

Measurement Uncertainty in the Totalisation of Quantity and Energy Measurement in Gas Grids

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Abstract: The total quantity and energy delivered through a gas grid is calculated using simple formulæ that sum the increments measured at regular time intervals. These calculations are described in international standards (e.g., ISO 15112 and EN 1776) and guidelines (e.g., OIML R140). These guidelines recommend that the associated measurement uncertainty is evaluated assuming the measurement results to be mutually independent. This assumption leads to the underestimation of the measurement uncertainty. To address the growing concern among transmission and distribution system operators, the underlying assumptions of these uncertainty evaluations are revisited and reworked to be more adequate. The dependence of measurement results coming from, e.g., the same flow meter and gas chromatograph will be assessed for correlations, as well as other effects, such as the effect of the chosen mathematical approximation of the totalisation integral and fluctuations in the flow rate and gas quality. In this paper, an outline is given for improvements that can be implemented in the measurement models to render them more responsive to the error structure of the measurement data, temporal effects in these data, and the fluctuations in the gas quality and gas quantity. By impact assessment using a simple scenario involving the injection of (renewable) hydrogen into a natural gas grid, it is shown that these improvements lead to a substantive difference. This preliminary work demonstrates that correlations occur both in the instrumental measurement uncertainty and due to temporal effects in the gas grid. To obtain a fit-for-purpose uncertainty budget for custody transfer and grid balancing, it is key to enhance the current models and standards accordingly.



Academic Editor: Kumar Patchigolla

Received: 30 November 2024

Revised: 3 March 2025

Accepted: 28 March 2025

Published: 3 April 2025

Citation: van der Veen, A.M.H.; Folgerø, K.; Gugole, F. Measurement Uncertainty in the Totalisation of Quantity and Energy Measurement in Gas Grids. *Gases* **2025**, *5*, 7. <https://doi.org/10.3390/gases5020007>

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Keywords: natural gas; hydrogen; flow rate; gas composition; correlation; integration error; serial correlation

1. Introduction

From exploration to the end-user, natural gas and other energy gases undergo many custody transfers. These changes in ownership involve financial transactions that are based on measurement results [1–5]. Requirements for these measurements are described in standards [6,7] and recommendations [8]. To aid the implementation of these documents, there are many standards describing flow metering [9–13], gas chromatography [14–19], and other measurement devices [20,21] to obtain the necessary measurement results. Many of these standards describe aspects like calibration, operation, and the performance requirements of equipment and methods, as well as the uncertainty evaluation of the measurement results. They represent the state of the art in the fiscal metering of natural gas and related energy gases.

The evaluation of measurement uncertainty is an integral part of these requirements [6–8] and is described in said standards [9–15,20,21]. Usually, the guidance provided is based on the law of propagation of uncertainty (LPU) from the Guide to the Expression of Uncertainty in Measurement (GUM) [22,23]. Knowing the measurement uncertainty is critical when performing conformity assessments [24,25]. A conformity assessment is performed to demonstrably meet contractual, regulatory, and legislative requirements.

In the evaluation of measurement uncertainty, usually, it is assumed that the measurement results obtained in fiscal metering are mutually independent [5,6,8]. It will be shown shortly that this assumption is inappropriate, as there are several factors that lead to results being correlated. Different factors lead to different kinds of correlations. The need to evaluate correlations as part of any measurement uncertainty evaluation is well covered in the GUM [22,23,26], irrespective of whether the LPU or the Monte Carlo method (MCM) is used. Some standards deal appropriately with correlations, such as ISO 6976 for the calculation of, e.g., the calorific value and the compressibility factor [27]. Including correlations in an uncertainty evaluation can increase or decrease the uncertainty of the output quantity [28]. If the correlations are strong, then it can be expected that ignoring them will lead to an incorrect value for the measurement uncertainty.

The models used for the calculation of the volume or energy delivered generally sum the volume or energy increments over time ([6], clause 10). With regard to the evaluation of measurement uncertainty, usually, it is assumed that the quantities of interest (e.g., volume and calorific value) are mutually independent and essentially normally distributed. Whereas the latter assumption is usually unproblematic, the assumption that the measurement results are mutually independent is only valid under quite specific conditions. These conditions include (1) a steady state with respect to the flow rate and composition of the gas stream and (2) negligible systematic effects in both the flow meter and the device used to measure the calorific value (often a gas chromatograph (GC)). Any violation of these conditions will give rise to an increase in the measurement uncertainty.

Steady-state conditions with respect to the flow rate and composition in gas grids are rare. Due to fluctuations in supply and demand, flow rates differ, and the use of different kinds of natural gas gives rise to fluctuations in composition. In an era in which gas grids are facing the further diversification of the gas entering the grid (e.g., biomethane, hydrogen, natural gas import), with the fluctuations also increasing, it is obvious that this diversification contributes to the even greater violation of these assumptions. Whereas the current guidance to some extent acknowledges these issues [6], the measurement models and the uncertainty calculations do not take the effects of the practical measurement conditions into account [5].

In the project called “Metrology for the hydrogen supply chain” (Met4H2) [29] within the European Partnership of Metrology programme, one objective is devoted to developing novel methods for the evaluation of measurement uncertainty along the supply chain, namely with regard to the measurement of the quantity and energy and impurity content of hydrogen and hydrogen blends.

The associated work is structured to start with natural gas (for which abundant experience and data are available) through hydrogen-enriched natural gas (blends of hydrogen from renewable sources and natural gas) to grids with hydrogen only.

To fully understand this objective, it is important to reiterate that the internationally agreed guidance on the evaluation of measurement uncertainty, namely the GUM, requires the evaluation of any covariances between dependent input quantities ([22], clause 5.2). This evaluation of covariances is perceived by many as difficult, yet it can constitute the difference between a realistic value for the uncertainty and an unrealistic one [30]. A realistic value for the uncertainty is required for both gas allocation purposes (i.e., the quantity

and energy balance in the grid [31]) and to demonstrate conformity with regulatory and contractual requirements.

In this paper, an overview of the ideas behind the envisaged novel methods for data evaluation is given. The overview focuses on three aspects:

- (a) the effects due to the measurement of the relevant parameters (Section 2);
- (b) temporal effects (Section 3); and
- (c) the approximation of the total volume, mass, or energy by a summation of increments (Section 4).

The methods to evaluate these effects under consideration are described. The theoretical arguments for the need for these improvements are corroborated by some motivating examples. The mentioned project [29] will provide a package of validated methods, supported by detailed examples of how the methods can be employed and their impact.

2. Volume, Mass, and Energy Measurement

2.1. Framework

The basis for computing the total mass, volume, and/or energy is given in ISO 15112 [6]. For the total mass and volume, the flow rate as a function of time is the key input. The evaluation of measurement uncertainty is described in several ISO standards [9–11,32]. Such methods for the evaluation of measurement uncertainty are fundamental in evaluating the measurement uncertainty associated with the total mass or volume of the gas metered.

For the measurement of energy, the calorific value, again measured as a function of time, comes into play, supplementing the measurement of the total mass or total volume. The calorific value can be measured directly using a calorimeter or some other inferential device [21] or by measuring the composition by gas chromatography [14,15], followed by the computation of the calorific value using ISO 6976 [27]. The standards ISO 6974 and ISO 6976 provide methods for the evaluation of the measurement uncertainty associated with the calorific value obtained from a measured natural gas composition. These methods do not account for the dynamic effects in gas grids, nor do they provide information about how to aggregate such measurement results.

There are many possible configurations and approaches to the measurement of energy [6], but, for modelling, it is sufficient to start with a simple configuration. Such a configuration could consist of one flow meter, one temperature transmitter, a pressure transmitter, and a gas chromatograph. Such a configuration suffices to outline the relevant improvements to the uncertainty evaluation. Once the methods to obtain a credible uncertainty statement have been developed for this instance, these methods can be applied to more complex configurations and used in gas networks, such as for gas allocation, attributing the quantity of gas attributed to a network user by a grid operator as an input or off-take for the purpose of determining the imbalance in the system [31].

Evaluating the dependencies between the input quantities in measurement models [33] is a requirement [22,33], and it can constitute the difference between a credible uncertainty statement and the serious under- or overrating of the measurement uncertainty. The evaluation of correlations in measurements is well established and covered by the relevant standards [14,15,27].

Relatively little attention is paid in the literature to correlations arising from using the same equipment to obtain a sequence of measurement results [5]. Most examples of uncertainty evaluation [22,23,26,34,35] and relevant standards [9–11,14,15,27,32] deal with a single measurement. As the uncertainty budget of a measurement result contains contributions in common with any following measurement result (e.g., from calibration), such

results are always mutually correlated. A method for the evaluation of such correlations involves using the uncertainty budgets of a pair of measurement results [30], which is in turn based on Annex F of JCGM 100 [22]. From the uncertainty budgets, the variables in common can be identified, and these contribute to the covariance between the pair of measurement results.

2.2. Mass

The mass of gas delivered over a time period can be obtained by integrating the mass flow rate as a function of time, viz.,

$$m(t_j) = \int_{t_0}^{t_j} Q_m(t) dt, \quad (1)$$

where $Q_m(t)$ denotes the mass flow rate as a function of time, and t_0 and t_j are the end points of the time interval. In practice, this integration is replaced with a summation, i.e.,

$$m(t_j) = \Delta t \sum_{i=1}^N Q_{m,i}, \quad (2)$$

where N denotes the number of mass flow measurements in the time interval $t_j - t_0$, and it is assumed that the flow rate measurements are performed at regular time intervals. Usually, the standard uncertainty of $m(t_j)$ is obtained using the LPU for uncorrelated input quantities ([22], Equation (10)). If the flow rate measurements are dependent, the standard uncertainty of $m(t_j)$ can be readily obtained using the LPU for correlated input quantities ([22], Equation (13)) or, alternatively, the LPU for multivariate measurement models from JCGM 102 [23]. The formulation of the LPU in the latter document is already in vector-matrix notation, easing implementation in computer software. The covariances can be obtained readily from the uncertainty budget for any pair $(Q_{m,i}, Q_{m,j})$, ($i \neq j$).

2.3. Volume

The treatment of volume is very similar to that of mass. The gas delivered over a time period can be obtained by integrating the volume flow rate as a function of time, viz.,

$$V(t_j) = \int_{t_0}^{t_j} Q_V(t) dt, \quad (3)$$

where $Q_V(t)$ denotes the volume flow rate as a function of time, and t_0 and t_j are the end points of the time interval. In practice, this integration is replaced with a summation, i.e.,

$$V(t_j) = \Delta t \sum_{i=1}^N Q_{V,i}, \quad (4)$$

where N denotes the number of volume flow rate measurements in the time interval $t_j - t_0$, and it is assumed that the flow rate measurements are performed at regular time intervals. The gas volume, as well as the volume flow rate, is pressure- and temperature-dependent. In the calculations for volume, the volume flow rate is converted from actual conditions (pressure p and temperature T during the measurement) to reference conditions [36]. These reference conditions differ between countries but have in common that they are fixed and without uncertainty. The conditions p, T are measured and hence have uncertainty. The correction factor is given by ([6], Annex C)

$$\frac{Q_{V_0}}{Q_{V_{\text{act}}}} = \frac{pT_0Z_0}{p_0TZ}, \quad (5)$$

where Z denotes the compressibility factor. The pressure, temperature, and compressibility factor at reference conditions are denoted by the corresponding symbols with a subscript 0. The compressibility factors in Equation (5) are functions of the gas composition [27,37]. Usually, different models are used for actual conditions and reference conditions. At reference conditions, often, ISO 6976 [27] is used, whereas, at actual conditions, equations of state are used, like AGA8 [38,39] or the GERG-2008 [37,40]. Instead of calculation from the gas composition, the compressibility factor can also be obtained from a measured density using the real gas law, provided that the molar mass of the gas is known.

Given the fact that the total volume needs to be computed at a single pressure and temperature, which are usually taken as the reference conditions [6,36], the propagation of the uncertainty for the total volume is markedly more difficult than for the case of the total mass. On the other hand, applying the LPU to Equation (4) is not much different from that to Equation (2). Only the evaluation of the covariances between pairs of $(Q_{V,i}, Q_{V,j})$, $(i \neq j)$ is more involved, as the covariance arising from the conversion factors from Equation (5) comes into play.

2.4. Energy

The energy of a gas flow is calculated from the basic differential equation [6]

$$e(t) = H(t) \cdot Q(t), \quad (6)$$

where e denotes an energy increment, H the calorific value, and Q is the flow rate of the gas. Equation (6) underlines that all quantities are functions of time. When using mass flow, the calorific value in Equation (6) is also on a mass basis, and, when using volume flow, the calorific value is that of a real gas at a volume basis. The reference conditions for the calorific value can be different from those of the flow metering [27]. Hence, the energy over a time interval $[t_0, t_1]$ is obtained by integration [6]:

$$E(t_j) = \int_{t_0}^{t_j} H(t)Q(t) dt. \quad (7)$$

From a physical point of view, it is reasonable to expect that $H(t)$ and $Q(t)$ are continuous functions. Even if, for example, a rapid change in the gas grid takes place, it takes some time before this change is visible in full in the measurement results obtained. In reality, flow meters and GCs perform measurements at regular time intervals, so all that only snapshots can be derived from the functions $H(t)$ and $Q(t)$.

For the energy determination during 1 h, the following two procedures are provided (see also paragraphs 7.2.2.1 and 7.2.2.2 in ISO 15112):

- the multiplication of the calculated volume under reference conditions with the averaged calculated calorific value of the same hour;
- in situ energy calculation in the volume conversion device using the actual measured entities for the calculation of energy based on the calculation of Q_j and H_j , followed by summing these single energy quantities over 1 h.

The latter approach approximates the integral in Equation (7) by increments over a period of time Δt , i.e.,

$$E(t_j) = \Delta t \cdot \sum_{i=1}^N H_i Q_i, \quad (8)$$

where it is assumed that the uncertainty associated with Δt is negligible in relation to the uncertainty associated with the summation of the increments. N denotes the number of increments in the period $t_j - t_0$.

Using the LPU for uncorrelated input quantities ([22], Equation (10)),

$$u^2(E) = (\Delta t)^2 \left[\sum_{i=1}^N H_i^2 u^2(Q_i) + \sum_{i=1}^N Q_i^2 u^2(H_i) \right], \quad (9)$$

where the argument t_j is dropped for brevity. If there only exist correlations among the Q_i and the H_i separately (so the covariance between any pair of (Q_i, H_j) would be zero), then the standard uncertainty associated with the energy can be obtained from

$$u^2(E) = (\Delta t)^2 \left[\sum_{i=1}^N H_i^2 u^2(Q_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N H_i H_j u(Q_i, Q_j) + \sum_{i=1}^N Q_i^2 u^2(H_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N Q_i Q_j u(H_i, H_j) \right]. \quad (10)$$

At first glance, one might assume that Equation (10) addresses all correlations. When realising that the volume flow rate was converted from actual to reference conditions [36], it becomes apparent that the Q_i in Equation (10) is correlated through the ratio of the compressibility factors Z_{act} (actual conditions) and Z_{ref} (reference conditions) dependent on the results of the GC analysis, as is the calorific value [27]. Thus, the correlation coefficient between Q_i and H_i would then be non-zero.

3. Temporal Effects

The discussion of the measurement uncertainty so far has addressed the uncertainty due to the measurement of flow rates and the calorific value. Thus, the uncertainty evaluated using Equation (10) only addresses (in part) the measurement. Under steady-state conditions, the uncertainty evaluation presented in Section 2 may provide a reasonable value for the uncertainty.

In practice, gas grids are used to support suppliers and users of gas, and, notwithstanding that the supply and demand are balanced, variations in the measured flow rates and calorific values occur. In distribution grids, for example, it can be expected that the demand is subject to a day-and-night rhythm, which might resemble a sinusoidal signal. This variability should be taken into account, as it affects the mean ([33], clause 11.7) of, say, the flow rate and, by implication, the total calculated as the sum of the increments (see Figure 1). The example given in JCGM GUM-6 shows a sinusoidal effect on the temperature of a water bath and the difference in uncertainty using a proper time-series model [41] and a naive type A evaluation assuming mutual independence of the observations ([22], clause 4.2). Periodical effects do not only occur in gas networks but, for example, also in water networks ([42], example E4.1).

Intuitively, one would expect that the obtained measurement results for the flow rates and calorific values become more uncertain with increasing dynamics in fluid flow and the diversity of the energy gases transmitted or distributed. Moreover, the magnitude of Δt plays a role here. In a gas grid with dynamics, one would expect the uncertainty of a calorific value taken as representative for a day to be more uncertain than one taken every 5 min.

Time series models can be fitted using frequentist [41] and Bayesian methods [43,44]. An important aspect in this description of the data is to find an acceptable model for the features in the data. The use of time series analysis may need data-driven modelling to be useful. Such a model choice also plays a role in the uncertainty evaluation ([33], clause 11.7), as well as the model uncertainty ([33], clause 11.10).

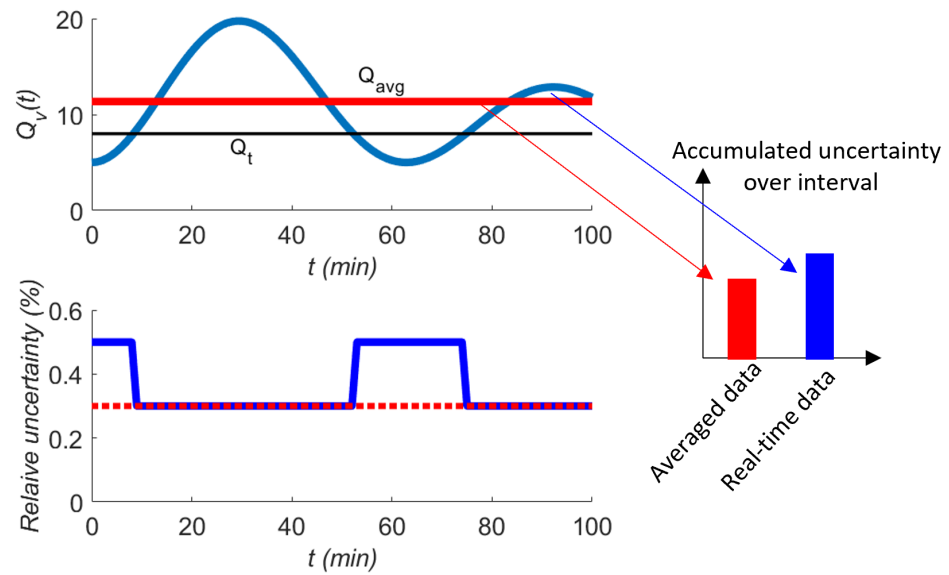


Figure 1. Schematic of the effect of dynamics on the mean and total volume measured in a metering line.

4. Totalisation

Finally, the question arises as to what extent the summations in Equations (2), (4) and (8) approximate the integrals in Equations (1), (3) and (7). This issue is visualised in Figure 2. The coloured area is the calculated total, and the area under the blue curve is the “true” total. In this example, the measurements are taken at time intervals of 10 min. With the same principle, the approximation would be improved if the measurements were taken with a higher frequency, e.g., every 1 min.

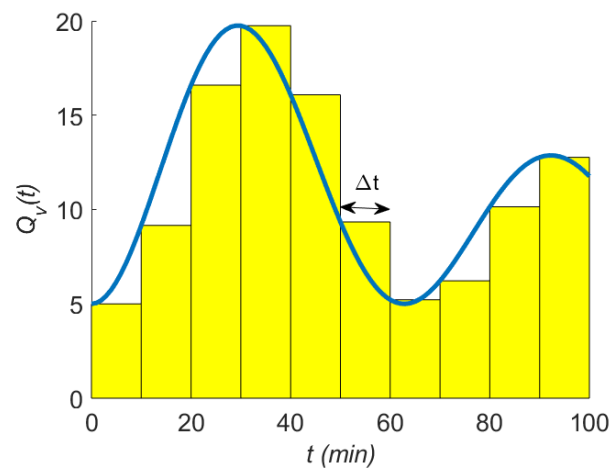


Figure 2. Numerical approximation of the integration of metering data using the approach of ISO 15112.

Apart from the time resolution of the measurements, the dynamics in the grid also come into play in this uncertainty component. A measurement result becomes less representative for a time interval if, in this interval, there are substantial changes in the quantity measured. A practical difficulty is that one has little insight into such changes (there are no measurements), yet, using the principle of the type B evaluation of measurement uncertainty ([22], clause 4.3), it should be possible to obtain a probability density function (PDF) based on the knowledge at hand. In a gas grid, there are more metering points,

and previous experience can, under some circumstances, also be applied to evaluate the measurement uncertainty arising due to changes in the grid.

For various approaches to numerical integration [45,46], the error due to the approximation of an integral by a summation is discussed. A practical issue when using these deliberations is that the solid curve in Figure 2 is not known, so it is not possible to use such approaches to estimate the error due to totalisation. Faster and even approximate measurements of the same or related quantities might help in evaluating this uncertainty component.

One of the methods considered is to use statistical filtering techniques to deal with the deterministic and random components of the signal separately. These filtering techniques perform said separation and enable the evaluation of the uncertainty of the components separately. The method and first results have been published elsewhere [47].

5. Impact of Correlations

To illustrate the impact of the issues discussed in previous sections, some sample calculations on a synthetic data set are presented. Figure 3 shows the volume flow rate of hydrogen-enriched natural gas over a period of one day. The simulated data represent flow rates at actual conditions, averaged over a 15 min time interval. The actual operating conditions are assumed to be constant at 20 °C and 50 bar over the studied day. The gas is a blend of hydrogen and natural gas, with a fixed natural gas composition and a variation in the hydrogen fraction between 15.2% and 16.8%. This scenario is among the simplest for the injection of (renewable) hydrogen into natural gas grids. Figure 4 shows the superior calorific value over the period. Table 1 lists the input quantities, their ranges, and the uncertainties applied in this example. The gas composition is shown in Table 2.

Table 1. Input uncertainties (95% coverage probability) for the studied example.

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%

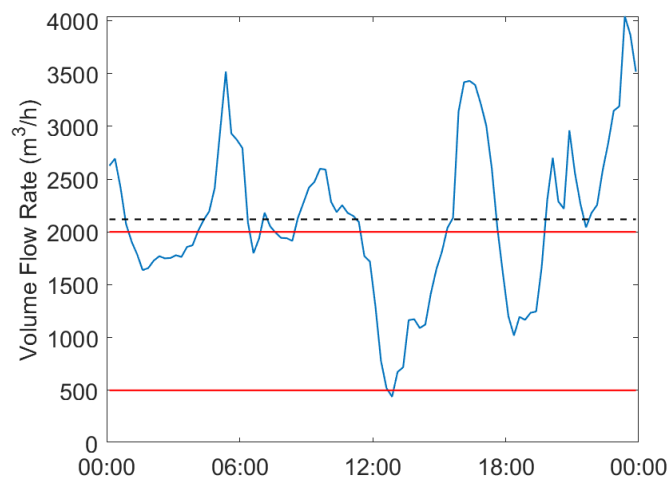


Figure 3. Volume flow rates per 15 min period at operating conditions 20 °C and 50 barg. The black line is the average volume flow rate. The red lines indicate the transition flow rate ($Q_{V,t}$) and the minimum flow rate ($Q_{V,min}$) of the flow meter.

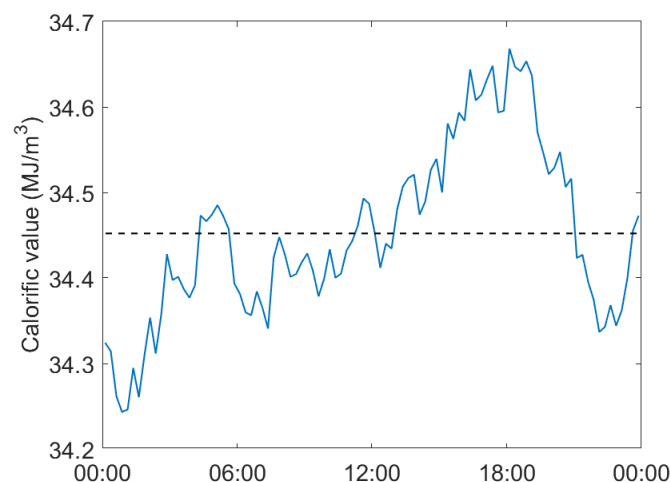


Figure 4. Superior calorific value per 15 min period for one day. The black line is the average calorific value.

Table 2. Gas composition expressed in amount fractions (x) with associated expanded uncertainty ($U(x)$, 95% coverage probability).

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

The system operator often evaluates the uncertainty of the flow daily. This evaluation may be performed based on the average flow rate at reference conditions and the average calorific value per day. In this example, the expanded relative uncertainties (with coverage factor $k = 2$) are $U_{\text{rel}}(Q_{V_0}) = 0.68\%$ and $U_{\text{rel}}(H) = 0.33\%$. These uncertainties are obtained by propagating the input uncertainties using the MCM [26]. The calorific value is calculated from the composition according to ISO 6976:2016 [27], while the volume flow rate at reference conditions is calculated using the conversion factor (Equation (5)). The compressibility factor is calculated from the composition using the GERG-2008 equation of state [40] with REFPROP [48]. If correlations between the input quantities are ignored, the relative uncertainty in energy is estimated as $U_{\text{rel}}(E) = 0.75\%$ using Equation (9). However, the uncertainties in Z , Z_0 , and H all originate from uncertainties in the composition [27,37]. Thus, the volume flow rate at reference conditions (calculated using Equation (5)) is correlated with the calorific value. This correlation coefficient is

$$r(Q_{V_0}, H) = \frac{u(Q_{V_0}, H)}{u(Q_{V_0})u(H)}, \quad (11)$$

where r denotes the correlation coefficient associated with Q_{V_0} and H . For the example case, this correlation coefficient is found to be approximately 0.48. If this correlation coefficient

is included in the uncertainty calculations as described in the GUM [22], the expanded uncertainty in energy increases from $U_{\text{rel}}(E) = 0.75\%$ to 0.89% . This increase in uncertainty underlines the importance of including correlations in the uncertainty evaluation.

The calculations in the scenario above are based on the daily average flow and composition measurements, ignoring all dynamics in the measurements. To illustrate the importance of including the flow dynamics, as was discussed in Section 4, the uncertainty in the energy flow rate for each period was evaluated, and the results shown in Figure 5. When using daily averages, the increased uncertainty at low flow rates (cf. Table 1) is missed. For this scenario, the expanded uncertainty in the accumulated energy over the day is now 0.97% when considering the flow dynamics and assuming full correlation between successive intervals, compared to 0.89% obtained using average values. This difference illustrates that the uncertainty analysis should preferably be performed based on short time intervals to capture the flow dynamics fully.

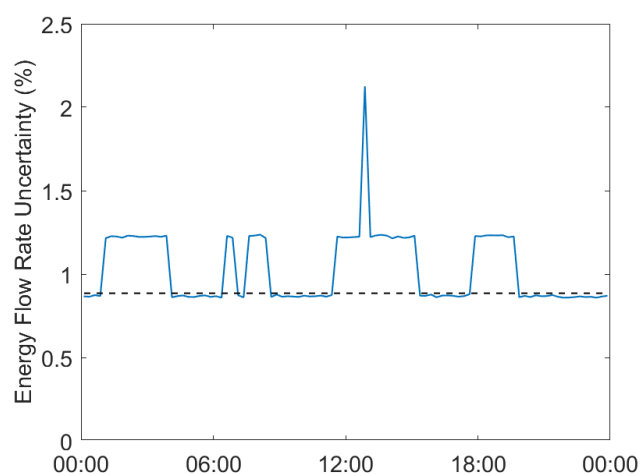


Figure 5. Uncertainty in energy flow rate for each period. The black line shows the uncertainty estimated based on the daily average flow rate and calorific value.

As emphasised in Section 2, correlations between successive measurements have a strong influence on the uncertainty in the accumulated (or averaged) energy. The uncertainties in flow rate and composition measurements are due to systematic and random effects. The systematic contributions come from, e.g., instrument calibration, which will remain constant until the next calibration, while the flow meter's repeatability is an example of a random contribution to the instrumental uncertainty. To illustrate the effect of systematic and random uncertainty contributions, the accumulated uncertainty during one day is evaluated for various values of the correlation coefficients $r(E_i, E_{i+1})$ and shown in Figure 6. Typically, the systematic effects will dominate the uncertainty, resulting in a correlation coefficient close to one. In this example, it is assumed that the uncertainty in energy for each 15 min period is calculated by including the covariance associated with Q_{V0} and H . Additionally, the correlations between all succeeding periods are assumed to be equal. Note that the calculations based on daily average values implicitly assume full correlation between the measurement periods.

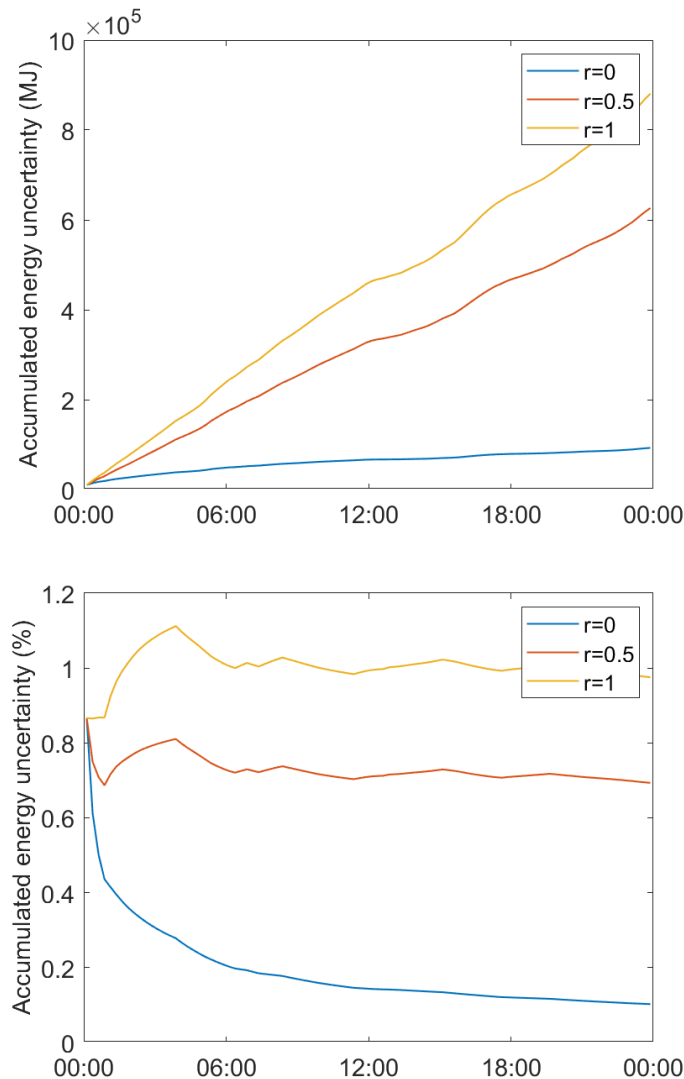


Figure 6. Absolute and relative uncertainty in accumulated energy over a day for various correlations between succeeding measurement periods.

6. Discussion and Outlook

In this paper, several shortcomings in the current uncertainty evaluation of the total mass, volume, and energy in gas grids are presented. Current models and standards assume that the measurement data are independent. Based on straightforward deliberations supported by calculations for a simple (yet realistic) scenario of blending hydrogen with a stream of natural gas, it is shown that this assumption is not sustainable. Whereas the uncertainty contributions due to temporal effects and approximating the integral by summation can be small under steady-state conditions, these uncertainty contributions can be substantial with a greater diversity of gases (e.g., biomethane, hydrogen, natural gas of different origins) in gas grids and with larger fluctuations in supply and demand.

Whereas efforts are made to balance the grid to ensure the supply of gas of adequate quality, such efforts cannot compensate entirely for the dynamics in the gas grids. In the ongoing transition from fossil natural gas to renewable gases, practices for fiscal metering need to be urgently improved to ensure that these grids can be operated safely and efficiently.

Finally, the correlation effects between measurement results coming from a single, calibrated instrument are relatively straightforward to capture with the framework of the

Guide to the Expression of Uncertainty in Measurement. Considering the large volumes of data, the use of vector-matrix algebra as described in JCGM 102 [23] is recommended to obtain a compact computer code. This approach has the additional advantage that the measurement models can be broken down into parts more freely, as the law of propagation of uncertainty for multivariate measurement models provides, by default, a full covariance matrix, so that all covariances can be readily propagated from one stage of the measurement model to the next. With the legacy GUM [22], this is much more difficult, as it presumes that a measurement model can be broken down in expressions with mutually uncorrelated input quantities.

Author Contributions: Conceptualization, A.M.H.v.d.V. and K.F.; methodology, A.M.H.v.d.V., K.F. and F.G.; investigation, A.M.H.v.d.V., K.F. and F.G.; writing—original draft preparation, A.M.H.v.d.V.; writing—review and editing, K.F. and F.G.; visualization, K.F.; supervision, A.M.H.v.d.V.; funding acquisition, A.M.H.v.d.V. and K.F. All authors have read and agreed to the published version of the manuscript.

Funding: The project 21GRD05 Met4H2 has received funding from the European Partnership on Metrology, co-financed by the European Union’s Horizon Europe Research and Innovation Programme and by the Participating States. VSL has received in part funding from the Ministry of Economic Affairs of the Netherlands for this work.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of the data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

GC	gas chromatograph
GUM	Guide to the Expression of Uncertainty in Measurement
ISO	International Organisation for Standardisation
JCGM	Joint Committee for Guides in Metrology
LPU	law of propagation of uncertainty
MCM	Monte Carlo method
MDPI	Multidisciplinary Digital Publishing Institute
PDF	probability density function

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