25 years of European harmonization of the natural gas metering reference

Menne D. Schakel, VSL B.V.
M. Workamp, VSL B.V.
F.M. Smits, VSL B.V.
B. Mickan, PTB
K. Rasmussen, FORCE Technology
A. Ouerdani, CESAME EXADEBIT
C. Windenberger, CESAME EXADEBIT
M. van der Beek, Euroloop
Jos van der Grinten

1 INTRODUCTION

In 2024, the European harmonization group for high-pressure natural gas flow calibrations celebrated its 25th anniversary. The group carries the name EuReGa, acronym of European Reference for Gas Metering and is comprised of FORCE, LNE-LADG, PTB, and VSL. It was founded to enhance the metrological basis for transnational trade of natural gas in Europe. In particular, prior to harmonization, several independent traceability chains stemming from national primary standards led to systematic measurement differences during custody transfer across borders, which were explainable by the employed uncertainties, but too large given the high monetary values involved. The harmonization group was thus founded in 1999 to improve overall measurement uncertainty. The harmonization process involves the performance of an intercomparison and is followed by a harmonization step, which corrects the reference values of each independent traceability chain to the harmonized value. Harmonization is a continuous process and results in smaller measurement uncertainties as long as the stochastic contributions to the overall measurement uncertainties are significantly smaller than the uncertainties arising from the traceability chain [1].

The 25 years of history yield the benefit of hindsight. It can now be concluded that important achievements have been established:
(1) the harmonization process has resulted in significant reduction of systematic differences between independent traceability chains, e.g. [2,3],
(2) dissemination of the unified reference value has spread across Europe and is in high demand globally, e.g. [4], and
(3) harmonization has proven itself as a respected metrological concept reducing overall measurement uncertainty to the benefit of the entire society.

EuReGa's history is highly relevant to the current development of the European hydrogen backbone, as new traceability chains for pure hydrogen high-pressure gas flow are being developed and transnational trade within the backbone is foreseen. Therefore, in this paper, the achievements of the EuReGa harmonization group will be illustrated followed by a description of currently ongoing activities in the development of independent traceability chains for pure hydrogen high-pressure gas flow, including scenarios towards harmonization of pure hydrogen gas flow references. The natural gas experience from EuReGa supports accelerating establishment of reliability in trading across Europe's integrated hydrogen backbone.

2 EuReGa's metrological achievements

2.1 EuReGa's history

Understanding EuReGa's metrological achievements is best illustrated by starting from a historical perspective. The following relies heavily on EuReGa's publications from its website [1] and written down in its communications (e.g., [5],[6],[7]) and other publications (e.g.,[2],[3],[8]).

In the 1960's a natural gas based economy evolved in the Netherlands, driven by the discovery of a large gas field in the North of the Netherlands. The reference value for high-pressure natural gas flow was created through several upscaling (bootstrapping) steps, from low-flow to high-flow and from nearly atmospheric pressure to network pressures of up to 61 bar. NMi VSL-Flow facilities in Bergum and Westerbork were used. The achieved measurement uncertainty was approximately at 0.3 % relative (k = 2) and the stability of the reference value was not better than a few tenths of a percent. In 1993, a new laboratory, pigsar™, was established in Dorsten, Germany. At pigsar™, an independent realization of the cubic meter was achieved directly at transmission grid pressures. Gas meter calibrations from the independent calibration facilities in the Netherlands and in Germany were performed, and differences of up to ±0.2 % in its error were observed. While the differences were explainable within the uncertainty claims made, a desire to reduce systematic differences and the overall measurement uncertainty rose. A 0.1 % difference in error could cause a financial imbalance of about 15 million euros in the Netherlands alone [5]. A solution was found by the National Metrology Institutes (NMI) of the Netherlands (VSL) and of Germany (PTB). It was decided to determine a Harmonized Reference Value (HRV), which removes the systematic difference so that financial risk in cross-border trading is at the minimum. Thus, in 1999, the predecessor of EuReGa was founded by signing a Memorandum of Understanding (MoU) between the NMI's of The Netherlands and Germany.

Figure 1 sketches the reference values of two independent traceability chains (NMi VSL-Flow, green curve; PIGSAR-PTB, blue curve) and the evolution of the Harmonized (Unified) Reference Value after 1999, the year in which harmonization started. The sketch highlights the following important points:

- Reference values of the independent (<1999) traceability chains were quite variable (reference value was not better than a few tenths of a percent)
- The harmonized (Unified) Reference value is at a level in between of the independent labs (compare <1999 graphs with >1999 graph)
- The harmonized (Unified) Reference is less variable, thus more stable over time
- The overall measurement uncertainty in the harmonized reference value is reduced with respect to that of the independent traceability chains (see vertical black bars)

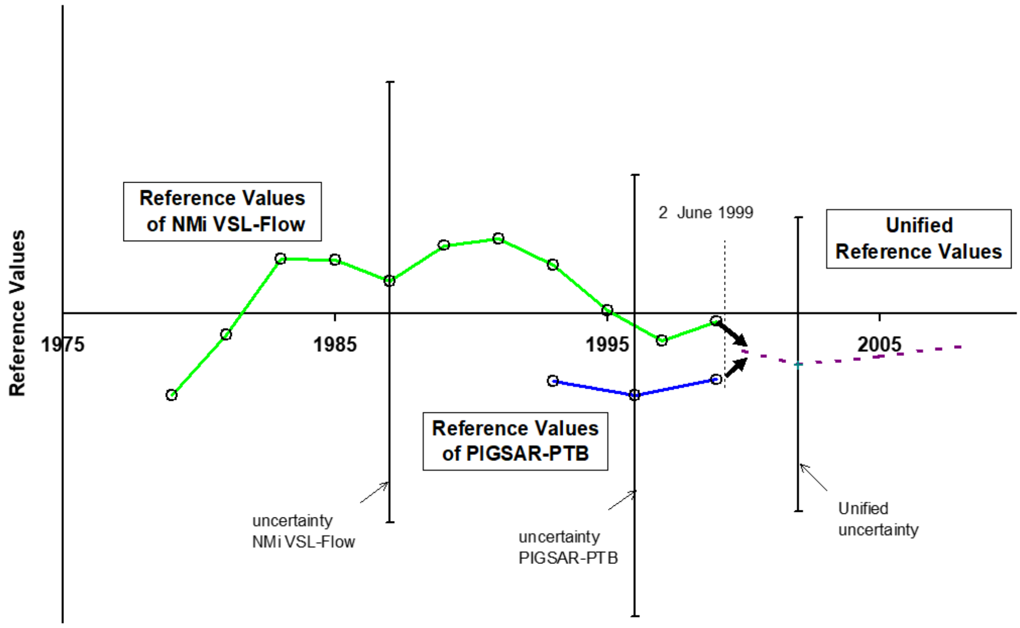

Fig. 1: Sketch of reference values of independent traceability chains over time (green and blue curve) and its culmination into the first Harmonized (Unified) Reference Value (purple curve). Reproduced from [5]. Reference values of NMi VSL-Flow are now implemented through separate entities VSL (NMI of the Netherlands; primary measurement standard and transfer devices) and EuroLoop (Calibration facility). Reference values of PIGSAR-PTB are implemented through separate entities PTB (NMI of Germany; primary measurement standard and transfer devices) and pigsar™ (Calibration facility).

The French NMI (LNE) joined the MoU in 2004 and the Danish Designated Institute (FORCE technology) joined in 2013 at which point the group was termed European Reference for Gas Metering: EuReGa.

An overview of the timeline is given in Figure 2. Harmonization intercomparisons (●) are performed at three years intervals. NMI/DIs of The Netherlands, Germany, France, and Denmark joined (○) in 1999, 1999, 2004, and 2013, respectively. The 2004 intercomparison is registered at the Bureau International des Poids et Mesures (BIPM) as Key Comparison CCM.FF-K5.a (▲). Subsequent BIPM (Δ) and EURAMET (Δ) bilateral intercomparisons and an EURAMET key comparison (■) were performed. The harmonization is performed at the relatively large scale of derived (from the primary level) reference standards at the flow rate scales of EuReGa partners' high-pressure gas flow facilities (up to 50 000 m³/h). In 2019, the first intercomparison of primary standards was performed (●).

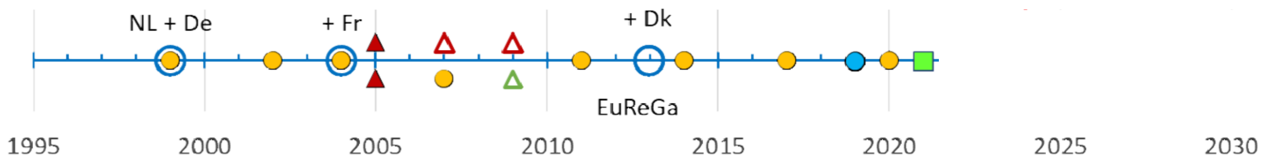

Fig. 2: Timeline of high-pressure natural gas harmonization milestones. EuReGa, in its current form, was founded in 2013. Reproduced with slight modifications from [6].

One of the requirements of a partner for participation into the EuReGa harmonization group is that it maintains a primary standard for the realization of the high-pressure gas cubic metre (m³). In Table 1 it is shown that three (different) piston provers and a *pVTt*-system are used in the independent realization of the high-pressure gas cubic metre (m³) for air or natural gas [8].

Table 1 – EuReGa's primary standards. Reproduced from [8] with slight modifications.

Traceability chain country	Institute(s)	Primary device	Traceable to	Fluid used
The Netherlands	VSL / EuroLoop	24″ Piston Prover	Length	Natural gas
Germany	PTB / pigsar	10″ Piston Prover	Length	Natural gas
France	Cesame-Exadebit s.a. / LNE-LADG	Constant volume tank (*pVTt*)	Mass	Air
Denmark	FORCE Technology	26″ Twin Piston Prover	Length	Natural gas

Figure 3 shows a schematic of the traceability chain of EuReGa's partners' high-pressure gas flow facilities. The primary standard realizes the unit [8]. The high-pressure gas cubic metre (m³) is realized at the primary standard which is used to calibrate transfer devices carrying the flow unit. These are in turn used to upscale (bootstrap) the SI-traceability to higher flow rates of the calibration facility. EuReGa's harmonization takes place at the references of the calibration facility (versus the primary or transfer device levels).

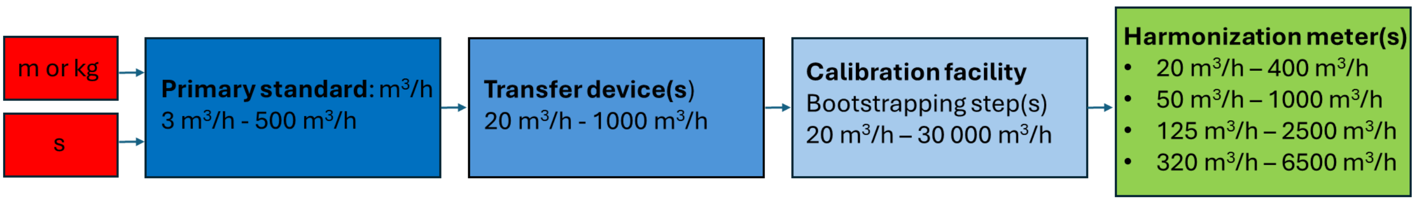

Fig. 3: Schematic of EuReGa's independent traceability chains. Harmonization takes place at the calibration facility level (corresponding to the 20 m³/h – 30 000 m³/h range). Flow rate ranges are indicative and will differ from actual flow rate ranges of EuReGa-partners.

Figure 4 and Figure 5 show normalized degrees of equivalence (Absolute E_n) and individual laboratories' differences *d* with the HRV from EuReGa's 2020 harmonization as a function of the Reynolds number (*Re*). Results of Figure 4 show that more than 80 % of the data match $|E_n| \leq ½$ and that none of the $|E_n|$-values are above the critical level of 1.2 (red). Results of Figure 5 show that most of the differences with the HRV lie within ±0.1 %. Bearing in mind the above statement that differences in calibration error of up to ±0.2

% are undesirable, it follows that the harmonization leads to an improvement in measurement accuracy and reliability.

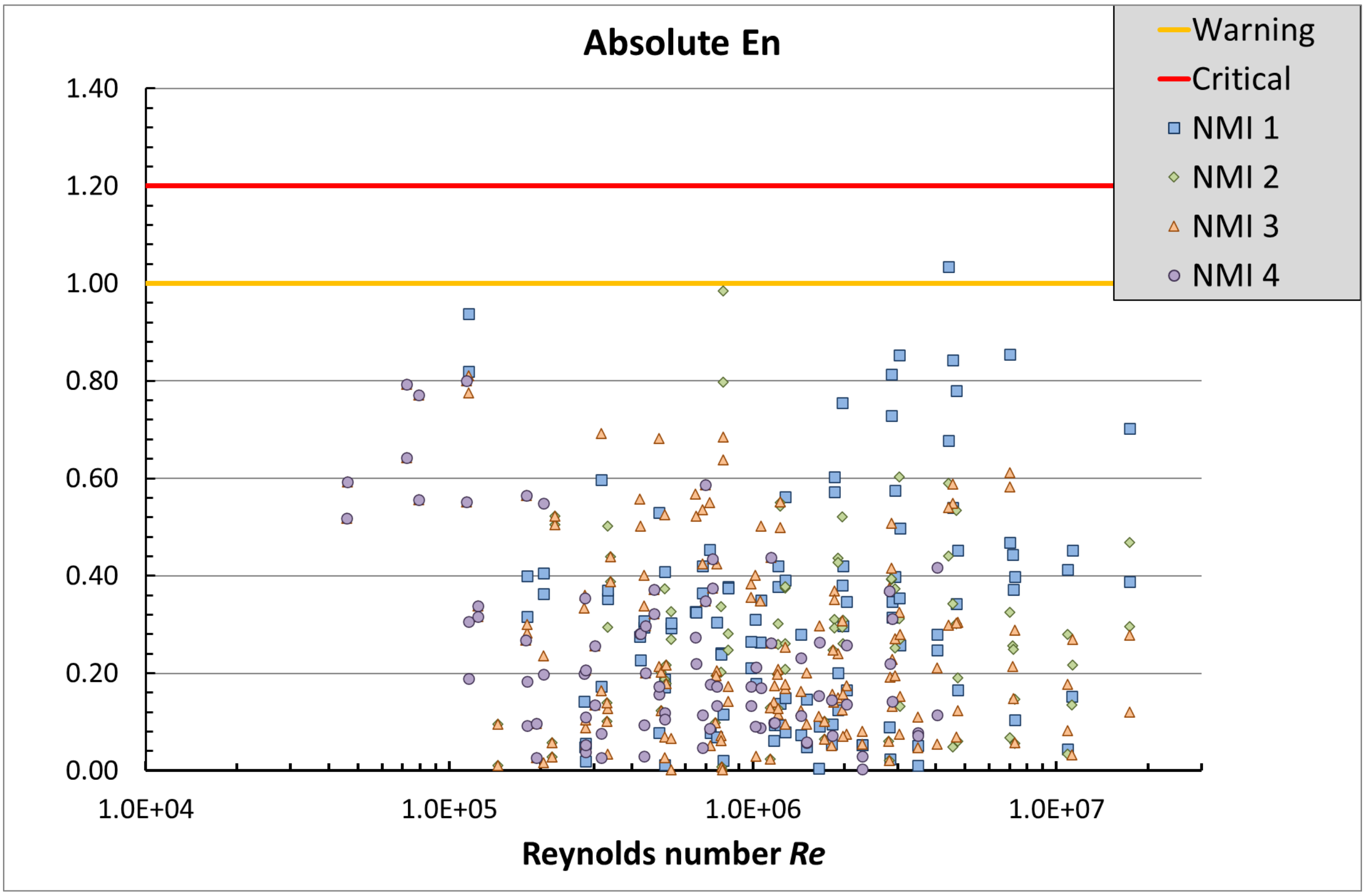

Fig. 4: $|E_n|$-values versus *Re* for EuReGa's 2020 intercomparison. Reprocessed from [7] with slight modifications.

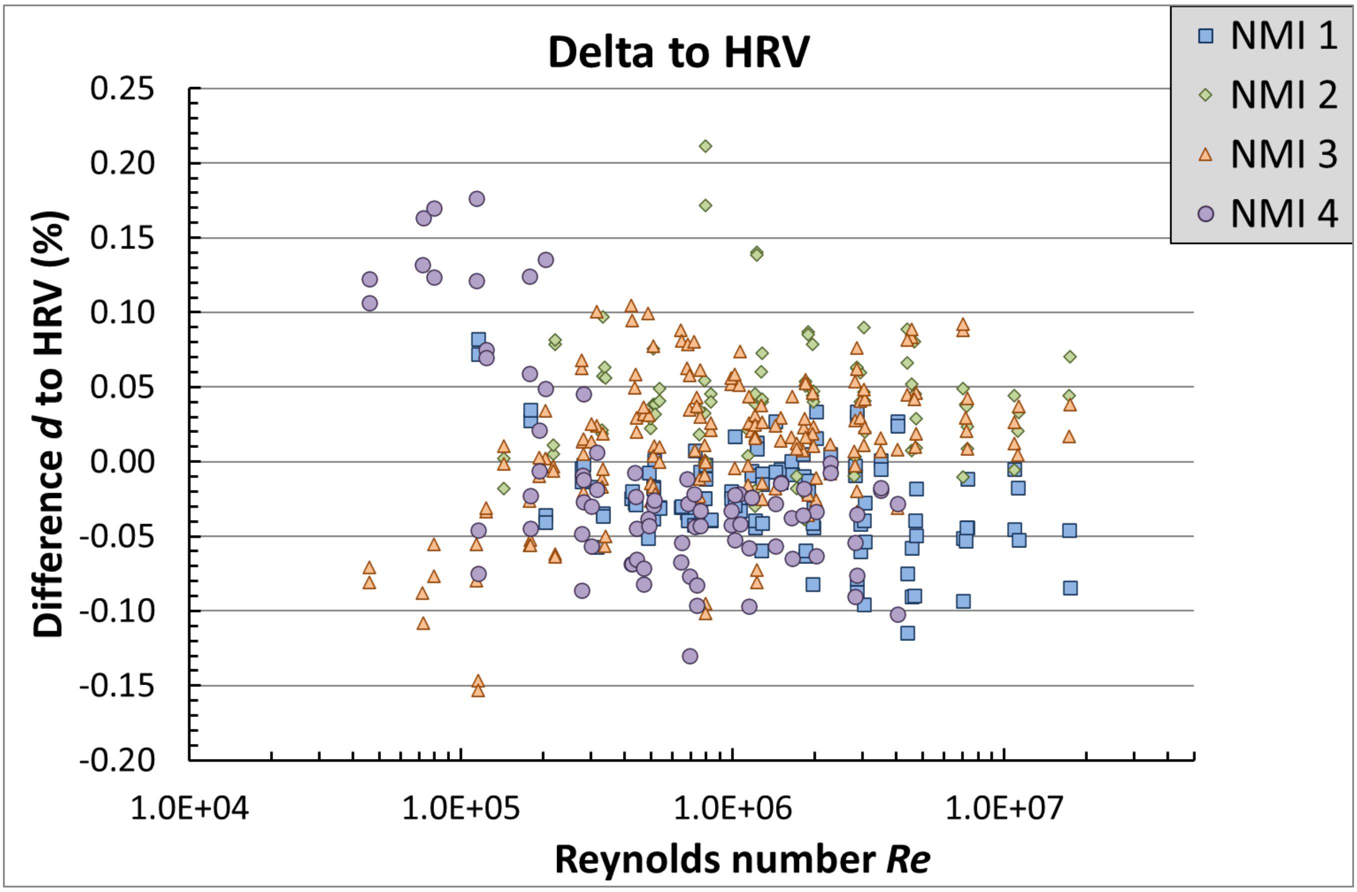

Fig. 5: Individual laboratories' differences *d* with the HRV versus *Re* for EuReGa's 2020 intercomparison. Reprocessed from [7] with slight modifications.

2.2 Harmonization method

The HRV is the weighted average of measurement results from the involved calibration facilities, with the weighting factor inversely proportional to the square of the uncertainty with which a laboratory can determine the gas volume. The HRV serves as the new reference value for all participating laboratories, with national reference values adjusted accordingly [1]. The full mathematical background is given in [2,9] of which a summary in words is given here. Within an EuReGa intercomparison, meter packages are sent around between the four participating laboratories. Every laboratory then calibrates (a subset of) the meter packages, depending on the flow rate range and pressure range that an individual laboratory can handle. The meter sizes range from 100 mm up to and including 400 mm (and EuReGa partners are currently expanding the intercomparison with a 600 mm sized meter). The mathematical process of the harmonization ensures that (relatively minor) differences in flow points, calibration pressures and temperatures, and natural gas compositions are corrected for through the establishment of error curves per calibration laboratory. These are then used for the creation of the common reference value (per nominal pressure), where the weighting factor of a laboratory is inversely proportional to the square of the uncertainty of the laboratory. It is further ensured that the common reference value is only determined in ranges that are overlapping between the calibration laboratories. Consistency checks are performed to remove probable outliers of an individual laboratory so that they don't affect the HRV. E_n-values are then computed of every laboratory with respect to the HRV. At the end of the process, the reduction of an individual laboratories' uncertainty can be evaluated and the laboratory benefits from the harmonization (through a reduced uncertainty with respect to its original CMC) when repeatability and reproducibility effects are much smaller than the CMC. Or, in other words, when the stochastic contributions to the overall measurement uncertainties are smaller than the CMC.

It is noteworthy that, contrary to an intercomparison, a last correction step is performed to effectuate the harmonization. The correction is comprised of applying a polynomial correction in terms of the logarithm (with base 10) of the mass flow rate to the reference value of each of the participating laboratories. The correction is applicable to all pressures and all flowrates with which a laboratory participated in the intercomparison. It is called the Generalized Feedback Factor (GFB) and is different for each laboratory.

2.3 Agreed reference values and reduction in uncertainty

Figure 6 shows the GFB (solid lines) versus mass flow rate from EuReGa's 2020 harmonization. The datapoints are the sign-reversed differences with the HRV (which are in Figure 5). The GFB is applied to individual laboratories' reference values so that they are harmonized between the laboratories. The stability (small drift) and agreement of EuReGa's laboratories is apparent from the relative small absolute values of the GFB's.

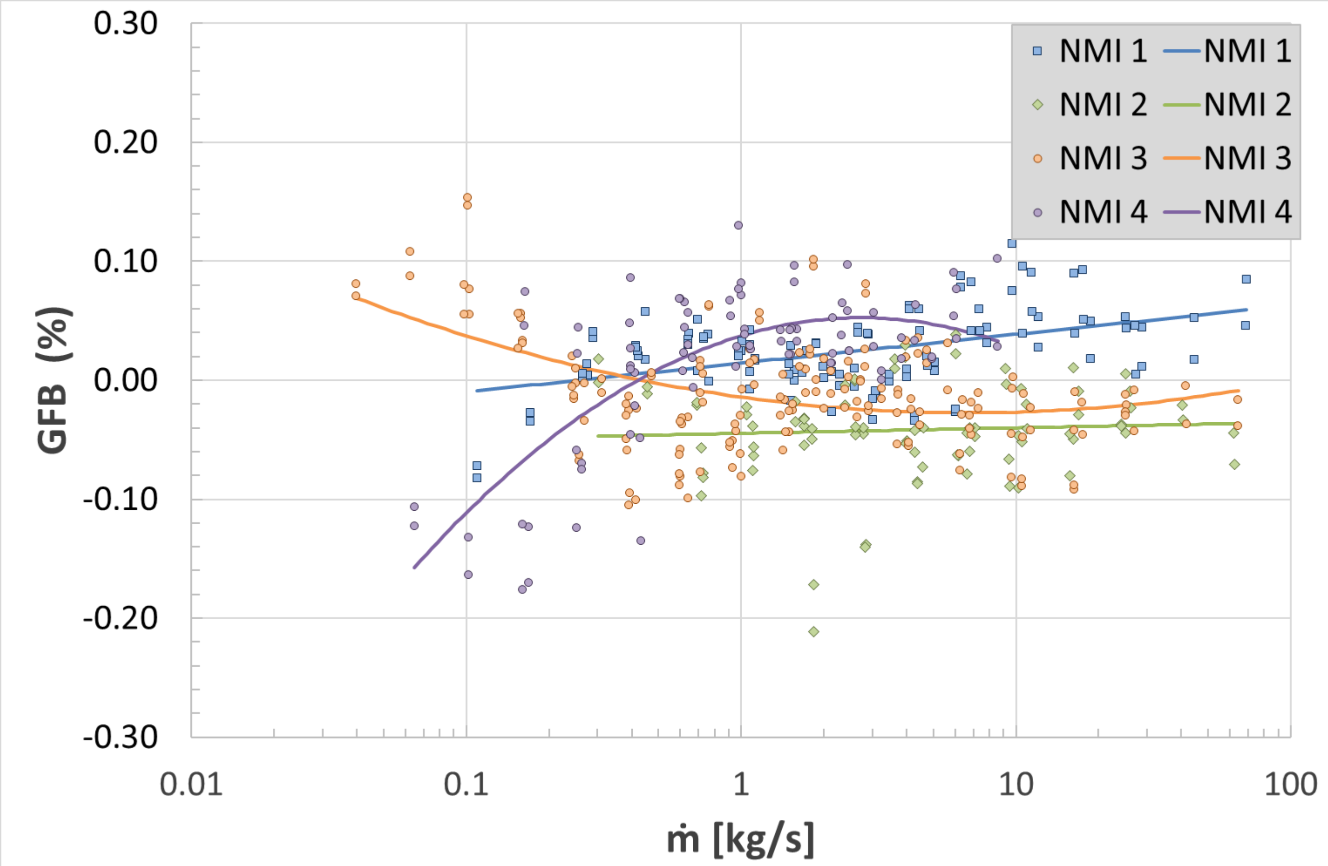

Fig. 6: GFB versus mass flow rate ṁ from EuReGa's 2020 harmonization.

Figure 7 shows the laboratories' differences with the HRV after their correction with the GFB. If the GFB's were perfectly matching the differences with the HRV, then no scatter would remain. The result clearly indicates that the harmonized values can be expected to be in agreement with each other to within ±0.1 %, a remarkable improvement with respect to the pre-EuReGa era where differences up to ±0.2 % in error were observed. This statement, of course, is valid once the GFB's are applied to the specific dataset of the intercomparison. Over time, calibration facilities' reference values can be expected to be subject to drift. For this reason, EuReGa-partners perform repeated intercomparisons in a three-years cycle.

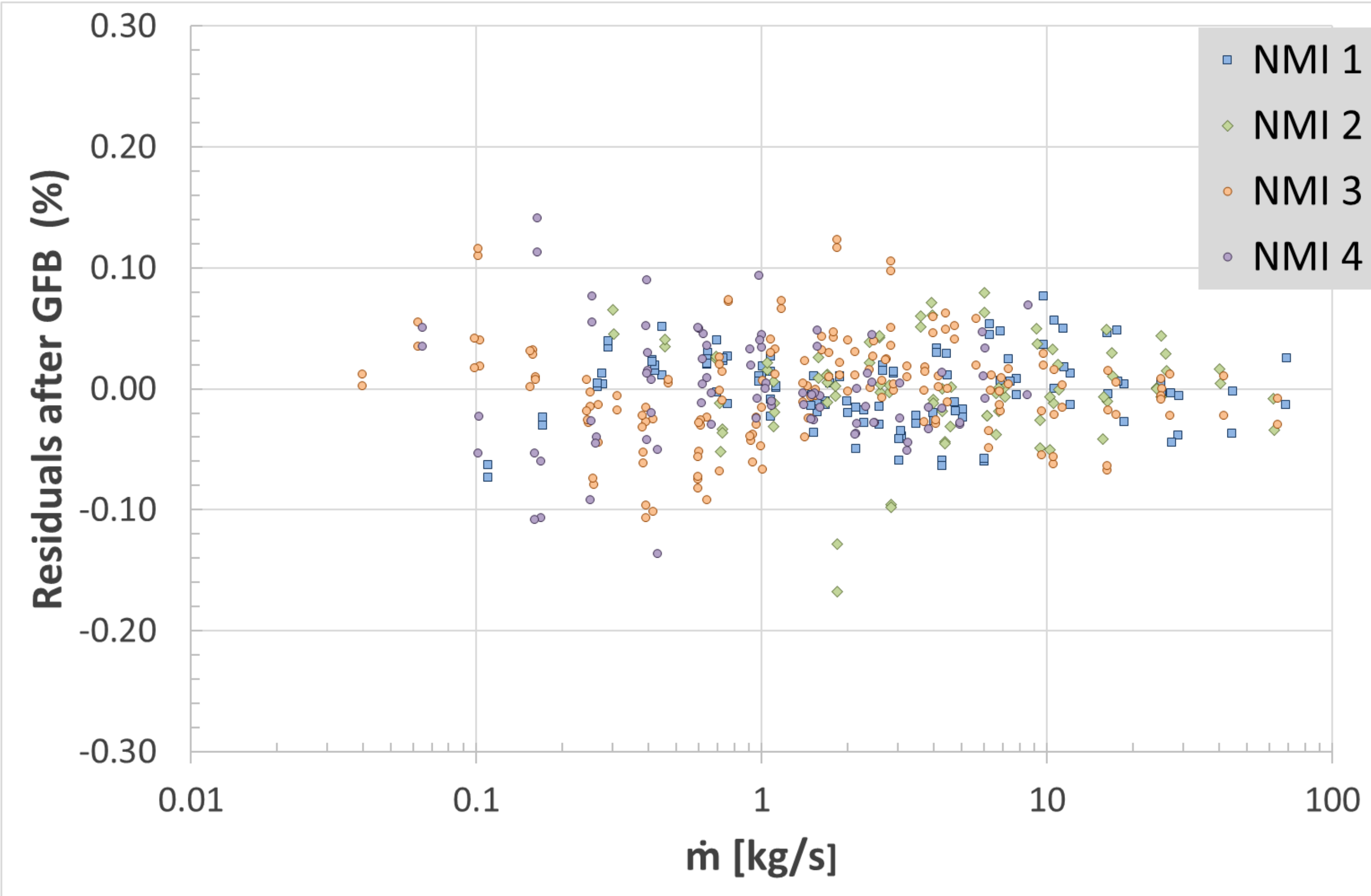

Fig. 7: Laboratories' residuals, i.e., *-d* from Figure 5 after their correction with the GFB.

During the history of EuReGa, additional metrological achievements have been made as a consequence of its knowledge sharing and commitment to the realization of the HRV.

Figure 8 shows that after the start of harmonizations in the year 2000, working standards average variability versus time reduced for the (identical, i.e., same meter types and models) working standards at Westerbork, which is a former calibration facility in The Netherlands [9].

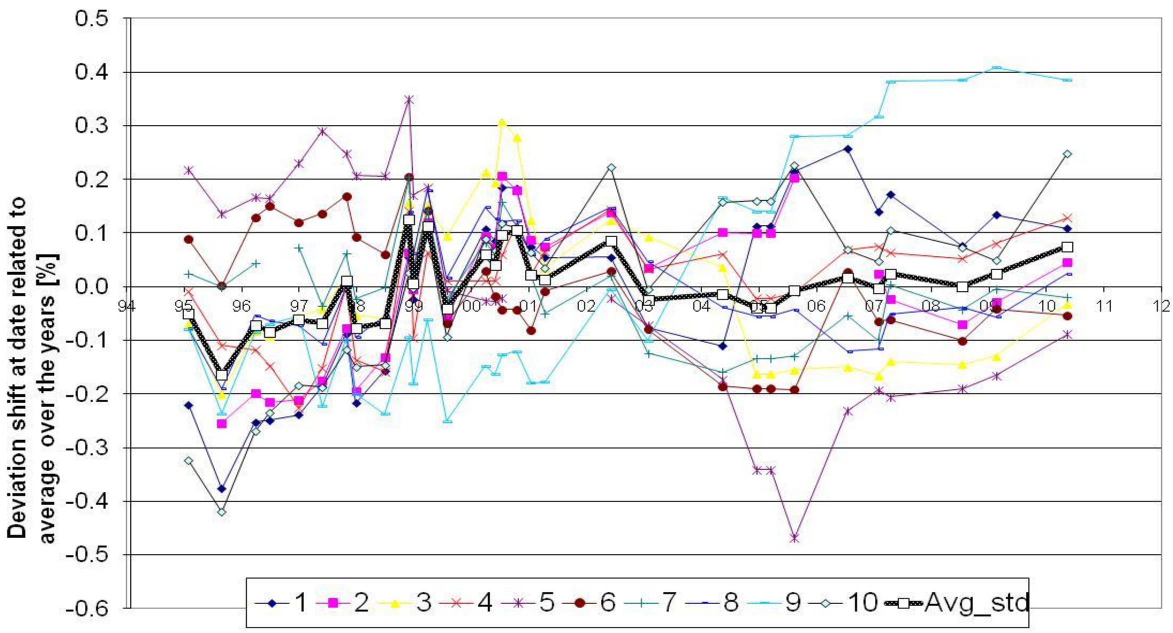

Fig. 8: Average deviation shifts of ten identical working standards from 1995 to 2011. Reprocessed from [5].

Table 2 shows specifications of three high-pressure gas piston provers belonging to EuReGa-partners showing the relatively small uncertainties of EuReGa's primary standards, which are the basis for the low uncertainties of the calibration facilities (c.f., Figure 3). As a result of EuReGa's continuous collaboration, these small uncertainties at the primary level were proven through (inter)comparisons (see [10],[11]). As can be inferred from Table 2, the CMC's of EuReGa's primary standards are below 0.10 % (k = 2) levels or, in other words, at sub-permille levels [3].

Table 2 – EuReGa's primary standards. Reproduced from [10,11] with slight modifications.

Institute & Country	Unit	VSL The Netherlands	PTB Germany	FORCE Denmark
Primary device		24" Piston Prover (GOPP)	10" Piston Prover (HPPP)	26" Twin Piston Prover
Piston		Passive	Passive	Active
Nominal diameter	mm	600	250	660
Absolute operating pressure	bar	1 – 65	8 – 51	1 – 66
Piston stroke	m	12	6	2.8
Effective piston stroke	m	6.5	3	0.6 – 2.7
Flowrate range	m^3/h	3 – 40; 40 – 230	3 – 480	2 – 400
Maximum piston speed	m/s	0.25	3	0.17
CMC (k = 2)	%	0.09 – 0.29; 0.06 – 0.09	0.065	0.080

The above results show that the EuReGa-partners have greatly stimulated the robustness of the traceability chains, from the primary level, to the transfer device(s), and up to the calibration facilities and in the (calibration history) of the harmonization meters. This is turn delivers the high accuracy trust in trading of huge volumes of natural gas.

2.4 Acceptance of the harmonization method

First harmonization efforts by the National Metrology Institutes (NMI) of the Netherlands (VSL) and of Germany (PTB) were accompanied with discussions on whether adjustment of units through harmonization can be accepted from a metrological point of view. To put it simply: a correction to a national reference value can be perceived as a form of manipulation. But such a perception does not recognize the fact that the establishment of the HRV of the independently calibrated harmonization meters brings more information than that what can be achieved by the independent laboratories alone. Indeed, even the laboratory with the lowest CMC can reduce its uncertainty so long as repeatability and reproducibility effects are much smaller than its CMC. A (hypothetical) numerical example illustrates the point. The standardized uncertainty u_{HRV} of the HRV is given by [2,12]:

$$\frac{1}{u_{HRV}^2} = \sum_{i=1}^{M} \frac{1}{u_i^2}. \qquad (1)$$

For a simple case with two laboratories (M = 2) having identical calibration uncertainties $u_1 = u_2 \equiv u$, this yields:

$$u_{HRV} = \frac{u}{\sqrt{2}}. \qquad (2)$$

Equation 2 shows that a reduction of about 30 % is achieved with respect to the individual laboratory uncertainty. The hypothetical example can be expanded to M laboratories yielding:

$$u_{HRV} = \frac{u}{\sqrt{M}}. \qquad (3)$$

Equation 3 suggests that for an infinite number of laboratories $\lim_{M \to \infty} u_{HRV} = 0$: there is no uncertainty in the HRV.

In practice, these examples are too simplistic. It must be noted that the "scatter", from type-A uncertainty sources, will always result in non-identical calibration uncertainties of the different laboratories. In addition, EuReGa's harmonization meters typically show drift in their error values of about 0.05 % per harmonization round (e.g., [2]), which also must be taken into account.

There is a more subtle, somewhat non-physical, reason to harmonize natural gas reference values. The confidence in its trading is stimulated not only by the accuracy (low uncertainty) of its measurements, but also by the reference values being *agreed* and therefore recognized between parties. Gas network imbalances are minimized by using the same reference values.

3 Energy gas harmonization for the European hydrogen backbone

3.1 Independent traceability chain development for hydrogen gas flow

Direct SI-traceable, pure hydrogen gas flow traceability up to 1000 m^3/h is developed within an ongoing European Partnership on Metrology project called H2FlowTrace [13]. The primary standard is a pressure, Volume, Temperature, time, (*pVTt*) system at Cesame, the Designated Institute of France, with which sonic nozzles are being calibrated with pure hydrogen at approximately 20 kg/h maximum flow rate. It is planned to use the calibrated nozzles in a parallelized fashion at Natran to calibrate another set of nozzles at approximately 120 kg/h hydrogen maximum flow rates. Thereafter it is planned to use the larger nozzles, again in parallelized mode, for the calibration of G400-sized rotary master meters at DNV [14]. The transfer devices to accommodate the flow and pressure upscaling steps are being developed by four NMI/DIs: Cesame, PTB, SMU, and VSL. The targeted uncertainty on the directly SI-traceable pure hydrogen gas flow traceability thus established is at ≤0.30 % ($k = 2$), planned to be delivered in 2026 [15].

Further initiatives for pure hydrogen gas flow *pVTt*-standard development at relatively small scale (4 kg/h and maximum absolute pressure at 30 bar) have been undertaken by several European NMIs (METAS, NEL, and JV). The targeted uncertainties are ≤0.3 % ($k = 2$). For the longer term, it is stated that these levels should be well within 0.2 % ($k = 2$) [16].

Pure hydrogen and hydrogen blend gas flow calibration facilities have been commissioned in recent years without direct SI-traceability [14,17]. Instead, they rely in their SI-traceability on alternative gas flow calibrations combined with sophisticated meter modelling (e.g., [18,19]).

3.2 Scenarios towards harmonization of pure hydrogen gas flow references: "EuReGaH2"

Current estimates of measurement uncertainties for pure hydrogen gas network calibration facilities are (expected) to be at a level of 0.2 % - 0.5 % ($k = 2$) [15, 17, 20] for (expected) absolute pressures up to 90 bar and flow rates up to 6500 m^3/h. As sketched above, the primary standards, transfer device(s), and SI-traceability method for pure hydrogen networks are under development and certainly not as mature as taken care of by EuReGa-partners for natural gas. Indeed, the full harmonization process leads to calibration facility uncertainties as low as 0.17 % ($k = 2$), for flow rates that go up to 50 000 m^3/h. From EuReGa's history, collaboration for harmonization of pure hydrogen cubic metre reference values as established by the different primary (and indirect) standards can be expected to yield metrological benefits. Systematic errors being made in a traceability chain have more chance to be identified. By the nature of the continuous intercomparison and harmonization, overall measurement uncertainty will be reduced. Knowledge transfer in a pure hydrogen collaboration group, here tentatively termed "EuReGaH2", will improve its calibration practices.

Figure 8 shows how a future EuReGaH2 could look like. Several independent, unbroken pure hydrogen gas flow traceability chains realize the pure hydrogen gas network cubic meter into a HRV for H_2: HH_2RV. The continuous harmonization makes use of harmonization meters and transfer device(s) already employed in European metrology projects, so that the longest possible history in calibration values is obtained. The intercomparison of EuReGaH2 will be registered at the Bureau International des Poids et Mesures (BIPM) in the Key Comparison Database (KCDB) so that participating NMIs/DIs can mutually recognize their reference values and other Regional Metrology Organisations (RMOs) can link to it. As time evolves, methods are developed that enable smooth participation of additional laboratories (Primary 4 and H_2 Loop 4) gradually lowering the uncertainty of the HH_2RV over time.

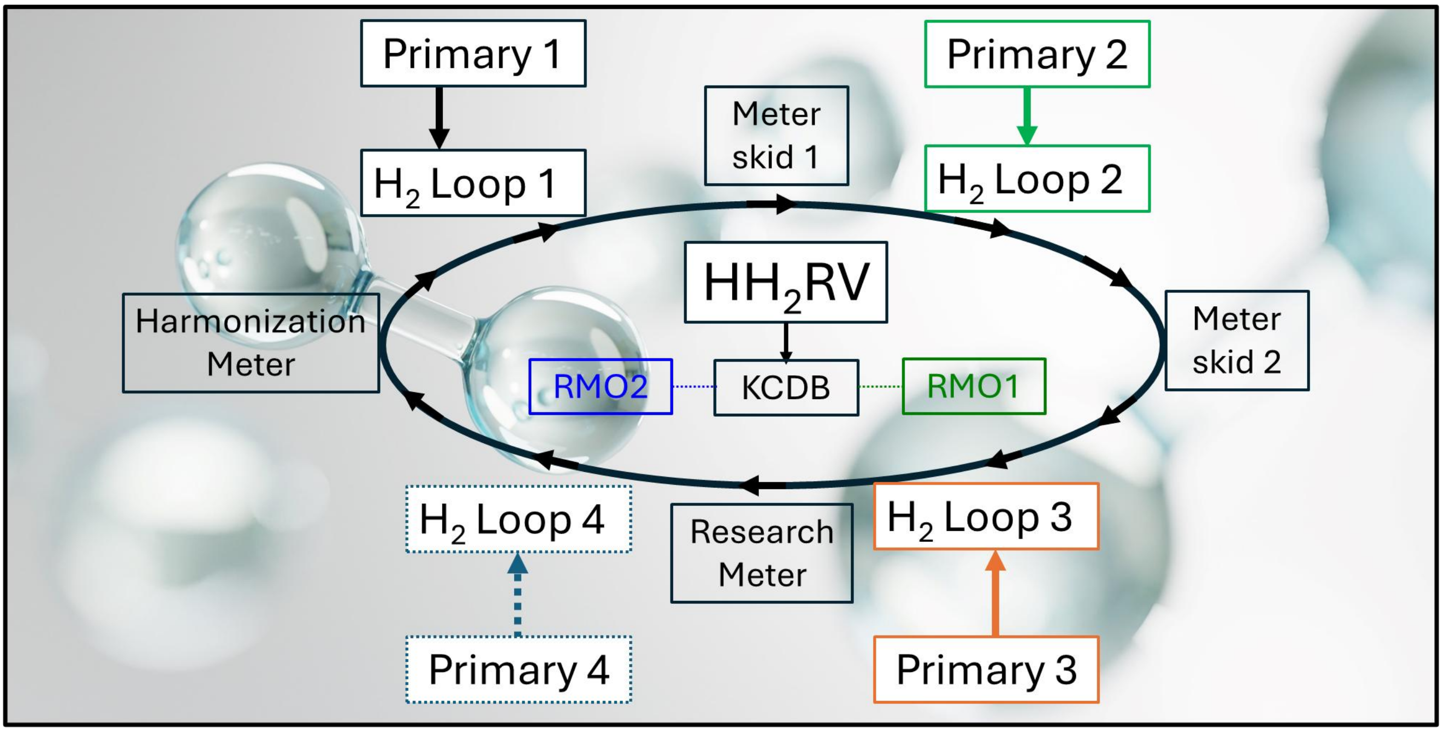

Fig. 8. Artist impression of future EuReGaH2 metrological infrastructure.

4 CONCLUDING REMARKS

Inherent to the process of harmonization, measurement uncertainties are reduced. Harmonization involves performance of continuous intercomparisons, of which agreed benefits are that they enable to identify systematic errors being made and, if agreement is found, support uncertainty claims with which reliable measurement is achieved. Harmonization takes a further step in reducing measurement uncertainty of the HRV by reducing a laboratories' measurement uncertainty (so long as the stochastic contributions to the overall measurement uncertainties are significantly smaller than the uncertainties arising from the independent traceability chain) by exploiting additional, independent, information from the other laboratories. A next step is made by ensuring that the same, *agreed*, reference level is achieved and used by different calibration laboratories. When trading natural gas of high monetary value, such agreement is needed to remove grid imbalances and fiscal risk. Indeed, reducing differences in calibration errors from 0.2 % to smaller than 0.1 % is crucial for Transmission and Distribution Grid Operators.

In 25 years of European harmonization of the natural gas metering reference the following was achieved:

- Sub-permille uncertainty of primary standards: i.e., below 0.10 % (k = 2).
- Stability of transfer device(s) and calibration laboratories.
- Differences in errors as established by different, independent calibration laboratories are within ±0.1 %.
- Smaller uncertainties from the mathematical processes employed for harmonization, and also from identification of best metrology practices and identification of systematic differences. Typical calibration facility CMC's at 0.17 % (k = 2) levels.
- Agreed, stable reference values for the high-pressure natural gas transmission grid.
- Best intercomparison and harmonization practices developed to make the optimal (apple-to-apple) comparison where relatively minor differences in calibration conditions are removed, and where an overall reduction of measurement uncertainty is achieved for every participating laboratory (when the stochastic contributions to the overall measurement uncertainties are smaller than the CMC).
- Considerable scientific metrology knowledge building and dissemination in scientific publications and training of metrologists in Europe and worldwide.
- Acceptance of the harmonization process by proving its benefits mathematically and economically.

The natural gas experience from EuReGa supports accelerating establishment of reliability in trading across Europe's integrated hydrogen backbone. With the ongoing pure hydrogen SI-traceability chain developments, the concepts, practices, and organisational structure for future H_2 harmonization are already in place. This is highly needed, as current uncertainty statements of high-pressure H_2 European backbone gas flows are currently relatively large (0.2 % - 0.5 %, k = 2). A future energy system with hydrogen will require them to be at levels currently seen for high-pressure natural gas trading as low as 0.17 % (k = 2) for the largest flows at the highest pressures (65 bar(a)).

5 NOTATION

u Standardized uncertainty constant with value u
u_{HRV} Standardized uncertainty of the HRV
u_i Standardized uncertainty of laboratory i
M Number of laboratories with independent traceability chain

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