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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

Analysis and modelling of natural gas grids in presence of biomethane and hydrogen injections

TESI MAGISTRALE IN ENERGY ENGINEERING – INGEGNERIA ENERGETICA

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1. Introduction

In the energy scenario projections, natural gas is expected to have an increasing role due to its lower carbon intensity with respect to the other fossil fuels. However, this solution is not able to satisfy the target of achieving zero-carbon emissions. Therefore, the introduction in the energy market of alternative fuels, such as biomethane and hydrogen, is fundamental in order to mitigate climate effects. Biomethane injection in the grid is already diffused in many parts of the world, whereas natural gas-hydrogen blending pilot projects are starting in the last years. In this new context, modelling and simulation of gas distribution networks becomes fundamental to study the effects of the injection of alternative fuels on natural gas grids, from the point of view of pressure, velocity and composition of the gas.

2. Alternative gases State of the Art

The injection of biomethane and green hydrogen is currently seen as the next step towards the decarbonization of the gas sector in several countries. However, the introduction of these two gases in existent infrastructures has energetic, material and operational implications that should be carefully looked at.

2.1. Biomethane

Biomethane is not different from a high-methane content natural gas: it is almost made of pure CH_4 (95-97%), the remaining part is CO_2 (1-3%). Therefore, the gas quality tracking is not required when it is admixed in natural gas grids.

It represents a very small fraction of natural gas demand today. However, an increasing number of government policies are supporting its injection into natural gas grids for decarbonising transport.

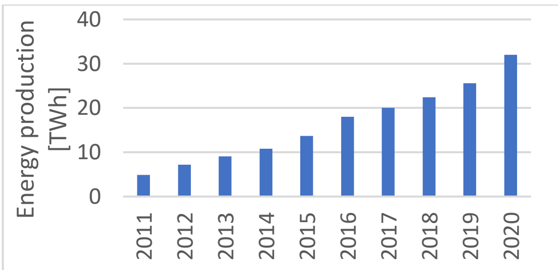

Figure 2.1: Evolution of biomethane production in Europe [1]

2.2. Hydrogen

Hydrogen is currently used mainly in the chemical industry for the production of ammonia and methanol and in the refinery sector, but the diversity of energy sources that can produce it makes hydrogen a promising energy carrier. However, its widely different properties, compared to those of natural gas, make hydrogen transportation in existent natural gas grids a complicated operation.
Blending hydrogen into the existing natural gas pipeline network has been proposed as a mean of increasing the output of renewable energy systems, because of the growth in installed wind power capacity. Therefore, an increasing number of projects and initiatives regarding the injection of hydrogen into the grid has been announced in last years. Some of them are reported in table 2.1.

Table 2.1: Projects of hydrogen blending into the natural gas grid

Project	Start-up date	% H_2 max
HyDeploy (UK)	2019	20
Snam (Italy)	2019	5, 10
Fort Saskatchewan (Canada)	2021	5
H21 (UK)	2029	100

Most of the projects announced plan, initially, to blend a limited fraction of hydrogen in the gas (maximum hydrogen fraction of 20% – 30%). However, many countries have set the goal to increase it, up to 100%, in the next years.

The reasons why the fraction of hydrogen injected in the natural gas grid is still limited are that its injection has a significant impact on combustion and on the existent infrastructures and appliances (because of the different properties between hydrogen and natural gas) and its production is expensive.

Regarding the combustion, the Wobbe Index (WI) is used to evaluate the fuel gas interchangeability:

$$WI = \frac{H_s}{\sqrt{d}} \tag{2.1}$$

Two gases that have the same Wobbe Index and are burned with the same nozzle pressure will release the same amount of heat.

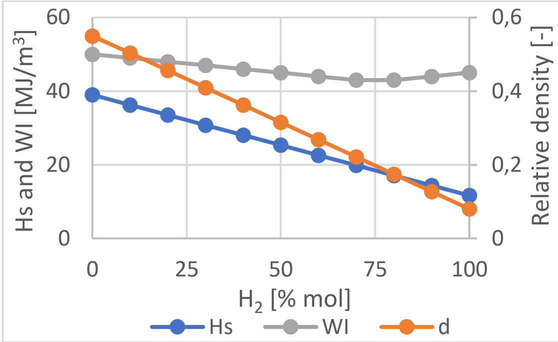

Figure 2.2: Relative densities, gross calorific values, Wobbe Indices for CH_4/H_2 blends [2]

Increasing the hydrogen fraction in the blend, the density and the gross calorific value of the mixture linearly decrease, whereas the decrease of the Wobbe Index is less pronounced.
Other issues linked to combustion are temperature and velocity of the flame. With higher levels of hydrogen, the adiabatic combustion temperature of the fuel blend increases, as long as the other operational parameters like the air excess ratio λ remain constant, that may cause local overheating of components and increased emissions of NOx. Also, the laminar combustion velocity increases significantly when H_2 is admixed to CH_4, increasing the risk of flashbacks in appliances.
These effects can be mitigated by a shift towards higher air excess ratios: this shift occurs when a combustion process was adjusted for a fuel gas and is then supplied with another fuel gas with a lower Wobbe Index and is inevitable in an appliance without combustion control but can also occur in controlled systems [2].

The main problem of transportation by pipelines is called hydrogen embrittlement [3]. This phenomenon has an important impact on durability and integrability of existing natural gas pipelines because it greatly degrades mechanical properties of steel. Thus, the fraction of hydrogen that can be injected into the gas without adjustments of the infrastructures is limited.

3. Fluid-dynamic model

The fluid-dynamics of compressible flows in pipelines is generally studied under the following assumption: (i) Constant pipeline section; (ii) one-dimensional flow; (iii) single phase flow; (iv) Newtonian fluid; (v) Compressible fluid [4].
Further assumptions have been done to develop this model:

- Isothermal flow, since heat exchange with the environment has different time scale and the internal heat sources are not relevant in distribution grids.
- Steady state condition, that is unlikely to be encountered in real life operations, but it may be a simple and efficient tool for design concerns, in order to derive an optimal network configuration.

The Papay correlation of the compressibility factor (3.1) has been compared, for different CH_4/H_2 blends, with the implicit z-correlation defined as the standard requirement by ISO-12213. Deviations below 0,3% have been found in the 0-5 bar range (proper of the distribution level).

$$z_{Papay}(p,T) = 1 - 3{,}52\, p_r\, e^{-2{,}260 T_r} + + 0{,}274\, p_r^2\, e^{-1{,}87\, T_r} \tag{3.1}$$

Hofer explicit approximation (3.2) of the friction factor has been compared, for different CH_4/H_2 blends, with the implicit Colebrook-White equation. Deviations below 0,8% have been found in the 5-25 m/s velocity range (proper of the distribution level).

$$f_{Hofer}\,(v) = \frac{1}{2\,\log_{10}(\frac{4{,}518}{Re}\,\log_{10}(\frac{Re}{7}) + \frac{K}{3{,}71\,D})^2} \tag{3.2}$$

The other correlations studied for compressibility factor and friction factor show worse performances.

4. Case study

In this work, the simulation of a gas network is performed using a Matlab program, considering the injection of biomethane and hydrogen in different positions of the grid and with different flow rates.
The gas distribution network analyzed is a medium pressure network resembling a medium-sized city, with a total demand of 11300 Sm^3/h (standard conditions: 1 bar, 15°C). The natural gas is injected into the network at a pressure of 5 bars by two city-gate stations (REMI), placed in the right (REMI A) and in the left (REMI B) areas of the grid. The network supplies gas to three industrial users (A2, A5, A11) and eleven domestic withdrawal nodes.

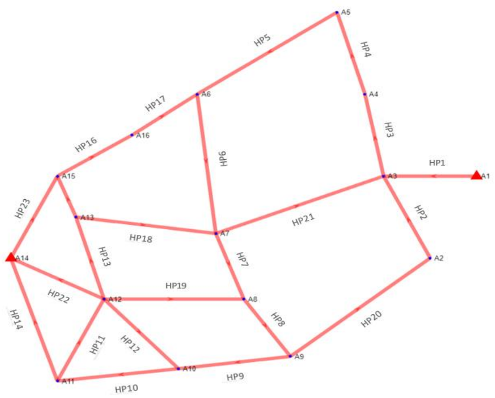

Figure 4.1: Gas distribution network simulated

In the base case, without injection of alternative gases, the pressure of the gas at the nodes varies between 4,33 (minimum) and 5 (maximum) bars, with the largest pressure drop equal to 11,7% in HP1. The velocity of the gas through the pipes is always below the allowable limit (25 m/s), the maximum velocity is 16 m/s in HP14.
All the cases simulated in this work are compared to the base case. This work also focuses on finding the parameters that can establish what are the better nodes near which placing a decentralized injection (biomethane or hydrogen), from the point of view of the amount of gas that can be injected before an intervention of the DSO is needed. The parameters consider, for each demand node *j*, the gas demand, its distance from the other withdrawal nodes and its distance from the natural gas injection stations.

$$\eta_j = \sum_{i=1}^{N_d} \frac{F_i}{dist\,(i,j)}\, [\frac{Sm^3}{h*m}] \tag{4.1}$$

$$\sigma_j = \sum_{i=1}^{N_{REMI}} \frac{F_{REMI,i}}{dist\,(i,j)}\, [\frac{Sm^3}{h*m}] \tag{4.2}$$

Two parameters that can link η and σ are introduced, considering that η should be maximized and σ should be minimized.

$$\mu_{j,1} = \eta_j + \sigma_j\, [\frac{Sm^3}{h*m}] \tag{4.3}$$

$$\mu_{j,2} = \frac{\eta_j}{\sigma_j}\, [-] \tag{4.4}$$

The injection should be placed near the nodes having low values of μ_1 and high values of μ_2.
In order to verify the validity of the parameters discussed, different positions of biomethane and hydrogen injection in the grid have been simulated.

4.1. Biomethane injection

The biomethane supply is modelled as a decentralized injection, with constant flow profile, meaning a gas flow rate that is set into the grid independently of its working conditions. The adding of a decentralized source may lead to an issue concerning the system pressure: the network is designed to resist at a maximum pressure level that is the nominal one (5 bar) imposed at the connection with the transmission lines; if the amount of gas injected exceeds the demand insisting on its branch, the exceeding gas flow travels towards the remaining part of the network, which means for the injection to work at a higher pressure than the reducing station. Therefore, an intervention of the Distribution System Operator (DSO) is needed to downgrade the pressure at the REMIs in order to keep the decentralized injection pressure below 5 bars.

Table 4.1: Positions of biomethane injection

Injection position	Nearest node	η $[\frac{Sm^3}{h\,m}]$	σ $[\frac{Sm^3}{h\,m}]$	μ_1 $[\frac{Sm^3}{h\,m}]$	μ_2 [-]
Pos. A	A2	5,74	5,43	11,17	1,06
Pos. B	A6	7,17	5,69	12,86	1,26
Pos. C	A11	6,39	17,46	23,85	0,37
Pos. D	A15	6,74	11,29	18,04	0,6
Pos. E	A4	8,22	5,15	13,38	1,6

First, a comparison at 3000 Sm³/h of biomethane injected is made, evaluating velocity and pressure of the gas in the pipes and the nodes of the network. Then, a sensitivity analysis is performed, varying the amount of biomethane injected between 500 and 3500 Sm³/h. The results show how the biomethane does not significantly influence the velocity of the gas through the pipes, having the same properties of natural gas. On the contrary, the pressure strongly depends on the position of injection.

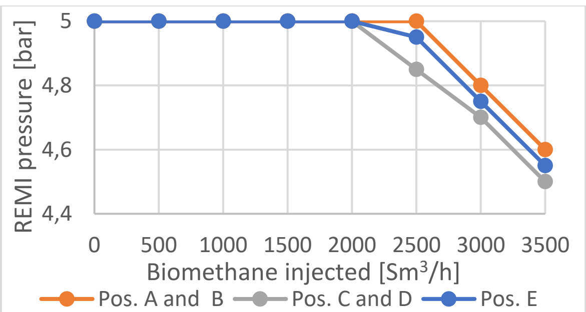

Figure 4.2: Natural gas REMI stations pressure as a function of biomethane injected

When biomethane is injected in positions C and D (high μ_1, low μ_2), the pressure at the natural gas stations is downgraded more than in the other positions and it starts to be reduced at a lower amount of biomethane than in the other positions. The main reason is that the nodes A11 and A15 are in a highly loaded branch (large number of nodes in a small area). Furthermore, A11 is an industrial node and it is positioned near REMI B. Instead, A2 and A6 are in a lowly loaded branch and A2 is closer to REMI A. The injections near these two nodes (positions A and B) seems more convenient from the point of view of the pressure level in the network, in agreement with the ranking of the nodes established by μ_1 and μ_2.

4.2. Hydrogen injection

When hydrogen is injected into the grid, it is not sufficient to evaluate pressure and velocity, but also the composition of the gas supplied to each withdrawal node has to be estimated, because of the different density and heating value of hydrogen compared to natural gas. The importance of knowing the composition of the gas is given by the fact that the thermal power (4.5) supplied to each withdrawal node depends on it (by ρ and LHV):

$$\dot{Q}\,[MW] = \sum_{i=1}^{N_d} \frac{F_i \left[\frac{Sm^3}{h}\right] * \rho_i \left[\frac{kg}{Sm^3}\right] * LHV_i \left[\frac{MJ}{kg}\right]}{3600} \qquad (4.5)$$

Therefore, in this work the concept of gas quality tracking is introduced in the simulation model, in order to understand if the gas supplied to each nodes satisfies the demand.

4.2.1. 100% H_2 grid

First of all, a grid supplied by 100% H_2 is studied. If the volumetric flow was kept constant to the natural gas case, the pressure drops through the pipes would be largely reduced thanks to the lower density of hydrogen, but only 30% of the thermal input needed would be supplied: since its LHV (in MJ/Sm³) is much lower than the one of natural gas, a larger volumetric flow is needed, so it increases by 3,4 times. The major problem linked to this increase is the growth of the velocity of the gas through the pipes, explained by (4.6).

$$v = \frac{F}{A} = \frac{\rho\,\dot{m}}{\pi\,\frac{D^2}{4}} \tag{4.6}$$

In particular, the gas reaches a maximum velocity of 54,5 m/s in HP1, connected to REMI A. Also, the gas is too fast in the pipes close to REMI B (HP14, HP22, HP23), where a large amount of hydrogen is injected. The consequence of the large increase of the amount of gas supplied is that the pressure in the network decreases, with a minimum pressure below 4 bar.
A solution is to add a tube in parallel to the ones already existent in the pipes in which the velocity overcomes the allowable limit of 25 m/s, in order to increase the passage area and, so, by (4.6), decrease the velocity. In particular, the diameter of HP1 is doubled and the one of HP14, HP22, HP23 is increased by 30%.

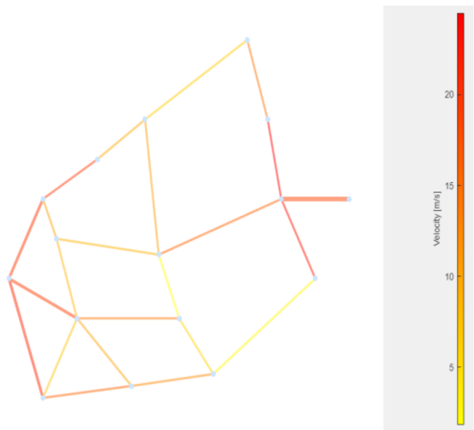

Figure 4.3: Gas velocity in a 100% H_2 grid, with diameter increased in four pipes

The enlargement of the passage area in some pipes also raises the pressure level in the network, since the pressure drops of the gas through those pipes are largely reduced.

Table 4.2: Main results of the simulations with 100% NG and 100% H_2

	100% NG	100% H_2 Constant F	100% H_2 Constant $\dot{Q}$	100% H_2 Constant $\dot{Q}$, D modified
F total [Sm^3/h]	11300	11300	38430	38430
Max P drop [mbar/m]	0,858	0,126	1,27	0,286
Min P [bar]	4,33	4,9	3,98	4,75
Max velocity [m/s]	16,02	15,5	54,55	24,24
$\dot{Q}$ total [MW]	105,2	31,6	105,2	105,2

4.2.2. H_2 decentralized injection

Another case studied is the hydrogen decentralized injection (as in the biomethane case). In this kind of simulation, gas quality tracking is required because of the mixing between natural gas and hydrogen. Four different positions of injections have been chosen.

Table 4.3: Positions of hydrogen injection

Injection position	Nearest nodes	η $[\frac{Sm^3}{h\,m}]$	σ $[\frac{Sm^3}{h\,m}]$	μ_1 $[\frac{Sm^3}{h\,m}]$	μ_2 [-]
Pos. F	A2	5,74	5,43	11,17	1,06
	A9	6,22	6,13	12,36	1,01
Pos. G	A5	6,07	4,88	10,95	1,25
	A6	7,17	5,69	12,86	1,26
Pos. H	A10	7,23	9,37	16,6	0,77
	A11	6,39	17,46	23,85	0,37
Pos. I	A11	6,39	17,46	23,85	0,37
	A14 (REMI)	-	-	-	-

As in the biomethane case, the analysis is firstly made injecting the same flow rate (2200 Sm^3/h) in the four positions and, then, a sensitivity analysis is made varying the quantity of hydrogen introduced in the network between 500 and 2500 Sm^3/h. The goal is to understand how pressure, velocity, composition of the gas change in the network and to verify if the ranking of the nodes introduced for the decentralized biomethane injection can be valid also in this case.
When 2200 Sm^3/h of hydrogen are injected, the total thermal power supplied to the network is 90,8 MW, that is 86,3% of the power needed, independently on the position of the injection. However, the composition of the gas withdrawn by every demand node, so also the power supplied to each of them, depends on the injection position.
The sensitivity analysis shows that, in order to keep the thermal power supplied to each node constant, the total gas demand linearly increases by 350 Sm^3/h every 500 Sm^3/h of hydrogen supplied, resulting in a decrease of the natural gas demand of 150 Sm^3/h, regardless of the position of injection. This result has been obtained by an iterative process in the simulations, in order to supply the required amount of energy to each withdrawal node.
Moreover, the evaluation of pressures and velocities shows that it is better to place the decentralized hydrogen injection in the same positions as in the biomethane case, from the point of view of the interventions of the DSO needed by the network. For example, the injection near A11

(pos. H and I) is the one in which a lower amount of hydrogen can be injected before the gas becomes faster than 25 m/s.

4.2.3. One NG supply and one H_2 supply

In this simulation, a city-gate station supplies natural gas to the grid and the other one supplies hydrogen. First, hydrogen injected is in REMI A and natural gas in REMI B and then vice versa. In these cases, the hydrogen is not supplied at a fixed flow rate, as in a decentralized injection, but at a fixed pressure (like the natural gas).

If the volumetric flow supplied to the demand nodes was kept constant, 63% of the power needed would be introduced in the first case and 39% in the second case. Therefore, gas quality tracking is required. Moreover, the diameter increase is not sufficient to keep the velocity below 25 m/s because, at fixed pressure, a larger hydrogen flow would be introduced because of the larger passage area, so the gas would be accelerated. Thus, the solution is to increase the diameter of the pipes connected to the hydrogen REMI and, at the same time, the hydrogen injection pressure has to be reduced (respectively 4,6 bar and 4,4 bar in the two cases). A larger amount of hydrogen can be introduced in the case in which it is injected in the left area of the network because it is a highly loaded branch, so its density allows it to reach a higher number of nodes. The total volumetric flow is 18900 Sm^3/h (58% H_2) in the first case and 28566 Sm^3/h (87% H_2) in the second case.

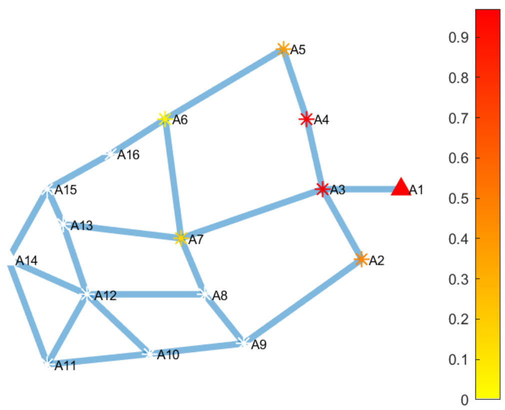

Figure 4.4: Gas quality tracking at the nodes when H_2 is injected in the left REMI station (white color: 100% H_2; red color: 100% NG)

5. Conclusions

Biomethane and hydrogen injection into the existent distribution grids has the potential to reduce and replace the use of natural gas in the future. Regarding biomethane, the main problem is about the pressure level of the network, that increases when the amount of biomethane injected goes up and can exceed the allowable limits. The impact of hydrogen is more relevant because of the different density and lower heating value compared to natural gas, that imply the need for a larger volumetric flow in order to satisfy the energy demand of the users. Therefore, a modification of the infrastructures and of the equipment can be necessary. Moreover, gas quality tracking is necessary to know the composition of the gas when natural gas and hydrogen mix.

As for the position of biomethane and hydrogen decentralized injection, it is more favourable to place it close to an industrial node and in a lowly loaded branch (lower concentration of nodes near the injection). The parameters introduced to rank the demand nodes, from the point of view of the need for an intervention of the DSO, seem appropriate to do a priori evaluation on which positions of the network are convenient to place a decentralized injection, but they can be further improved by considering other factors like the mesh of the grid and the fact that the demand profile is variable in the real situations.

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