Creation of Representative Gas Distribution Networks for Multi-vector Energy System Studies

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Creation of Representative Gas Distribution Networks for Multi-vector Energy System Studies

Andrea Mazza, Marco Cavana, Edgardo Luis Mercado Medina, Gianfranco Chicco, Pierluigi Leone
Dipartimento Energia "Galileo Ferraris"
Politecnico di Torino
Torino, Italy
{andrea.mazza, marco.cavana, gianfranco.chicco, pierluigi.leone}@polito.it, edgardo.medina@studenti.polito.it

***Abstract*— The recent evolution of the electrical systems has seen the introduction of large shares of renewable energy sources connected to the electrical distribution networks, and the coupling of the electricity and gas distribution systems. The exploitation of power-to-gas technologies enables stronger coupling between the electricity and gas networks. However, a limiting factor is that the gas quality should be maintained. This paper introduces a procedure to create a representative natural gas network based on a predefined electrical system topology. Furthermore, by using a detailed gas system model, the paper addresses the suitability of the coupling between gas and electrical systems through the power-to-gas technology, in terms of gas quality targets.**

Keywords— electrical distribution system, gas distribution system, representative network, power-to-gas, multi-vector energy system.

I. Introduction

The recent years were clearly distinguished by the installation of plants exploiting Variable Renewable Energy Sources (VRES), such as solar and wind, whose production is strongly dependent on the availability of the primary source, which cannot be controlled. The electrical system paradigm started to change, to fully exploit solar and wind potential, by requiring for example storage systems to match the variable production and load [1]. In addition, fundamental and well-established procedures, such as frequency control, faced new challenges due to the reduction of the inertia of the systems, leading to think about new definitions and approaches [2] and novel controls [3][4]. The usual size of the photovoltaic (PV) panels, as well as the incentives for feed-in tariffs [5] introduced by governments, pushed towards an increase of the number of PV plants connected to the distribution system, introducing a number of operational issues [6], such as voltage problems [7], reverse power flows [8], and so forth. In particular, suitable planning of the distribution system is becoming fundamental [9], as the presence of Distributed Energy Resources (DERs) definitely affects the concept of the "worst condition scenario", due to several combinations of loads and generation profiles [10].

On the one hand, if urban areas are considered, all the above aspects result more complex, due to the presence of several buildings and infrastructures that limit the space for definitive interventions. On the other hand, the presence of different infrastructures could be properly exploited for managing non-controllable DERs connected to proper conversion systems. Especially in Europe, cities and towns present wide infrastructures for electricity and gas distribution, that could be coupled together. This coupling, already existing from gas-to-power through the use of micro-cogeneration, could cover also the power-to-gas (P2G) process [11].

The acronym P2G, in the literature, essentially indicates two different process chains: the first has hydrogen as the final product,, whereas the other produces methane, and thus a methanation process is required, cascaded to the hydrogen production. Both processes present advantages and disadvantages:

- Power-to-methane allows producing directly Synthetic Natural Gas (SNG), fully compatible with the gas quality indices required by the gas system operator. However, it requires reactors and availability of CO_2, which decrease the total efficiency and make the process more complex.
- Power-to-hydrogen is composed of only one transformation step (i.e., electrolysis), which leads to higher efficiency. However, the final product is hydrogen, which has to be stored in a tank or blended in the gas network, and the consequences in the latter case should be properly investigated [12].

In case of urban areas, the use of power-to-hydrogen facilities seems more reasonable, even if different aspects (not only technical feasibility, but also for example social acceptance) should be properly analysed. However, the presence of information regarding an electrical network and its corresponding gas network are very rare, not only in the real world but also in case of test systems. This paper aims to cover this gap by suggesting a procedure to model a representative gas network by starting from an existent electrical network. Based on the types of loads and their electrical consumption, a corresponding gas consumption and gas load location is created. This kind of approach is applied in the case of the urban electrical network developed in the framework of the project *ATLANTIDE* [13], and is followed here on the gas side.

The next sections of this paper are organised as follows. Section II illustrates the gas network infrastructure. Section III addresses the creation of the representative gas network. Section IV shows a case study application. The last section contains the conclusions.

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II. GAS NETWORK INFRASTRUCTURE

A. The gas network in the Smart Grid era

Concerning the gas infrastructure, the wave of innovation following the diffusion of RES lagged to invest the sector, in contrast with what happened in the electrical sector. The academic literature on smart gas grids is still scarce and addresses the matter in a conceptual way. In this sense, a definition of the smart gas grid concept is given in [14], where two main features are identified: i) the presence of smart metering and control systems, and ii) the possibility to allow the injection of non-conventional gases within the pipelines.

Interestingly, the implementation of both features is currently considered among the gas sector stakeholders. Regarding the implementation of remote-controlled smart metering systems, a strong pulse was given by the European Directive 2006/32/CE (Art.17) [15]. In fact, it generates a commitment on the national energy authorities to enforce a substitution plan of traditional metering devices. Countries such as Italy, France, UK, and the Netherlands are undertaking the mass rollout phase (see e.g., [16]). This massive upgrading of the gas distribution infrastructure will be beneficial especially for the final consumers in terms of actual billing, consumption awareness and facilitations in gas retailer switching. Furthermore, on the distribution system operator (DSO) side the availability of a complete set of time-refined gas consumption data will contribute to improve gas network management techniques, paving the way to further innovation. Additional local flexibility is expected to be exploited thanks to a decentralised and dynamic control of pressures, gas flows and gas quality as expressed in [17].

In this sense, there is a growing consensus among gas system stakeholders and consortia that the future of the gas network will have to deal with renewable gas integration within the natural gas flux. This means that gas infrastructure will have to allow distributed injection of unconventional gases, ranging from bio-methane to hydrogen and syngas.

B. Modelling of gas network for mixture of fluids

The gas network is modelled through a non-isothermal and multi-component model, similar to the one presented in [18]. Unlike most of the models presented in the literature or usually adopted in distribution system operators' software, this model treats the natural gas as a mixture of components. Thus, the fluid-dynamic properties as well as the energy content of the gas are defined by its composition and may vary following its variation. This feature is crucial in a study focusing on distributed injection of unconventional gas within the natural gas stream. A quasi-transient gas network simulation framework is generated by means of the iterative application of the fluid-dynamic model on the network infrastructure each time step. Due to the hypothesis of steady state conditions, neither inertia terms nor accumulation phenomena are considered, implying a continuous balance between gas flows entering and exiting the whole network. This strong hypothesis is justified considering enough wide time steps (i.e., *hourly* time step).

It is worth also mentioning that gas consumption profiles will be given in terms of hourly energy requirements rather than flow rates, because different composition of the natural gas also means different energy availability to the users.

C. Description of the gas quality

Three main indices are considered to evaluate the impact of unconventional gas injection and blending:

- *Higher heating value (HHV)* or *gross calorific value* [MJ/Sm^3]: it measures the thermal energy released by a unit quantity of fuel with the water resulting from the combustion condensed to water. In case of fuel gases, it is often referred to 1 cubic meter at 15 °C and 1 atm – standard conditions.
- *Relative Density (RD)* or *specific gravity* [-]: it is the density of the gas ρ_{gas} referred to the density of dry air ρ_{air}, both at standard conditions. It is obtained from the ratio ρ_{gas}/ρ_{air}
- *Wobbe Index* [MJ/Sm^3]: it is calculated from the ratio $HHV/\sqrt{RD}$. It is a measure of the interchangeability of fuel gases, since it is an evaluation of the energy output of the gaseous fuel at a burner during its combustion. Different gases having the same Wobbe Index will show the same energy output at the same burner.

These indices have been chosen due to their role in several European technical norms. In the Italian regulatory framework, the quality of the gas flowing within the whole infrastructure is specified in the recently renewed technical rule set in [19]. It is worth noting that the natural gas quality is mainly evaluated on the basis of three parameters above rather than on the composition of each single light hydrocarbons within the gas. The only limit on composition are enforced on chemical species that may be hazardous for users' health or pipelines integrity. This approach is widely shared within the European countries as it is shown in [17].

It should be noted that the European norms do not specify so much about hydrogen presence or injection within the natural gas infrastructure. In general, any gas not complying with the quality ranges of natural gas is not allowed within the gas infrastructure. For this reason, biogas needs to be upgraded to bio-methane. The presence of hydrogen and unconventional gases in the natural gas is a controversial topic. On the one hand, the decarbonisation opportunities offered by renewable gas blending are promising. On the other hand, many issues related to the gas interchangeability and quality standardisation need to be prevented. In the field of gas quality harmonisation, the European Commission assigned to CEN (European Committee for Standardization) the mandate M/400 EN [20]. The latest achievement of CEN technical committee is the publication of the norm EN 16726 [21] on standardisation of gas quality (group H), whose content had be implemented by January 2019. As it is clearly stated in its introduction, the norm is a first step towards harmonisation. However, no common ranges for the Wobbe index have been found yet. Additionally, it is worth noting that limits on specific compounds such as carbon dioxide and oxygen are given with multiple limits, allowing more loose values under special cases or further verification of the possible impacts. Finally, the case of hydrogen injection is mentioned in an informative annex, reporting the results presented in [22] and concluding with the impossibility of setting a common limiting value for hydrogen in the European infrastructure and recommending a case-by-case analysis. The case-by-case analysis, especially within the framework of local distribution infrastructure, offers interesting opportunities to implement unconventional gas blending and sector coupling with a limited impact.

III. Construction of the Representative Gas Network

The construction of the representative gas network is made by a four-step procedure (Fig. 1) detailed in the next sections.

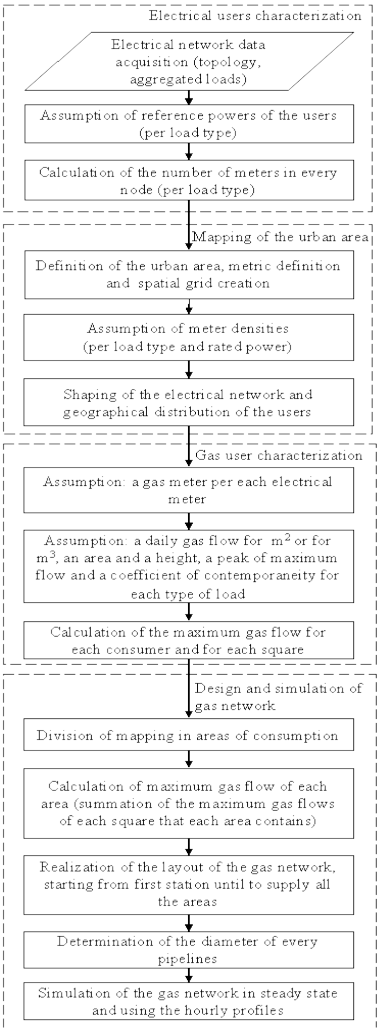

Fig. 1. Block scheme of the procedure

A. *Characterisation of the electricity grid*

The construction of the representative gas network starts from the estimated consumption supplied by the network. The number of consumers is estimated from the nodal installed power. In every node, different types of load could be connected, i.e., residential, office, commercial and industrial, and every type of node is represented through the value of aggregate power referring to the different types of loads.

For estimating the number of customers, some reference powers has been chosen for each load type. Furthermore, in order to shape the representative gas network, a topographic mapping of the urban context is needed. An area of 4.4 × 5 km is considered, with spatial resolution of 0.1 × 0.1 km. The different assumptions are summarized in Table I.

B. *Estimation of the maximum gas flow*

In order to represent the gas distribution network, the maximum gas flow required by users is needed. First of all, the total number of gas users has to be calculated. It is assumed that each electrical meter corresponds to a gas meter, so that each final user is connected to both the electrical and the gas infrastructures.

The estimation of the gas consumption may be carried out through semi-empirical methodologies [23–26]. To calculate the maximum gas flow, for final user type, a methodology presented in [26] is used.

TABLE I. HYPOTHESIS FOR THE EELECTRICAL GRID CHARACTERIZATION

Type of loads	Nominal Power [kW]	Users' counter densities
Residential	3	*based on population density
Office	3	30 meters/area element
	6	15 meters/area element
	9	10 meters/area element
Commercial	6	10 meters/area element
	10	4 meters/area element
	15	2 meters/area element
	20	1.5 meters/area element
	30	1 meters/area element
Industrial	From network information	Depending on the nominal power

*Three different housing densities for the residential loads: high density (1500 inhabitants/km^2), medium density (1000 inhabitants/km^2) and low density (500 inhabitants/km^2). With these hypothesis, the number of residential counters for each area element is calculated resulting in the following counter densities: 4.7 counters/area element for high density areas, 3.1 counters/area element for medium density areas and 1.6 for counters/area element for low density ones.

The methodology is mainly devoted to assess the maximum heating demand, that is, the predominant component for gas consumption. For residential users, as well as office and smaller commercial users, the maximum daily consumption of gas per square meter of the final user's covered surface is assumed. Differently, for bigger commercial and industrial type users, the reference consumption value is assumed per unit of volume, considering the shed-like type of buildings. Assumptions on this estimation are summarized in Table II.

The maximum gas flows need to be provided as hourly values. The daily consumption is converted into a hourly one assuming that the peak load may be expressed as a percentage of the daily load and considering an attenuation factor to take into account the non-simultaneity of each users' peaks (coefficient of simultaneity). The results of the maximum gas flow calculation are presented in Table III.

C. *Gas network representation*

Similarly to the electrical network architecture, in which medium voltage distribution networks feed MV/LV substations aggregating many single final users, the medium pressure gas networks feeds the so called "*Final Reduction Stations*" (FRSs), from which lower pressure networks feeding the final users start.

The urban context is divided in areas of consumption, so that each area has roughly the same maximum gas flow. As for the electrical grid, industrial users are assumed to be directly connected to the medium pressure level. For sizing every branch, the operating pressure has been assume, according to the Italian classification of network levels: the most common type for the medium pressure level is the 4th species, corresponding to pressures between 1.5 and 5 bar.

TABLE II. ASSUMPTIONS FOR THE MAXIMUM GAS FLOW CALCULATION

Type of loads	Daily gas flow [Sm^3/day/m^2]	Area [m^2]		Peak max load [%]	Coeff. of simult.
Res.	0.25	100		6.3	0.55
Office 3 kW		50			
Office 6 kW	0.25	100		6.3	0.9
Office 9 kW		150			
Comm. 6 kW	0.25	100		6.3	0.9
	Daily gas flow [Sm^3/day/m^3]	**Area [m^2]**	**height [m]**	**Peak max load [%]**	**Coeff. of simult.**
Comm. 10 kW	0.055	500	3		
Comm. 15 kW	0.055	1000	3	5.5	0.9
Comm. 20 kW	0.055	2500	5		
Comm. 30 kW	0.055	3500	6		
Industrial	0.06	*	7	5.5	0.9

*varying case-by-case, depending on the covered surface.

The sizing process consists of the calculation of the pipeline diameters as a function of the gas flow, so that the pressure drop between the farther node and the city-gate complies with the maximum available pressure drop (3.5 bar).

First of all, the gas flows within each branch are obtained using the incidence matrix and knowing the gas demand at users' nodes. The sizing is obtained dividing the network into five feeder. For each feeder, a pressure equal to 1.5 bar is assigned to the farthest users node. A tentative pipeline diameter is assumed for each branch. Pressure drops are then calculated. The sum of the pressure drops along the feeder should be less than the maximum available pressure drop, for preserving the pressure ranges. The method consists in varying the diameter of each pipeline in the main path of the feeder (to have a uniformly distributed pressure drop), verifying that the pressures remain within operational limits. For the sizing of the pipelines that are connected to the feeders but not belonging to the main path, the process is reverse: starting from the known pressure of the node in the main path, the pressure drops are subtracted until arriving to the terminal nodes with pressures greater than 1.5 bar.

D. Gas network simulations

Once designed the gas grid, fluid-dynamic simulations are carried out, based on the thermo-fluid-dynamic model presented in [18]: the values of pressures, temperatures and gas composition on nodal basis as well as values of pressure drops and gas flows along the branches are then evaluated.

A preliminary simulation to check the consistency of the design method was carried out by running a steady state simulation at peak hour (most critical case). The results prove the consistency of the designing process, as pressure ranges are respected even in the worst-case scenario.

Then the model has been extended to a quasi-dynamic simulation on an hourly basis.

TABLE III. MAXIMUM HOURLY GAS FLOW CONSUMPTION

Type of loads	**Per area element [Sm^3/h]**	**Per customer [Sm^3/h]**
Residential low density	1.35	0.87
Residential medium density	2.71	
Residential low density	4.06	
Office 3 kW	21.26	0.71
Office 6 kW		1.42
Office 9 kW		2.13
Commercial 6 kW	1.42	14.18
Commercial 10 kW	4.08	16.34
Commercial 15 kW	8.17	16.34
Commercial 20 kW	34.03	51.56
Commercial 30 kW	57.17	57.17
	Per company (heating only) [Sm^3/h]	**Per company (technological use) [Sm^3/h]**
Industrial*	9542.61	3799.64

* industrial consumers may use natural gas for their process besides the space heating. This use is referred to as "technological use". It was assumed that each company belongs to an industrial sector.

Starting from the daily gas consumption estimations for each consumer type, the respective profiles have been inferred from the known electric profiles and from the buildings occupancy trends assumed for each type of load. These profiles are expressed as an hourly percentage of the daily consumption thus the integral value returns the daily consumption.

The creation of the gas consumption profiles concludes the steps towards the creation of the representative distribution network for gas, allowing generating case studies where the two distribution infrastructures may be simulated to investigate the effects of different energy scenarios.

IV. CASE STUDY

The proposed procedure has been applied to the urban network developed by the project *ATLANTIDE* [13], shown in Fig. 2. The area of the network has been decomposed into about 2200 square elements. The total number of households (and then residential meters) obtained is equal to 3578, meaning, by considering 3.2 persons/house, approximately 11500 inhabitants. The offices result to be 1704, whereas the commercial customers are 243. The initial data indicated 22 industrial customers, which have their own meter system (because connected to the MV network).

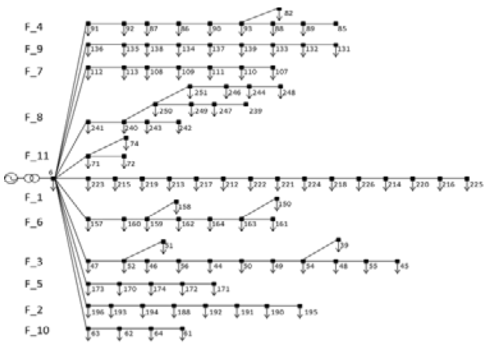

Fig. 2. Urban network of the project *ATLANTIDE*.

After having characterised the areas occupied by the different electrical customers, 12 areas of gas consumption are obtained plus the 22 industrial companies, resulting in 34 final zones, each one with its maximum gas flow to be satisfied by the distribution network.

The path of the distribution network pipelines has been arbitrary decided. A metering station (M/R station), also called *city-gate*, in which gas from transmission level is withdrawn, has been located outside the urban context limits. The FRSs have also been arbitrarily located at each consumption area defining the position of the aggregated consumption nodes. The industrial nodes and the FRSs have been connected through a feeders to the city-gate, shaping the gas network layout, composed of 65 nodes and 64 branches. The areas occupied by the different electrical loads and the resulting gas network are shown in Fig. 3.

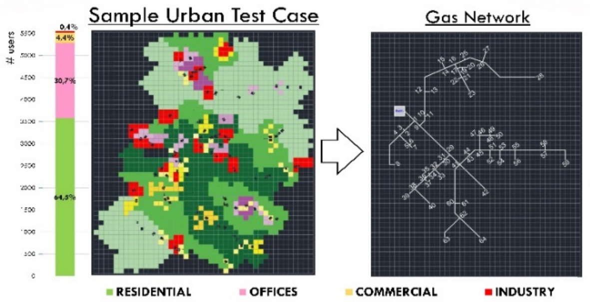

Fig. 3. Mapping of the electrical network and resulting gas network.

A scenario consisting of a strong penetration of PV has been considered. Particularly, the Italian target of 33.5 % of electrical RES on the electrical energy consumption has been applied locally to the area. As a further assumption, only the residential and office type users have been equipped with PV panels. As a consequence, the nominal power of the installed PV plants has been assumed to be 4 kWp. By considering the load and generation profiles provided available from [13] and [27] respectively, the share of PV resulted to be about 35.6%.

The electrical network has been simulated by means of the backward-forward sweep method by considering a time step equal to 15 min. Twelve average days throughout the year (one each month) have been considered. During the load flow calculation, the network constraints were verified and the presence of reverse power flow was assessed.

Within the case here considered, both voltage and current constraints were verified. Conversely, reverse power flows events happened during the summer months, especially in July. Fig. 4 shows the active power flowing through the slack bus: negative values indicate the presence of reverse power flows from the distribution to the transmission system. This situation of local over-production gives the possibility to set up the framework for an hypothesis of sector coupling more precisely power-to-hydrogen technology.

Assuming to install a suitable electrolyser in the surrounding of the HV/MV substation, the excess energy from PV generation is used to produce hydrogen to be injected in the gas network. Considering a PEM (Proton Exchange Membrane) electrolyser with $\eta = 0.7$, the curve of producible hydrogen is shown in Fig. 5.

Thanks to the topographic characterisation of the urban context, the slack of the electrical grid is close to the barycentric node of the gas network, along its main feeder. Following a proximity criteria, this node (29) has been chosen as the hydrogen injection node. Thus, the distribution gas network is fed by two inlet streams of different gases during few hours a day. This is a peculiar situation that the model presented in [18] is able to model.

Due to the presence of reverse power flow in July, the gas consumption profiles are reduced to 15% with respect to the ones used for designing the gas network, to take into account the seasonality of the space heating using of natural gas (exception made for the consumption for technological use in industry).

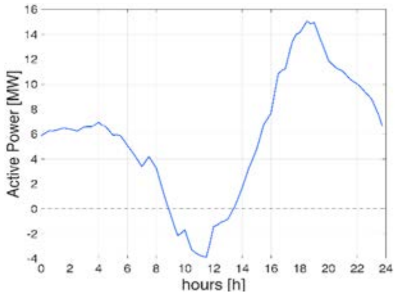

Fig. 4. Active power flowing through the slack bus (negative values indicate the presence of reverse power flow).

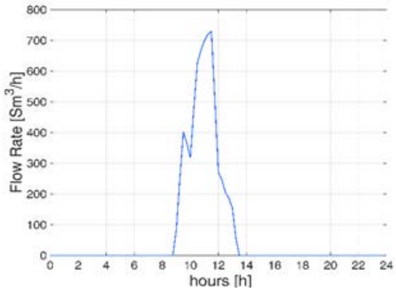

Fig. 5. Hydrogen production using the reverse power flow.

The main result of the thermo-fluid-dynamic simulation of the gas network under hydrogen injection scenario is given in Fig. 6, where the hourly variation of the percentage of hydrogen within the gas system is given. This variation invest all the nodes downstream the injection one. No perturbations are observed upstream, due to the unidirectional gas flow.

Since it has been assumed the direct injection of the produced hydrogen within the gas network, its percentage evolution (in terms of molar composition) perfectly follows the solar trend. It is worth noting the magnitude of the impact of a similar injection pattern: in few hours the gas composition may possibly range from 0% up to 18%.

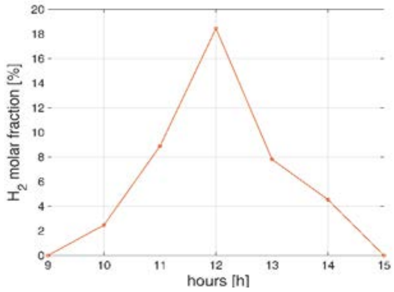

Fig. 6. Hydrogen molar fraction during the considered day

To assess the acceptability of a natural gas quality perturbation with this amplitude, a verification of the three gas quality indicators have been carried out as shown in Table IV. As it can be seen, the practice of blending hydrogen within fossil natural gas leads to unacceptable perturbations already with a hydrogen percentage exceeding 7 % (it also depends on composition of the natural gas). According to the current limits on natural gas quality, ignoring extra restrictions or limits to the hydrogen presence within the gas infrastructure, the simulated practice may be too impactful on the gas system to be a viable option to locally store surplus of renewable energy, already with moderate share of renewables.

TABLE IV. GAS QUALITY VARIATION DUE TO H_2 INJECTION

	Ranges*		**Hours**						
	min	**max**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
HHV [MJ/Sm^3]	34.95	45.28	39.3	38.6	36.8	34.2	37.1	38.0	39.3
RD [-]	0.55	0.7	0.59	0.58	0.54	0.49	0.55	0.57	0.59
WI [MJ/Sm^3]	47.31	52.31	51.2	50.8	49.9	48.7	50.1	50.6	51.2
%mol H_2			0.0	2.5	8.9	18.4	7.8	4.5	0.0

*****according to the Italian norm [19].

V. CONCLUDING REMARKS

The case study presented has a twofold aim: on the one hand, it is devoted to highlight a new methodology of combined simulation of energy infrastructures at local level in order to assess consequences of future energy scenarios, under a multi-energy vector point of view. On the other hand, it aims at exploring an example of sector coupling modelling the impact of the power-to-gas pathway on the energy distribution infrastructure at urban level. The preliminary results on the case study showed some criticalities that this kind of sector coupling may meet. In fact, the attempt to store excess of renewable energy production within hydrogen directly injected in the local infrastructure does not fit with the actual gas quality requirements and may lead to more serious issues affecting the gas network. More extended studies on sector coupling through power-to-gas, based on the simulation of the infrastructures, should be carried out in order to better depict all the variables sensible to the injection practice. Furthermore, a deeper discussion on the interchangeability of fuel gas and gas quality requirement restriction should be addressed. In general terms, the series of activities presented in this paper underlines the importance of the evaluation of the energy scenarios on the energy infrastructures in order to verify their suitability and highlight possible bottlenecks. The methodology presented, may be even more effective having available real data on infrastructures and energy statistics of the areas under investigation, being a powerful instrument within the energy planning of local decision makers.

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