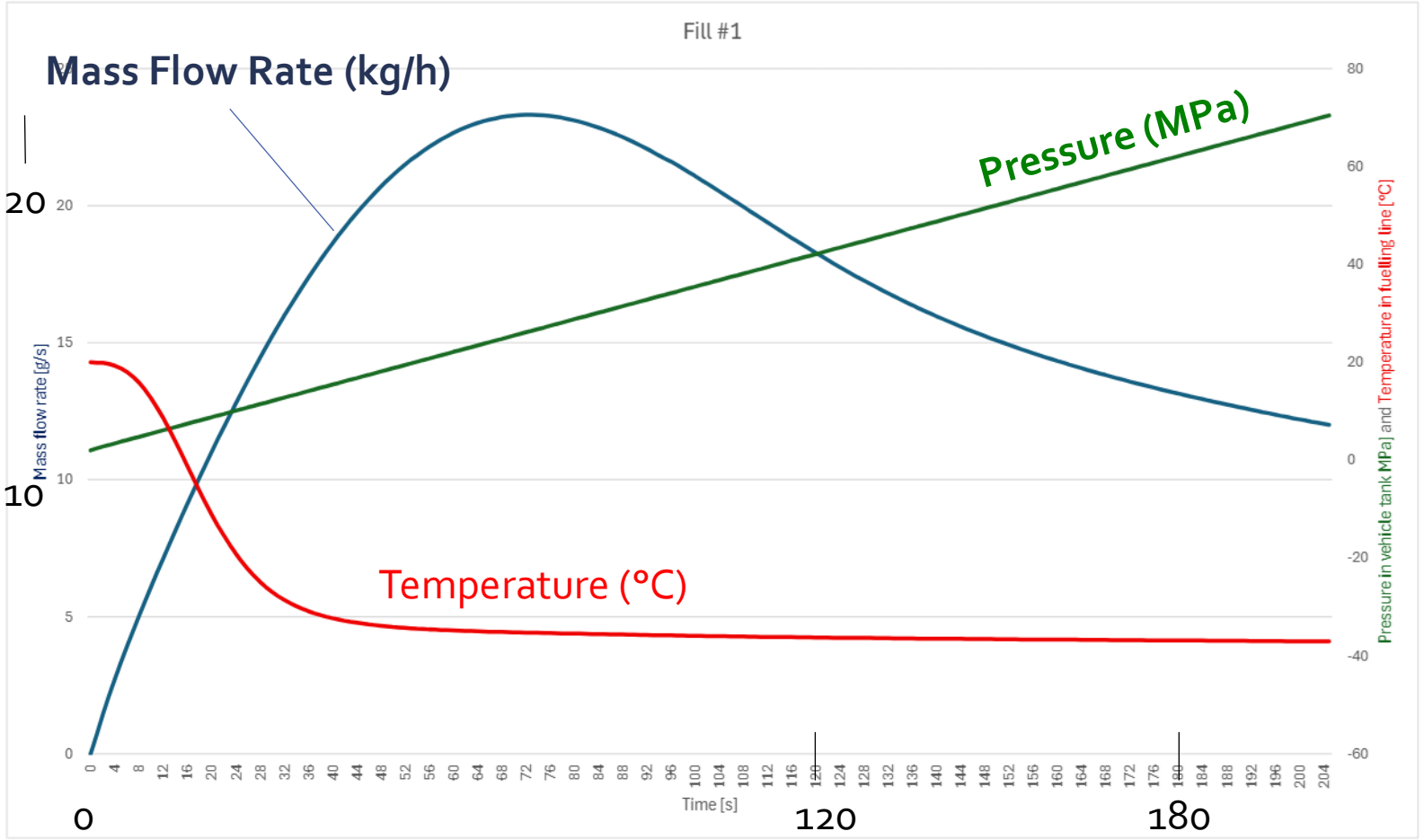
- Measurand: Total mass delivered during refuelling

$$m_{\text{tot}} = \sum_{t=1}^{N} m_t$$

TYPICAL FILLING PROFILE (SIMULATED)

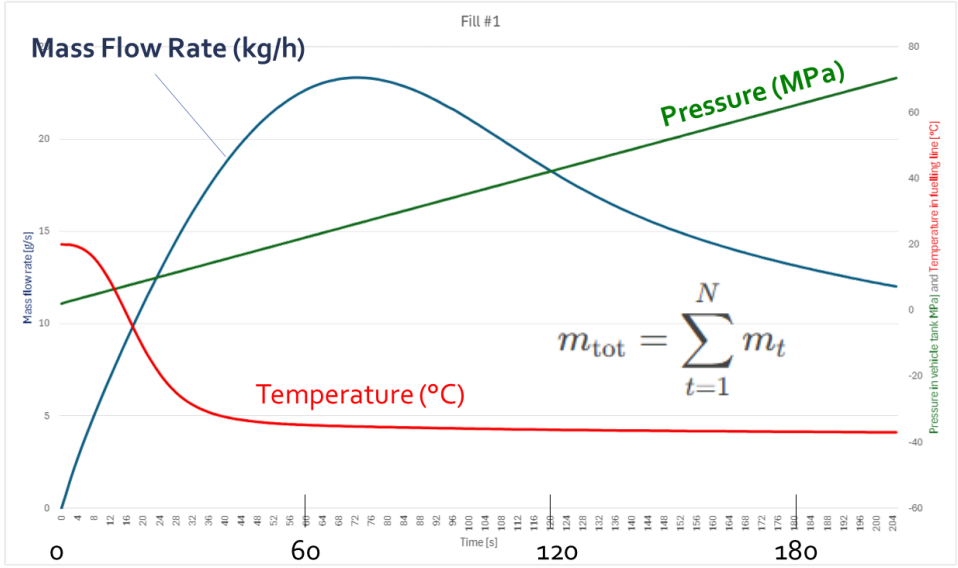
- Short time scale
- Transient mass flow rate
- Rapid temperature decrease

$$m_{\text{tot}} = \sum_{t=1}^{N} m_t$$



UNCERTAINTY CALCULATION

- Instrumental correlations
  - Uncertainty due to e.g. calibration & installation effects
  - *Can be esimtaed by detailed uncertianty analysis dividing uncertianties in to correlated, partly correlated and uncorrelated uncertainties*
- Totalization uncertainty
  - Numerical effect of time sampling
  - *May be estimated by splitting into random and deterministic components (using Savitzky-Golay filtering)*
- Temporal effects
  - Typically a non-stationary data series
  - ARMA-models not suited to calculate correlations
- *Need for robust methods to calculate serial correlation coefficient for dynamic measurements*



CONCLUSION

- Examples on how to apply methods from the best-practice guide presented
- Illustrates the importance to include (instrumental and temporal) correlations
- Robust methods needed to evaluate highly dynamic responses
  - Will be investigated in SmartGasNet project recently started

CONTRIBUTORS

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