Unaccounted for gas in natural gas transport networks.

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Abstract

One of the main issues in the natural gas (NG) transport networks management is represented by the Unaccounted for Gas (UAG). UAG is the quantity to be considered in the balance equation to take into account the unavoidable errors due to measurements and estimations. The resulting problem is twofold: on one hand fiscal and contractual, on the other hand the unavoidable pressure from the national authorities to reduce UAG.

In this paper the authors analyse the UAG trends in natural gas (NG) transport networks and present: i) an investigation about UAG in international networks; ii) a statistical analysis of annual and monthly trends for UAG; iii) the analysis of UAG causes.

1. Introduction

Nowadays, the modern markets for energy fluids through pipeline networks, such as fuels, natural gas, heat, water, require complex technologies for their management, together with adequate measuring systems and devices for the monitoring of the fluxes. As a consequence, the balance of each network represents a fundamental tool for its management from several points of view: i) economic (in order to correctly allocate costs among the users), ii) operational (in order to guarantee a safe operation of the network) and iii) environmental [1, 2, 3].

In the case of natural gas transport, the balance potentially involve extraction and production, treatment, regasification, storage, transport, distribution. The network balance represents a very important tool because of the large number of users and the wide geographical area to which it applies. In modern networks gases from different origins are normally transported (i.e. LNG, biomethane, shale gas) and a wide variability of the composition of these gases is registered. Furthermore, even though it is essential to measure the NG transported in terms of mass or energy, today's technologies only allow direct measurements of NG volumes. Then, the volume measurements need to be successively converted into base conditions (15 °C and 101325 Pa) by employing auxiliary volume conversion devices.

Thus, for a safe and efficient operation, it is necessary to guarantee the necessary quality and effectiveness of the NG flowrate measurements and of the related thermodynamic and chemical-physical properties, such as pressure, temperature, density and Heat Value (H_s).

In any case, because of the unavoidable measuring errors and of the statistic evaluation of some terms, the closure of the Natural Gas Transport Network (NGTN) balance equation is not achievable in practice. Then it is crucial to understand the nature of the errors affecting the UAG (i.e. the difference between left-hand side and right-hand side of the balance equation) and, in particular, if these errors are physiologic or if they come from the unavoidable deterioration of the systems and components of NGTN.

Thus, the accurate knowledge of the metrological performance at operative conditions of each measuring plant in terms of uncertainty is needed.

2. The NG transport network energy balance

The physical balance of a NGTN deals with the NG transportation from the entry points (i.e. importation, production and storage) to the supply points.

To correctly perform the balancing of a system, it is clearly known that a conservative quantity (i.e. energy or mass) has to be used. Besides, for NGTN, energy is a derived quantity obtained multiplying the mass (i.e. a conservative quantity) by the heat value of the natural gas flowing. Thus, in a given control surface (i.e. the network) and for a fixed period (generally a day, a month or a whole year), neglecting both generation and destruction terms, the NGTN balance equation can be written as follows [4]:

$$I + S = P + C + PE + \Delta LP + UAG \qquad (1)$$

where, during the investigated period:

- I is the NG entering the NGTN from the entry points;
- S is the NG extracted (positive) and injected (negative) from a storage field;
- P is the NG delivered to the supply points (both individual/system supply points and connected system exit points);
- C is the own use NG needed for the functioning of the network (i.e. the gas used in running compressors and for preheating, sampling, etc.);
- PE is the estimated total losses and emissions from the NGTN (i.e. the nonvoluntary emission to atmosphere, vented for pipelines maintenance, faults and leaks);
- ΔLP is the variation of NG in the NGTN due to Line-Pack (LP);
- UAG is the unaccounted for gas.

All these terms contribute to the UAG because of the errors affecting their measurements and estimations. From equation (1) it follows that UAG does not actually represent a loss from the NGTN, but it is the difference between the different terms of the balance equation, that is between the NG entering and leaving the NGTN.

Figure 1 schematically describes typical issues of a NGTN and the corresponding terms in the balance equation of the network.

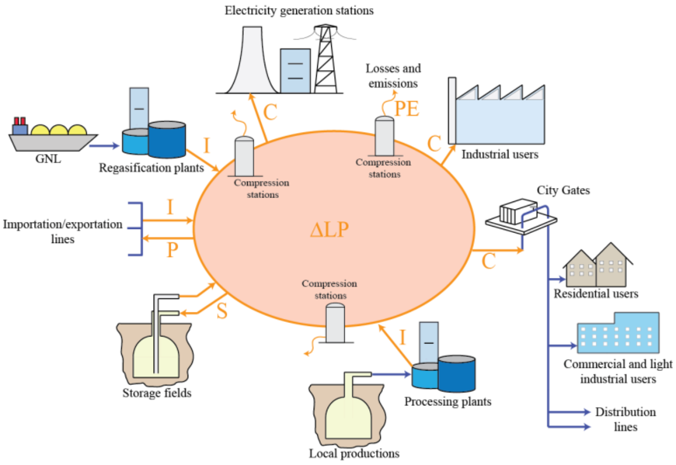

Figure 1 – Main issues of a natural gas transport network

The NG entering (i.e. importations including regasification, national productions and extractions from storage fields) and the one delivered at supply points and injected in storage fields are accurately measured by means of complex measurement chains [5]. On the other hand, some terms of the NG leaving the network (i.e. losses and emissions, own use and line-pack) are estimated by means of approximated models.

To convert the volume from operative (T, P) into base conditions (T_b, P_b) the knowledge of the NG chemical composition is strictly needed to evaluate the compressibility factor at both standard (Z_b) and operative (Z) conditions. Ideally, if the NG chemical composition is perfectly constant through the NGTN, the volume conversion into base condition could be sufficient to overtake the balancing issues previously underlined. Unfortunately, the NG composition widely varies along modern NGTNs (as an example, in fig.2 the Italian NGTN is depicted) in an unpredictable way, because of storage, importations and production dynamics. Thus, to correctly quantify the NG transported, the knowledge of the NG composition and of the thermodynamic conditions (T, P, Z) at the measuring plant is necessary.

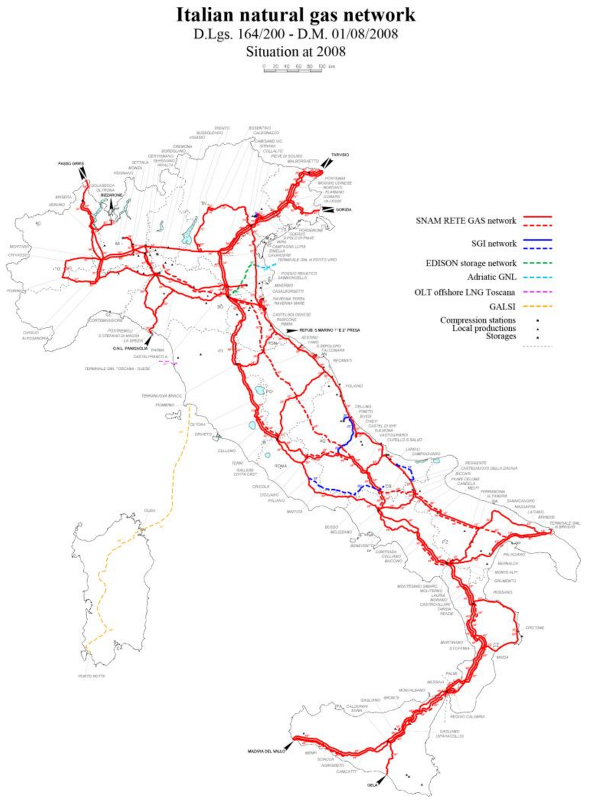

Figure 2 – Italian natural gas transport network (courtesy of SNAM)

Besides, information about NG volume at base condition must be accompanied by accurate data about the energy of the NG. In fact, since NG is a fuel which produces heat in a combustion process, NG commercial transactions must refer to the energy delivered, instead of the volume (even if at base conditions), by multiplying the NG volume by its H_S.

3. UAG in international NGTNs

In order to better understand and analyse issues related to NGTNs balancing and to correctly estimate UAG, several international NG transport networks have been investigated by the authors. In particular, the annual NGTN balances in terms of energy with reference to the Italian [6], UK [7] and US [8, 9] NGTNs have been focused.

From the data available, it can be observed that:

- UAG is always larger than zero in the Italian NGTN and it normally ranges from about 0.2% to 0.5% of the NG transported;
- UAG is generally positive in UK;
- in the last ten years UAG has been always positive in US and its average annual value is about +0.6%.

Similar UAG values and trends have been found also in the Canadian[10], New Zealand [11], Californian [12] NGTNs.

Investigation about monthly UAG trend is particularly interesting. From the available data of the Italian (see fig.3) and UK NGTN (fig. 4), similar seasonal behaviours emerge, especially for the monthly UAG trend. Furthermore, the positive trend of UAG in summer (in average about +1.4%) is much larger than the negative one in winter (in average about -0.3%). In particular, from the analysis of the available data, it can be shown that typically the negative peaks are registered in February, whereas the positive ones occur in July. Furthermore, the UAG winter variations normally cannot fully compensate the larger positive summer variation.

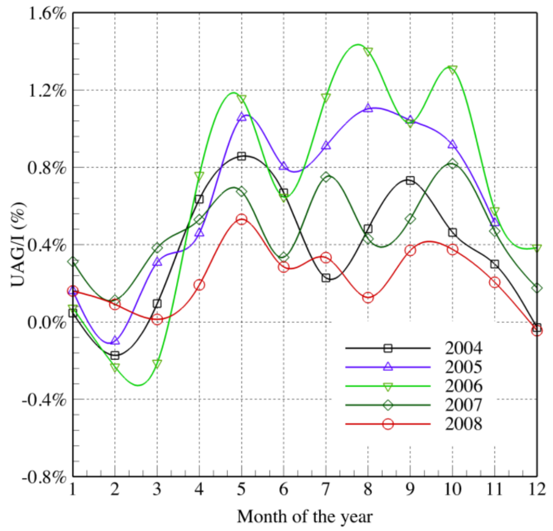

Figure 3 - Monthly UAG trend in the Italian transport network

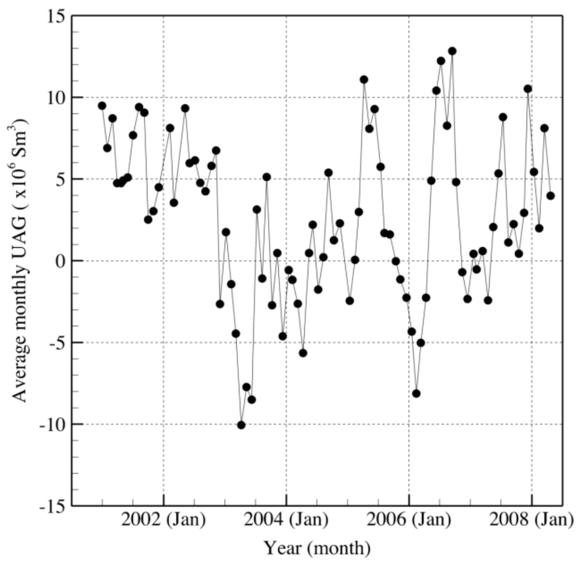

Figure 4 - Monthly UAG trend in the UK transport network

In the UK NGTN, the winter variations are larger than the corresponding ones observed in the Italian NGTN. This is probably due to the UK climate that is much colder in winter and normally presents multi-modal oscillations (generally with two/three peaks) in summer. In addition, the Italian NGTN presents a larger variability in the gas composition, due to the different importations, whereas in UK the gas composition is more homogeneous.

4. Analysis of the UAG causes

Many causes can significantly increase UAG in a NGTN [3]. As above mentioned, UAG is a consequence of the unavoidable errors in the estimation of the terms of the NGTN balance equation and, obviously, it is expected to be theoretically equal to zero. In reality, all the terms in the balance equation contribute to UAG because they cannot be exactly measured or estimated.

Each network is affected by these causes in a different way, but the main UAG causes can be considered: i) the measuring error of the NG entering and leaving the network; ii) the error in the estimation of NG losses and emissions through the network; iii) the error in the estimation of the own use NG and of the line pack variation.

In particular, the larger contribution for UAG is represented by the errors due to the complex measuring chains at the entry and supply points of the network. In fact:

- NG losses and emissions through the network are often wrongly included in UAG even though they are expected to be in a range from one tenth (in transport network) up to 10 times (in distribution networks) the UAG;
- line pack variations are negligible if estimated in a long period (i.e. one year) whereas they are consistent in the short period (i.e. day/month) and, consequently, they have to be necessarily considered in a daily and monthly UAG balance;
- the own use NG is measured only in the larger networks, where compressor stations and pre-heating systems are currently present, whereas in the other networks this contribution is normally estimated.

Finally, to correctly estimate UAG and its uncertainty and to effectively define adequate reduction strategies it is necessary: i) to determine the possible correlations between the errors of the single terms of the balance equation; ii) to predict the propagation criteria of these errors.

4.1 Correlation analysis

From the available data, a correlation between external environmental temperature and the monthly UAG is evident. This can be ascribed both to the radiative and conductive effects on the temperature transmitter (i.e. installation effects) and to the fluctuation of the gas supplied in the network due to the different consumptions among the year especially for civil purposes (accuracy effect due to the different gas flowrates).

Figure 5 and 6 show this correlation between the monthly UAG and the average temperature of the gas at the supply points, in a large and a medium transport network in Italy.

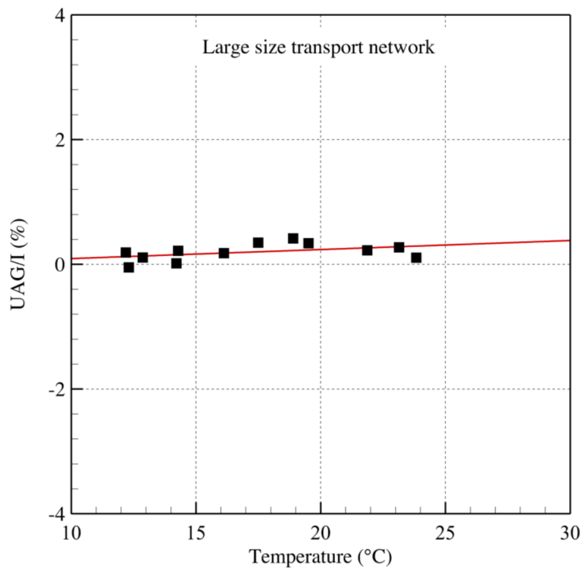

Figure 5 – Correlation between the average monthly UAG and the gas average temperature in a large transport network (≈10,000 km)

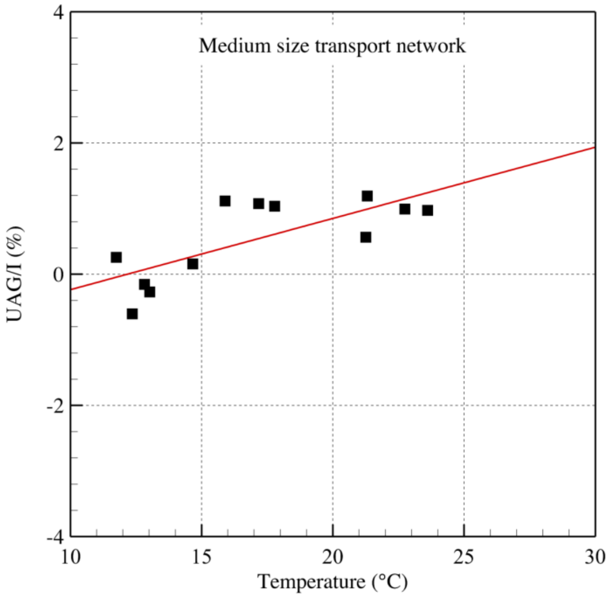

Figure 6 – Correlation between the average monthly UAG and the gas average temperature in a medium transport network (≈1000 km)

The gas temperature measurement, in fact, strictly depends on the temperature of the internal surfaces of the pipe (i.e. on the environmental temperature conditions) that irradiate the sheath of the sensor and, even if in a minor way, to the conductive contribution of the sheath on the sensor itself. Obviously, if this effect is perfectly the same both at the entry and supply points, it could not affect the balance equation and, consequently, the UAG. Unfortunately, it is usual to observe on the networks a bigger attention to the large flowrate measurements (i.e. entry points, with bigger pipe diameters) rather than to the small ones (i.e. supply points). These latter, in fact, only rarely are thermally insulated and they usually present a lower average velocity of the flux (i.e. with a consequent amplification of the radiative effect on the sensor) and small diameter of the pipeline (i.e. with a consequent amplification of the conductive effect on the sheath).

On the other hand, the seasonal correlation of UAG could be ascribed to the NG volumes transported and to the underestimation of the flowrates that generally all the “volumetric” gas flowmeters (especially the turbine ones) present at low regimes. This happens especially in summer, when the NG civil consumptions are strongly reduced.

In fact, from fig. 7 and 8, a correlation between the volumes transported and the monthly UAG clearly emerges, both in a large and in a medium NGTN. In addition, the measuring plants are normally designed with a nominal safety flowrate that rarely correspond to the average one and, therefore, they are generally oversized. Consequently, the limited rangeability of the measuring device and the not systematic application of seasonal line substitution (when possible) magnifies this effect.

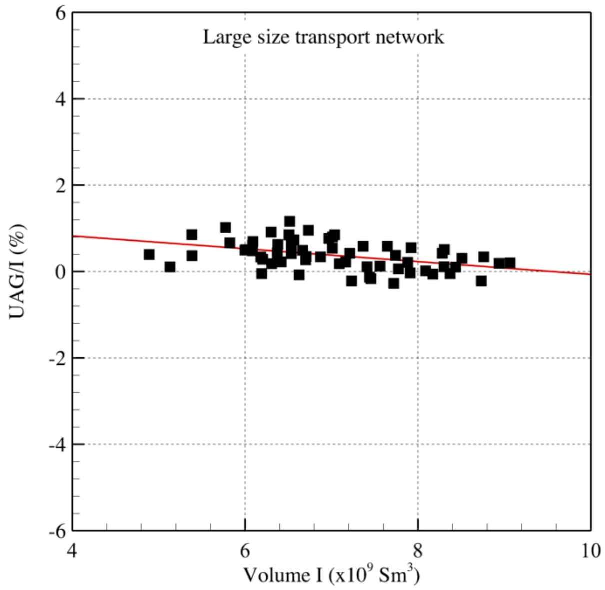

Figure 7 – Correlation between monthly UAG and natural gas transported in a large transport network (≈10,000 km)

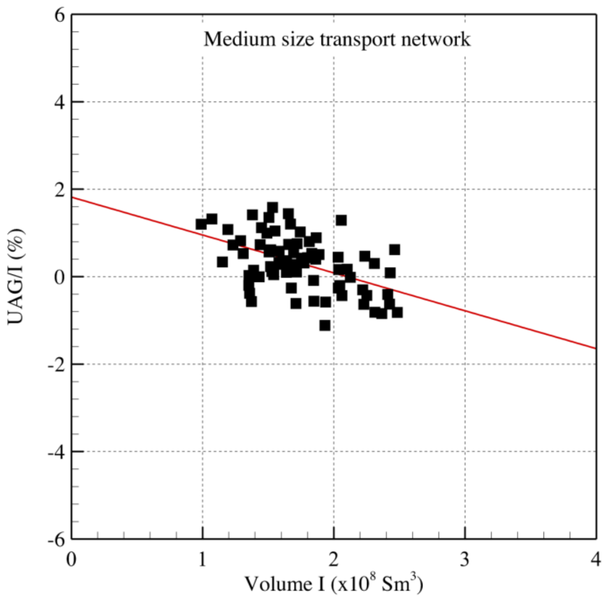

Figure 8 – Correlation between monthly UAG and natural gas transported in a medium transport network (≈1,000 km)

This undesirable effect could be strongly reduced both by adopting a proper design of the measuring plant taking into account the actual flowrates and their yearly variations and by substituting the oversized meters. In addition, meters with larger nominal rangeability or installing in the plant more measuring lines with different capacity could reduce this effect. Finally an effective management of the measuring lines has to be strongly encouraged (i.e. application of seasonal line change, automatic acquisition and control of the average, minimum and maximum flowrates).

4.2 UAG uncertainty estimation

To evaluate the possible faults in the network management it is possible to compare the actual error with the expected one, that is with the UAG expanded uncertainty, U_{UAG}.

UAG uncertainty is estimated quantifying the relative uncertainties of each term of the balance equation (1) and combining them by means of the uncertainty propagation law [13,14]. To this aim, the uncertainty of the entering and leaving NG has to be firstly known together with the metrological performance and to the operative conditions of each measuring chain installed in the network.

Thus, for the calculation of U_{UAG} in the case of uncorrelated measurements, the following equation will be used.

$$U_{UAG} = \sqrt{\sum^{n_I} U_I^2 + \sum^{n_S} U_S^2 + \sum^{n_P} U_P^2 + U_C^2 + U_{PE}^2 + U_{DLP}^2} \quad (2)$$

where, U_I, U_S, U_P, U_C, U_{PE} e $U_{\Delta LP}$ are, respectively, the expanded absolute uncertainties of the entering, stored, supplied, own used, lost and packed NG in the network under investigation.

As concerning the entering NG measurement, because of the possible compensation of random errors, the very large number of measuring plants at supply points reduces the whole uncertainty. In fact, a simplifying hypothesis could be: i) low correlation of the measurements, ii) relative uncertainty of the measurement plant not depending on the NG supplied, iii) same NG volumes supplied at different supply points and constant. In these conditions, the relative uncertainty of the NG supplied is given by the following equation.

$$u_P = \left(\frac{1}{P^2} \sum_{i=1}^{N_u} P_i^2 u_{P,i}^2 \right)^{\frac{1}{2}} \approx \frac{u_{P,i}}{\sqrt{N_P}} = u_{P,i} K_A \quad (3)$$

where: P is the NG supplied in the whole network (Sm^3), ii) P_i is the NG supplied at the i^{th} supply point (Sm^3); iii) $u_{P,i}$ is the relative combined uncertainty of the i^{th} supply point, adimensional, iv) N_P is the number of supply points in the network, $K_A = N_P^{-0.5}$ is an adimensional coefficient function of the number of supply points in the network. Therefore, in these conditions the relative uncertainty of the NG supplied could depend only on the relative uncertainty of each measuring chain (considered all equal) and on the number of supply points.

As an example, in a large network with about 10,000 supply points the relative uncertainty of the NG supplied could be reduced to 1/100 of the relative uncertainty of each measuring plant. On the other hand, in a small network with about 100 supply points the reduction could be of 1/10. Consequently the uncertainty of the NG supplied in a small network could be greater than the one of the large network with same metrological performance at the supply points, with obvious consequences on the whole UAG uncertainty.

Nevertheless, the quadratic reduction of the relative uncertainty could be true only if each measuring plant works the same NG amount with the same uncertainties, then, for a more strict analysis, the uncertainty evaluation of the different measuring plants typologies for the subsequent propagation is needed.

Even though this approach represents a great simplification in the NG supplied evaluation (given the high number of supply points in the larger network), this cannot be extended to the NG entering as the number of entry points is much less than the supply one (basically 1-2 orders of magnitude). Moreover, it must be underlined that the hypothesis of uncorrelated measurements at supply points is really optimistic as several systematic effects have been above demonstrated (i.e. the environmental conditions in terms of temperature and pressure, the flowrate regimes compared to the rangeability of the measuring device). In many operative conditions, the systematic effects can assume the same sign and then they can cause a positive or negative systematic error in UAG estimation.

Therefore, a more realistic uncertainty evaluation model could take into account the systematic effects introducing an estimated correlation coefficient $r_{i,j}$ (supposed to be constant) and the equation (3) changes as follows:

$$u_P = \left[\frac{1}{P^2} \left(\sum_{i=1}^{N_u} P_i^2 \; u_{P,i}^2 + 2 \sum_{i=1}^{N_P - 1} \sum_{j=i+1}^{N_P} r_{i,j} \, P_i \, u_{P,i} \; P_j \, u_{P,j} \right) \right]^{\frac{1}{2}} \approx \quad (4)$$

$$\approx u_{P_i} \sqrt{\frac{1}{N_P} + r \; \frac{(N_P - 1)}{N_P}} = u_{P_i} \, K_A(r)$$

In (4), K_A(r) is a multiplying coefficient function of the N_P supply points in the network and of the correlation coefficient. As it is always K_A<1, the effect of this coefficient is to reduce the whole uncertainty of the supply points as a function of their number and because of the mutual compensation of the errors that can happen in the investigated network. On the other hand, as above mentioned, the correlation effect is expected to be higher in small networks and this could be due to the bigger influence of the systematic effects. Thus, as $r_{i,j}$ ranges from 0 to 1, from eq.(4) is easy to carry out that if $r_{i,j}$=0 then the eq.(4) is equal to eq.(3), whereas the UAG uncertainty grows as $r_{i,j}$ increases and it becomes equal to the whole uncertainty of the measurement chain if $r_{i,j}$=1.

4.3 UAG uncertainty in the italian NGTN

From the available data of the Italian NGTN an UAG expanded uncertainty of about 0.6% have been estimated by the authors and this value seems to be consistent with the actual data of the last years. For a bigger reliability of the evaluation, the real actual metrological performance of the measuring chains installed have been considered.

In fig. 9 and 10 the estimation of the different uncertainty contributions of each single term of the balance equation is reported applying the above described uncertainty estimation model.

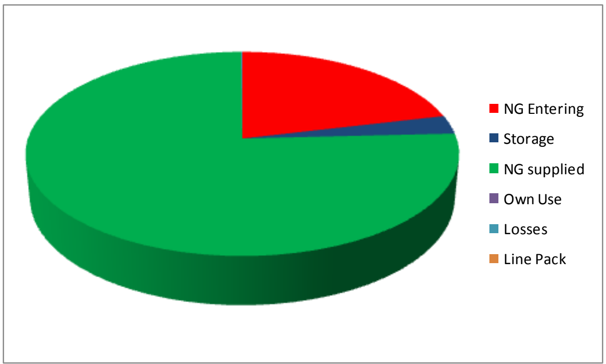

Figure 9 – UAG uncertainty contributions (large network)

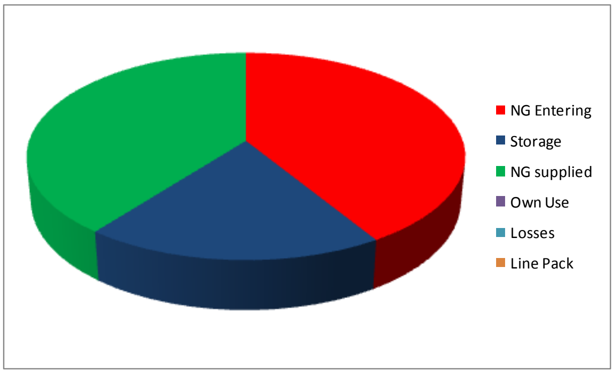

Figure 10 – UAG uncertainty contributions (medium network with storage fields)

From the figures it can be pointed out that:

- even though the measuring plants at entry points always present the best available metrological performance, they however give a relevant contribution to the whole UAG uncertainty because from eq.(3) and (4) a significant compensation of the errors is not allowed because of their low number;
- if the measuring uncertainties of the measuring devices of the supply points are not correlated, their contribution could be really low, because of their large number; but it is evident that this is not reasonable and, therefore, to limit the amplification of the error due to the unavoidable correlations the reduction of the systematic contributions is needed;
- the losses contribution (even though quite low) could be significant when their uncertainty evaluation is relevant, depending, as an example, on the estimation of the average emission factors;
- the contribution of the line pack variation is always negligible if the balance is performed in a long period (i.e. one year).

5 Conclusions

UAG comes from the unavoidable error in the estimation of each term of the NGTN balance equation. From the analysis of the available data it can be pointed out that:

- seasonal UAG trends characterize all national and international natural gas networks;
- the main UAG causes can be ascribed to the measuring error of the NG entering and leaving the network;
- a correlation between external environmental temperature and monthly UAG have been

found, due to radiative and conductive effects on temperature measurement (i.e. installation effects)

- a further correlation between UAG and the amount of the NG transported have been found and this is ascribed to the underestimation of the NG flowrates that generally the installed meters present at low regimes;
- line pack variations are negligible if estimated in a long period (i.e. one year) whereas they can be consistent in the short period (i.e. day/month).

Acknowledgements

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