The holistic view of the energy systems promotes the increase of prosumer flexibility by coupling electricity and gas infrastructures

Promoting the new energy system era through a holistic vision

Andrea Ademollo[1(1)], Albana Ilo[2 (2)], Carlo Carcasci[(1)]

[(1)]Università degli studi di Firenze, Via di Santa Marta 3, Firenze, +39 334 5891455, andrea.ademollo@unifi.it

[(2)]TU Wien, Gußhausstraße 25/370-1, +43 (0)1 58801 370114, ilo@ea.tuwien.ac.at

ABSTRACT

The overall climate change commitments require integrating energy systems belonging to various economic sectors to decarbonize them. Cities offer great potential to couple electricity and gas vectors using the available infrastructure, thus protecting the environment. This paper analyses the electricity and gas distribution grids together for the first time. It focuses on the issues related to an extended rooftop Photovoltaic installation on each Customer Plant, evaluating the exploitation of the electricity surplus through a holistic approach in two different ways: injection back into the electricity grid or production of Synthetic Natural Gas and injection into the Natural Gas grid. The goal is to evaluate if voltage or pressure limit violations occur in the respective grids. Results show that injecting electricity surplus back into the Low Voltage grid can create voltage problems, while technical limitations shown by the alternative solution are much lower. Another advantage of the gas network is the possibility of exploiting the linepack effect, i.e., the pipeline storage capacity, which increases supply flexibility without using any storage appliance.

Keywords: Gas grid, Electricity grid, Parallelism, Holistic LINK-solution, Sector Coupling, Hydrogen, Synthetic Natural Gas, Distributed Injections

1 INTRODUCTION

Environment protection policies strictly require the decarbonization of all sectors of the economy, which is one of the most significant challenges of this century. Integrating Energy Systems of various economic sectors is considered the most suitable way to decarbonize. This revolution involves several technical and economic issues and requires a holistic and integrated approach [1].

From this perspective, exploiting a Distributed Generation (DG) of energy becomes increasingly important [2]. But the increasing share of distributed energy resources, such as rooftop Photovoltaic (PV) installations, aggravates voltage limits compliance within the electric power system.

[1] Università di Firenze ,Santa Marta 3, Firenze, +39 334 5891455, andrea.ademollo@unifi.it

[2] TU Wien, Gußhausstraße 25/370-1, +43 (0)1 58801 370114, ilo@ea.tuwien.ac.at

Gas grids are also moving towards partial decarbonization through the injection of substitute Natural Gases (NG). A viable solution to integrate the surplus from renewable energy sources is the electricity conversion into H_2 and then, eventually, into other alternative fuels. A solution envisaged by different strategies, and deeply analyzed in the literature, is the direct H_2 injection into existing NG pipelines. Cheli et al. [3] simulated a Low Pressure (LP) natural gas distribution network serving industrial and residential users and subjected it to one localized injection of hydrogen produced by renewable energy sources. Guzzo et al. [4] defined the maximum mixable percentage of hydrogen as a function of the gas composition, underlining the importance of not adopting a single hydrogen limit. H_2 can also be combined with CO_2 to produce Synthetic Natural Gas (SNG) through a methanation reactor [5] and then injected into the NG grid.

The holistic *LINK* architecture structures cross-vector sector coupling in all voltage levels of power grids and the end-user sector coupling [6], opening the perspective of jointly investigating power and gas grids and power and gas appliances at the Customer Plant (CP) level.

The paper's scope is on the networks' final elements, the Low Voltage (LV) feeders for electricity and the LP pipelines for gas. In addition to issues related to distributed injections, CPs and Coupling Components (CCs) such as electrolyze, and methanation-reactor are also addressed. The paper focuses on finding an alternative solution to solve the problems created by a distributed electricity injection generated by rooftop PV plants back into the LV grid. It consists of coupling components exploitation to produce SNG and inject it back into the LP grid. The goal is to find the minimum LP pipeline diameter allowing the absence of pressure problems inside the gas grid to make the alternative solution feasible. The linepack effect dependency on the diameter has been studied too.

2 ELECTRICITY AND GAS GRID COMPARISON

The electricity grid and the gas grid have a lot of common aspects but even some differences. First, both are conceived as a holistic structure, i.e., their features are repeated at each level with scaled parameters, then the main elements composing the grids are the same:

- Producers
- Transmission lines (Transportation pipelines)
- Distribution feeders (Distribution pipelines)
- Storage plants
- Consumers

Even though in the gas grid there are pipelines (not lines), and the transmission level is called transportation (not transmission), there are similarities regarding the complex management of such grids. In fact, there’s usually one Transmission System Operator (TSO) for each grid in every country while for the distribution level in both grids there are more Distribution System Operators (DSOs). Therefore, even though the ‘driving force’ for the electricity grid is the voltage and for the gas grid is the pressure, thanks to the holistic structure the grid parameters are scaled up from level to level in the same way: for instance, diameters and lengths of the lines (pipelines), size of grid components, consumers, and storage plants.

Finally, an analogy between velocity inside pipelines and current flowing through the lines can be found because in both cases power losses (for the electricity grid) and pressure losses (for the gas grid) increase with the respective physical quantity squared.

The technologies exploited, as well as their operation in the network, are obviously different and summarized in Table 1:

	ELECTRICITY GRID	**GAS GRID**
Producers	Thermoelectric, Hydroelectric, Photovoltaic, Nuclear, Wind energy, Tidal energy plants	Gas wells, Shale gas, Biomethane plants
Transmission - Transportation	UHV: > 150 kV HV: 30 kV ÷ 150 kV	HP: 5 bar ÷ 200 bar
Distribution (Medium level)	MV: 1 kV ÷ 30 kV	MP: 0,04 bar ÷ 5 bar
Distribution (Low level)	LV: 0,220 kV ÷ 1 kV	LP: 0,019 bar ÷ 0,04 bar
Storage plants	Batteries, Supercapacitors, Flywheels, Hydrogen, Compressed air, Hydroelectric reservoirs	Liquefied NG, Compressed NG, Synthetic NG, Underground Gas Storage
Consumers	Residential, Commercial, Industrial, Agriculture, E-cars	Residential, Commercial, Industrial, Agriculture, Thermoelectric plants, Gas stations

Table 1: Analogies between gas grid and electricity grid

There are other fundamental elements in the structure of both grids which are different but with similar functions. In Table 2 are represented all the elements composing the grids accompanied by a brief description and most common symbol used in scientific literature.

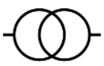
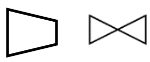
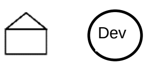
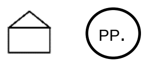
ELECTRICITY GRID			***GAS GRID***		
Element	**Symbol**	**Description**	**Element**	**Symbol**	**Description**
Bus bar		Rigid conductor used for connecting several circuits	Node		Connection point for connecting several pipelines
Line overhead		Electrical line built overhead	Pipeline overhead		Pipeline built overhead
Line underground		Electrical line built underground	Pipeline underground		Pipeline built underground
Producer		Electric power plant	Gas well		Gas production well
Transformer		Device that transforms an AC input voltage into a higher or lower AC output voltage	Compressor/ Lamination valve		Engine that increases (compressor) or reduces (lamination valve) gas pressure
Storage		Appliance which stores energy produced at one time to use it when is more needed	Storage		Appliance which stores energy produced at one time to use it when is more needed
Load		Electrical component or portion of a circuit which consumes electric power	Load		Customer that consumes gas
Circuit braker/ fuse		Electrical component used to interrupt the flux of current	Non-return valve		Component used to interrupt the flux of gas in one direction

Table 2: grids elements' symbolism

2.1 Differences between gas grid and electricity grid

- The bus bar is a physical object instead the node is realized by welding different pipelines.
- If the electricity lines are mainly realized overhead, NG pipelines are mainly installed underground.
- Transformer is an electric component able to change voltage level in both directions (step-up and step-down transformers), instead for the gas grid a compressor is needed to increase the pressure and a valve to decrease it.
- The meaning of storage is of primary importance and it’s the same in both grids, but NG grid claims to have seasonal storage units, for example Underground Gas Storage (UGS), Liquefied Natural Gas (LNG) or Compressed Natural Gas (CNG). This is due to the different nature of these resources: the first one is a primary source while the other one is an energy vector to be produced in a Power Plant (PP).
- In the gas grid there’s the need to feed big power generation plant with huge number of cubic meters of gas. In the electricity grid can’t be found a parallelism, i.e., appliances that consume a huge amount of electricity proportionally to the one which is produced.
- A big difference between electricity grid and gas grid is that in the first case the flux of current can’t be reduced but only interrupted (through circuit breakers or fuses), instead, in the second case, using lamination valve the flux of gas can be reduced because, increasing concentrated pressure losses and thus diminishing the pressure, even flow rate diminishes as a result.
- If the flux of electricity can be bidirectional, the flux of gas can evolve in both directions only in specific cases with specific bidirectional valves.
- In the electricity grid not all the power is consumed because of the existence of the reactive power, instead, in the gas grid the whole amount of NG entering in the pipelines will be consumed, so it can’t be found a parallelism for the reactive power.

2.2 Topology

The analogy between both grids can be appreciated by representing their topology using the symbolism discussed above and highlighting the different competence's areas, as in Figure 1 and Figure 2.

ELECTRICITY GRID

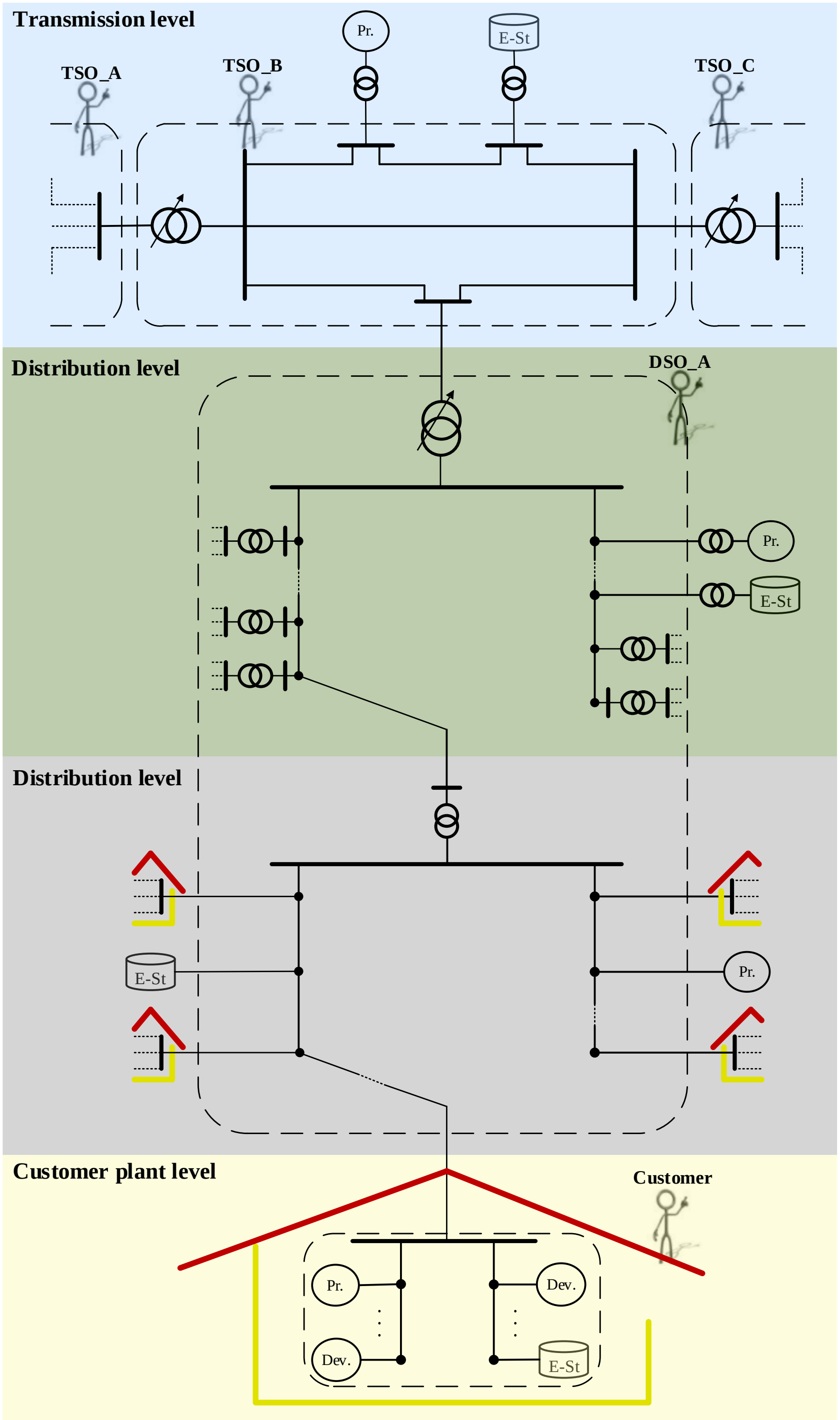


Figure 1: Electricity grid topology

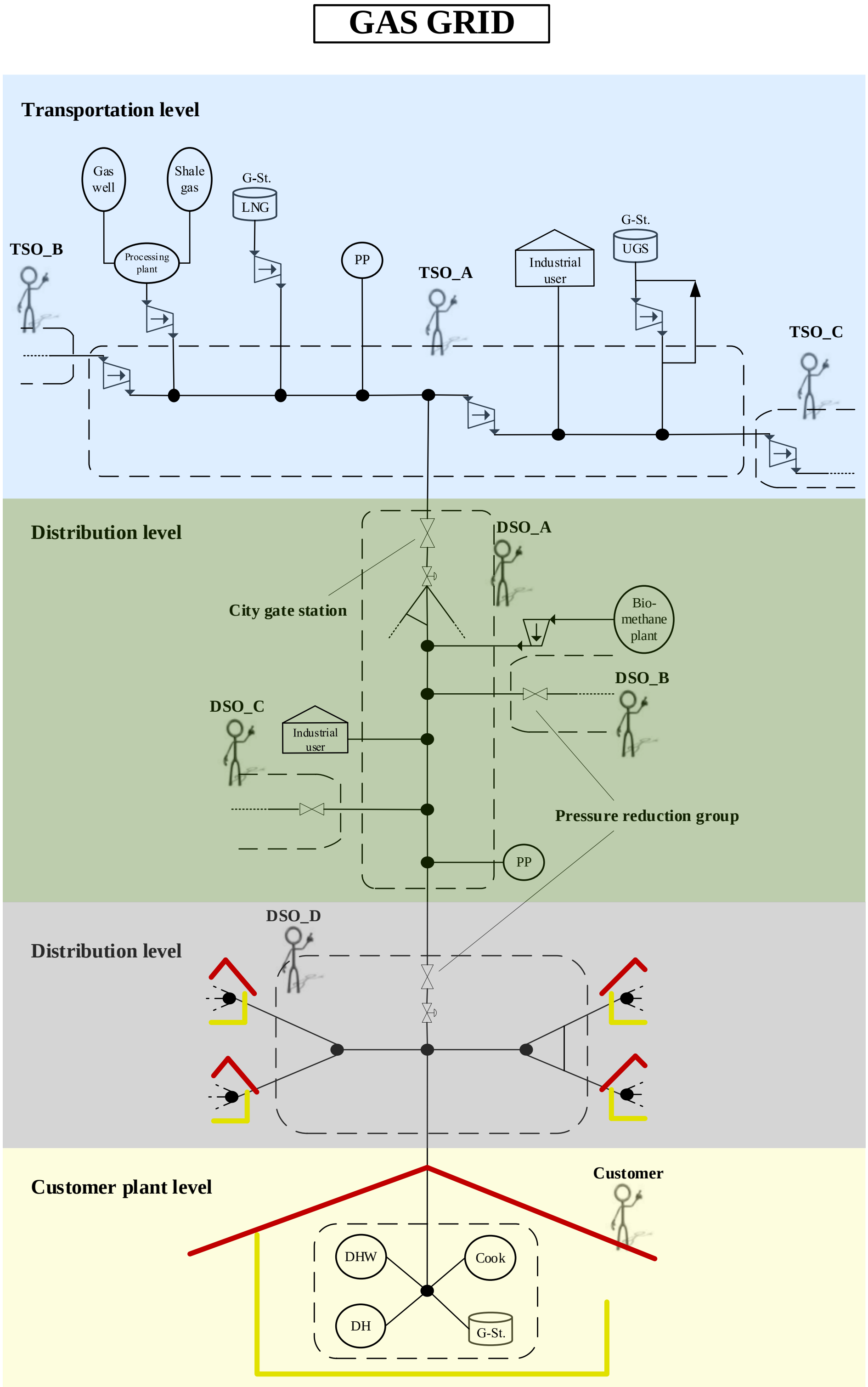


Figure 2: Gas grid topology

3 MATERIALS AND METHODS

The electricity and gas grids, the coupling elements such as the electrolyze and methanation reactor, and the linepack effect are described in the following.

3.1 Electricity and gas grids

The study subject is a residential area composed of twenty identical CPs connected to electricity and gas grids. The electricity grid consists of an LV grid connected to a Medium Voltage (MV) feeder through a Distribution Transformer (DTR). In comparison, the NG grid consists of an LP grid connected to a Medium Pressure (MP) pipeline by a Pressure Reduction Group (PRG), as in Figure 3.

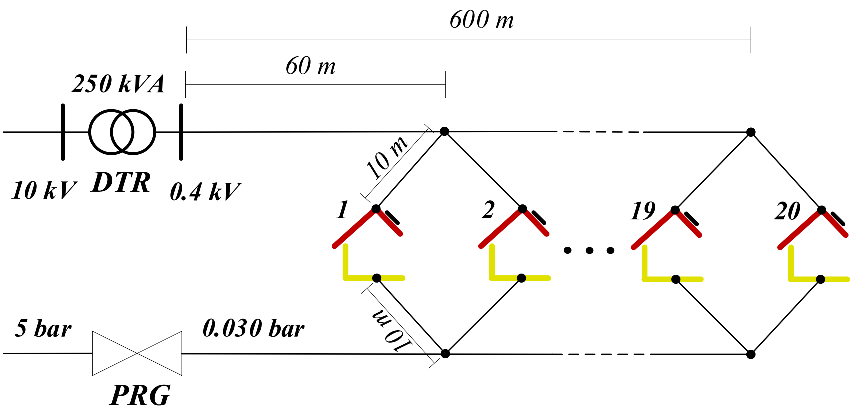


Figure 3: Structure of the simulated electricity and gas grids connecting the same customer plants.

Each CP represents a typical single-family house with four people, having a 7 kWp rooftop PV. It has appliances requiring electricity, i.e., electrical Devices, Power-to-Gas technologies (P2G), Electric Storage and others needing NG for Cooking, Domestic Hot Water (DHW), District Heating (DH) and Gas Storage. CCs represent P2G technologies, i.e., electrolyze and methanation-reactor, Figure 4.

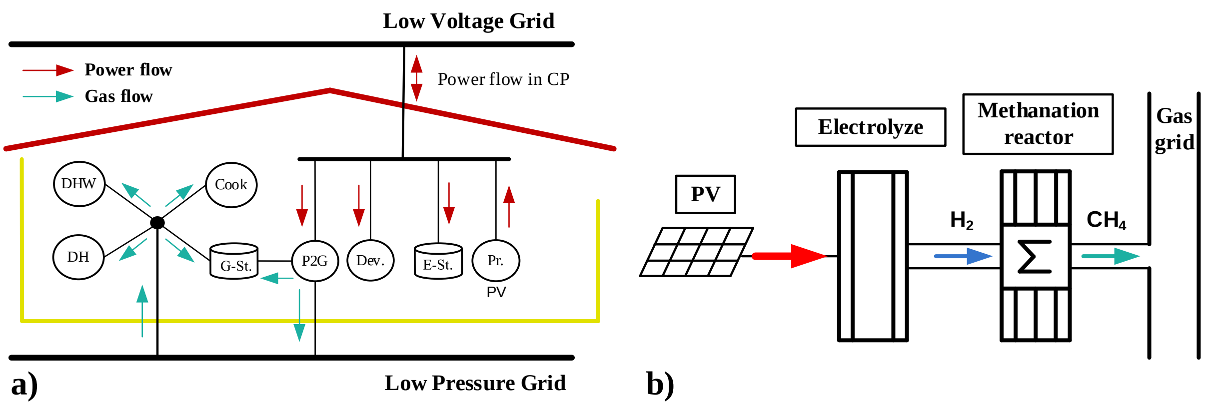


Figure 4: a) Customer plant power and gas flows scheme. b) P2G technologies inside each CP

Load profiles are used to characterize the CP electric and gas loads. DHW and gas cookers give the gas load profile because, in summer, no DH is necessary, Figure 5. They are extracted from an area of Turin, Italy, on a sunny August day having a peak electric power of 3 kWp and a peak thermal power of 1.2 kWp.

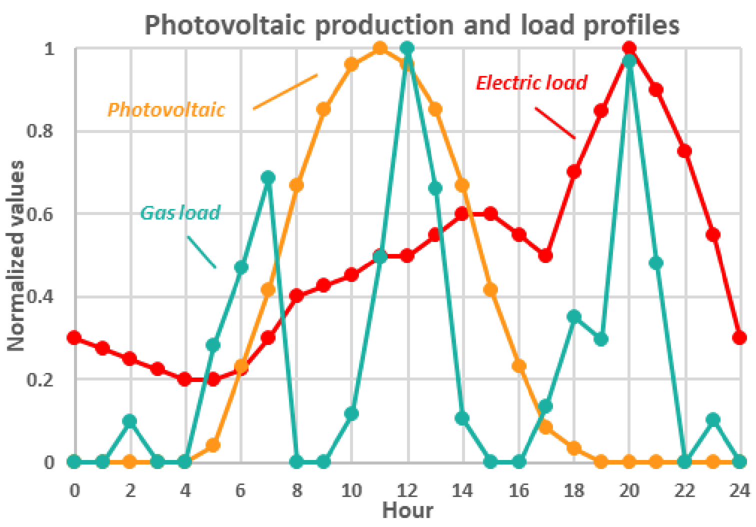


Figure 5: PV production, electricity and gas load profiles in each CP, August, Turin.

3.2 Main parameters

3.2.1 Connection points of DTR in MV feeder

While simulating the LV grid, depending on where the DTR is connected through the MV network, the input voltage could be different from the nominal value. If the LV grid is connected at the MV Feeder Head (FHd) (point A), the voltage can be 2% lower than the nominal one because the DTRs are not equipped with On-Line Tap Changer (OLTC), while at the end (point B), the voltage can be up to 6% higher as highlighted in Figure 6.

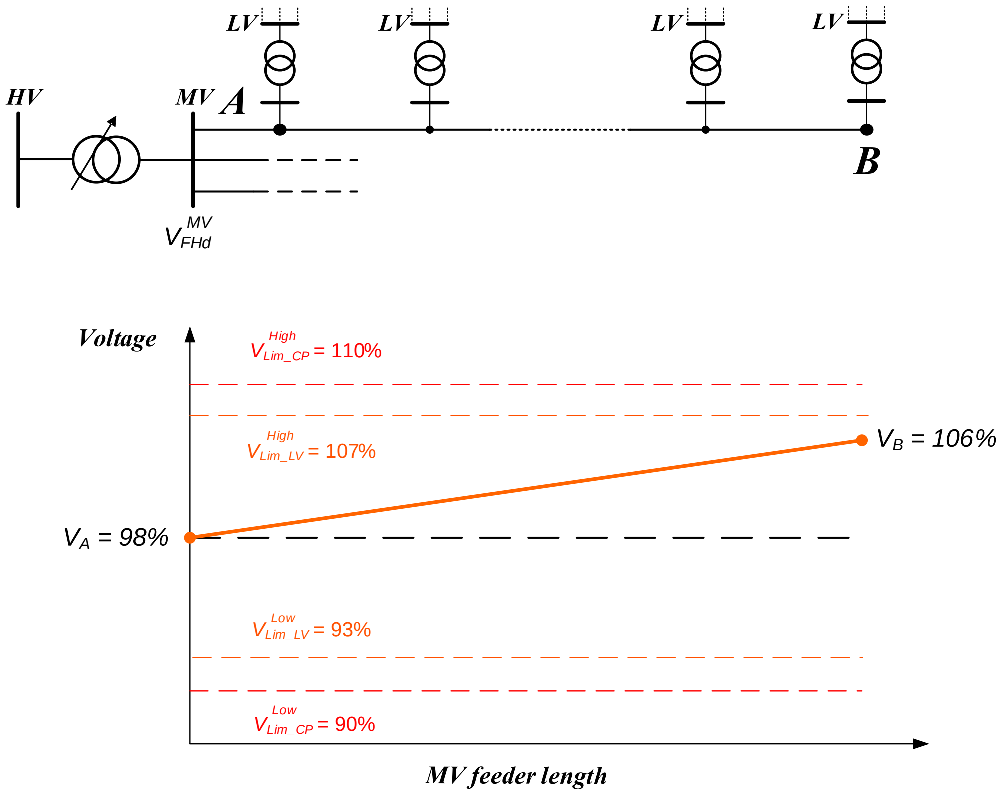


Figure 6: Connection point of DTR in MV feeder; VA=98%; VB=106%

The reduction of available thresholds is not the only consequence of this behavior since, if the voltage decreases, the load decreases too, leading to a higher electricity surplus.

The setting of the downstream nominal pressure value in the PRG is easier because the lamination valve doesn't work setting the pressure ratio but imposing the downstream pressure adapting its obstruction depending on the upstream pressure value. So, even if the pressure increases or decreases along the MP pipeline, the available threshold to inject or consume gas without violating the limits is everywhere and at each hour the same.

Thus, two input voltage values must be studied, i.e., V=106% and V=98%.

3.2.2 Primary LP pipeline diameter size

The primary LP pipeline diameter significantly impacts technical limitations inside the gas grid and the linepack effect so that it will be the main variable in this paper.

3.2.3 Nominal pressure value downstream of the PRG

The downstream nominal pressure value in the PRG has an impact on the pipeline storage capability because if it's higher, the linepack effect is lower.

3.3 Electricity and gas grid limits

The CP appliances must be supplied with a well-defined voltage level, regardless if they are consuming or injecting electricity. Therefore, the grid must provide electricity with a voltage threshold of ±10% of the nominal value. But inside each CP, there's a further small grid connecting all the appliances. The voltage drop in the CP network is planned not to exceed ±3% of the nominal value. It follows that the limits in the LV grid should be set to ±7% [7].

Like the electricity grid, the CP appliances in the gas grid need to be supplied with a well-defined pressure level, which should be very close to the atmospheric one. Nowadays, if relative pressure inside the LP pipelines drops below 19 mbar, appliances like boilers and gas cookers automatically interrupt the gas flow because there's the risk of not being supplied with a sufficient driving force, and if it goes over 40 mbar there's the risk of explosion [8].

Thus, the limits of both grids are represented in Table 3.

Electricity grid	
$\boldsymbol{V_{Nom}}$	400 V
$\boldsymbol{V_{Lim\_CP}^{High}}$	110 % V_{Nom}
$\boldsymbol{V_{Lim\_CP}^{Low}}$	90 % V_{Nom}
$\boldsymbol{V_{Lim\_LV}^{High}}$	107 % V_{Nom}
$\boldsymbol{V_{Lim\_LV}^{Low}}$	93 % V_{Nom}
Gas grid	
$\boldsymbol{P_{Nom}^{Pr}}$	25÷30 mbar
$\boldsymbol{P_{Lim\_CP}^{\mathrm{Pr}\_High}}$	40 mbar
$\boldsymbol{P_{Lim\_CP}^{\mathrm{Pr}\_Low}}$	19 mbar

Table 3: Electricity and gas grid limits

3.4 Electrolyze and methanation reactor

3.4.1 Electrolyze

Electrolysis of H_2O dissociates H_2 and O_2 by the application of electricity (direct current) using an electrolysis cell (eq. (1)).

$$H_2O_{(l)} = H_{2(g)} + \frac{1}{2}O_{2(g)} \quad (1)$$

The electrolyze needs to be supplied with pressurized hot H_2O and electricity. For this reason, a pump, a boiler, and a source of electricity lead to a higher thermal and electric load. Knowing the electrolyze type, the PV electricity surplus ($P_{Surplus}^{Power}$) and the hydrogen conversion rate ($F_{H_2} = 4.8\,\mathrm{kWh}/Nm^3$), the H_2 volumetric flow rate production (Q_{H_2}) is calculated as in eq. (2).

$$Q_{H_2} = \frac{P_{Surplus}^{Power}}{F_{H_2}} \quad (2)$$

3.4.2 Methanation reactor

The methanation reaction of CO_2 is an exothermic catalytic reaction producing SNG (treated as CH_4). It is typically operated at a temperature between 150 °C and 550 °C and pressure between 1 bar and 30 bar, depending on the exploited catalyst (eq. (3)).

$$CO_2 + 4H_2 = CH_4 + 2H_2O \quad (3)$$

In the hypothesis of having a pressurized CO_2 tank and the same operating pressure in the electrolyze and methanation reactor, there is no need for additional electrical power consumption. Still, it should be considered only an additional thermal load.

Since the H_2 mass flow rate is preserved, it is possible to find the CH_4 normal volumetric flow rate ($Q_{CH_4}^n$) [Nm^3/h] produced by eq. (5).

$$Q_{CH_4} = \frac{\frac{mol_{H_2}}{4} \times Mw_{CH_4} \times F_{CO_2}}{\rho_{CH_4}} \quad (4)$$

$$Q_{CH_4}^n = Q_{CH_4} \times \left(\frac{P_{met}^{Pr}}{P_n^{Pr}} \times \frac{T_n}{T_{met}}\right) \quad (5)$$

Where P_{met}^{Pr} and F_{CO_2} are the absolute pressure of the methanation reactor [Pa] and the CO_2 conversion efficiency factor [-], respectively. The latter depends on the operative pressure and temperature inside the methanation reactor [9]. In this paper, it is set to 0.98.

3.4.3 Overall efficiency of the electricity-CH_4 conversion process

To understand the potential of this solution it's showed an example to understand how much CH_4 can be extracted exploiting surplus energy generated by a PV power plant. Having a 5 kW PV plant, H_2 can be produced (compressing H_2O to 8 bar and heating it up to 50 °C) into an AEM electrolyze having a conversion rate of 4.8 kWh/Nm^3. At this point, compressing CO_2 to 8 bar and heating CO_2 and H_2 to 300 °C, it can be obtained CH_4 through a methanation process having, as explained above, a CO_2 conversion efficiency factor of 98%. In this way, 0.25 Nm^3/h of CH_4 are generated. Figure 7 highlights the whole process.

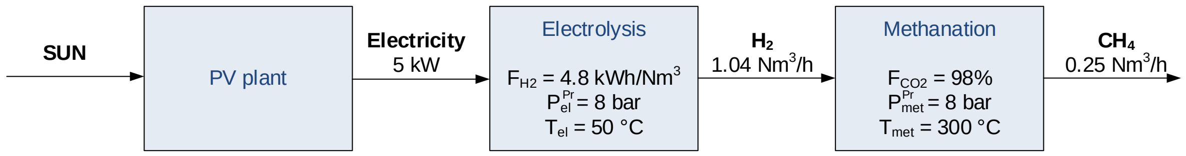


Figure 7: Flow of the conversion process

Though, the overall efficiency of the process is highlighted in eq.(6).

$$\eta_{tot} = \frac{Q_{CH_4} \times HHV_{CH_4}}{Electricity\ input} = 55{,}5\% \tag{6}$$

Where HHV_{CH_4} is the CH_4 higher heating value.

3.5 Gas grid: linepack effect

Pipelines, having a certain diameter and hosting compressible gas, can work as storage systems, the so-called linepack. The linepack effect is higher if the downstream nominal pressure value in the PRG is lower. The maximum storage capacity is achieved once the pressure inside the pipelines reaches the maximum allowable one (40 mbar); thus, the maximum injectable mass of gas from each CP (m_{inj}^{mass}) [kg] is found by eq. (9).

$$m_{in}^{mass} = \frac{P_{in}^{Pr}}{Z \times R \times T} \times Vol \tag{7}$$

$$m_{fin}^{mass} = \frac{P_{fin}^{Pr}}{Z \times R \times T} \times \mathrm{Vol} \tag{8}$$

$$m_{inj}^{mass} = \frac{m_{in}^{mass} - m_{fin}^{mass}}{N_{CPs}} \tag{9}$$

Where Vol, P_{in}^{Pr}, P_{fin}^{Pr}, m_{in}^{mass}, m_{fin}^{mass}, Z, R, T and N_{CPs} are respectively the pipes' volume [m^3], the initial and final pressure [Pa], the initial and final pipes' mass of gas [kg], the compressibility factor [-], the gas constant [J/kgK], the temperature [K] and the number of connected CPs [-].

4 RESULTS AND DISCUSSION

In this section the effect of distributed electricity and gas injections is studied, as well as the linepack effect.

4.1 Distributed electricity injections

Results show that if the DTR is connected at the MV FHd, thus when *V*=98%, if the electricity surplus is injected back into the LV grid, no voltage problems occur. However, if the DTR is connected at the end of the MV one (*V*=106%), voltage problems occur despite the higher load and the lower power surplus feedback.

Figure 8 shows that when electricity is supplied from the MV grid (17:00 and 20:00) no voltage problems occur, but at 11:00, when 5.2 kW are injected back in the grid from each CP, it is evident how they occur.

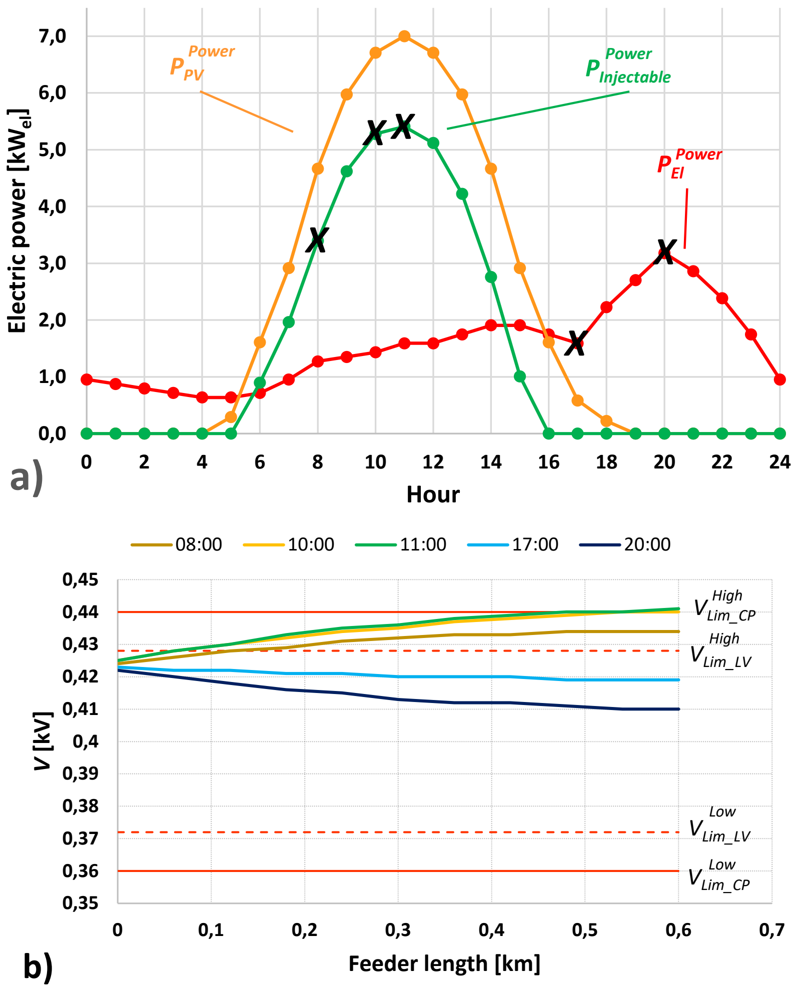


Figure 8: a) Electricity profiles for each CP. b) Voltage profiles in the analyzed hours, V=106%

4.2 Distributed Natural Gas (NG) injections

Thus, because of the hosting capability limits showed by the electricity grid the electricity surplus can be exploited to produce Synthetic Natural Gas (SNG), to be used partly inside the building and partly for injection back into the gas grid. The additional power requested to compress H_2O, and to heat H_2O, CO_2 and H_2 increase electric and gas loads for each CP, as highlighted in Figure 9.

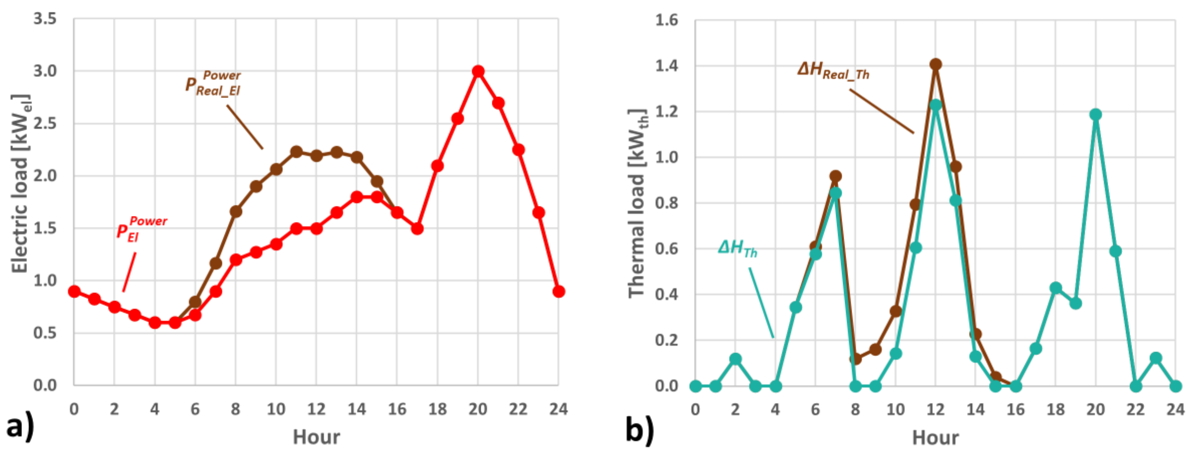


Figure 9: Daily load profiles after electrolysis and methanation. a) Electric load; b) Thermal load

On a daily analysis the impact of voltage value at the beginning of the LV feeder on SNG production is highlighted in Figure 10.

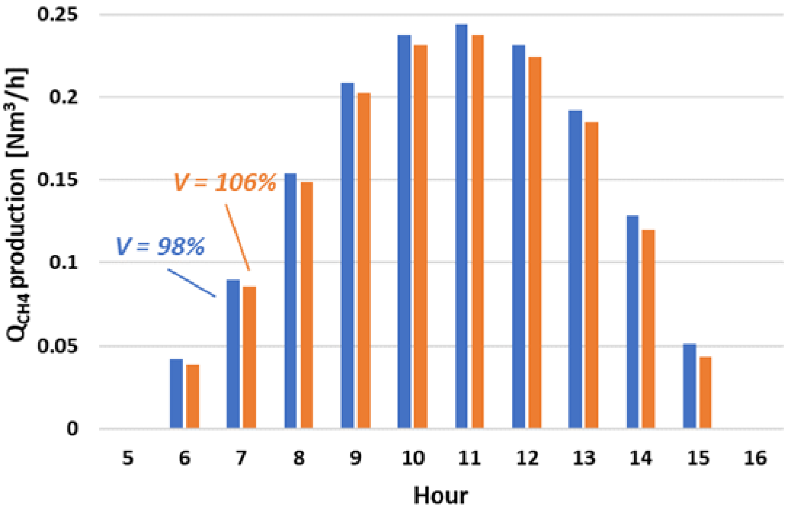


Figure 10: Daily voltage dependency on SNG production

This figure shows that electricity surplus is available only between 6 and 15 o'clock. It's evident how SNG production increases if voltage value is lower because it goes hand in hand with the electricity surplus generated by PV plant. Thus, the most critical scenario regarding gas injections is the case of a LV feeder connected at the MV FHd (*V*=98%).

LP gas grid's simulations have been carried out in the same hours analyzed even for the LV electricity grid, Figure 11. It is evident how, differently from the injectable electricity, the time of maximum SNG surplus (0.21 Nm^3/h) is 10:00 because, despite production being similar, consumption is lower than 11:00

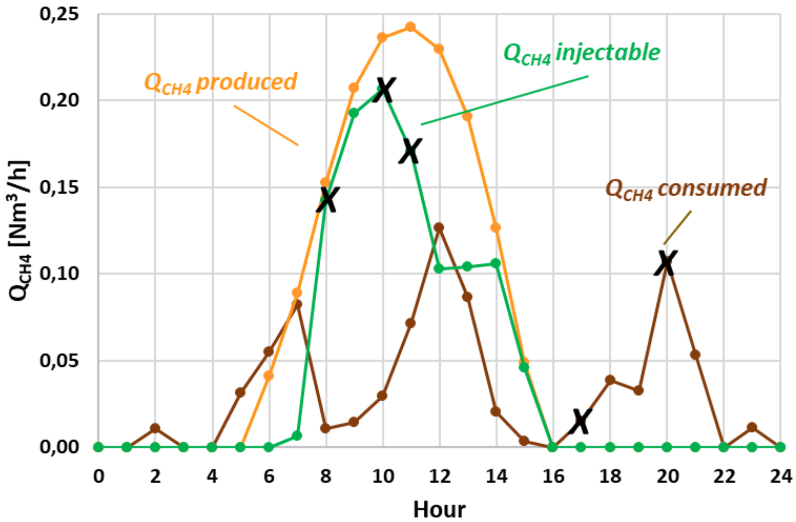


Figure 11: Thermal profiles for each CP, V=98%

LP gas grid's simulations are carried out considering that the PRG is upgraded with a compressor to allow the bidirectional gas transfer.

So, for *V*=98%, a primary LP pipeline diameter of 30 mm, a secondary LP pipelines diameter of 15 mm and a nominal pressure downstream, the PRG of 30 mbar gas grid results are showed in Figure 12.

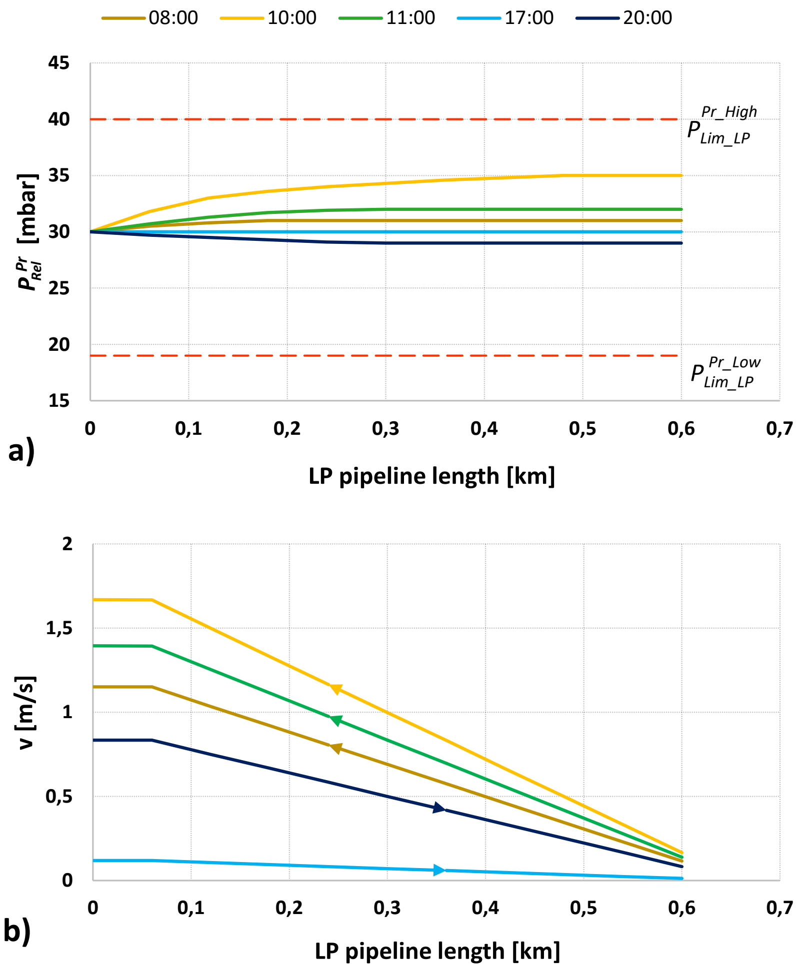


Figure 12: LP pipeline: d=30mm, P_{nom}=30mbar, V=98%; a) Pressure profiles; b) Velocity profiles

The figure shows that when NG is supplied from the MP grid (17:00 and 20:00), no pressure problems occur, but, differently from the electricity grid, at 20:00, when SNG injections are maximum, no pressure problems arise too. The upper-velocity limit is 5 m/s; thus, neither velocity problems appear.

Gas grid results are influenced by the pipeline diameter size, Figure 13.

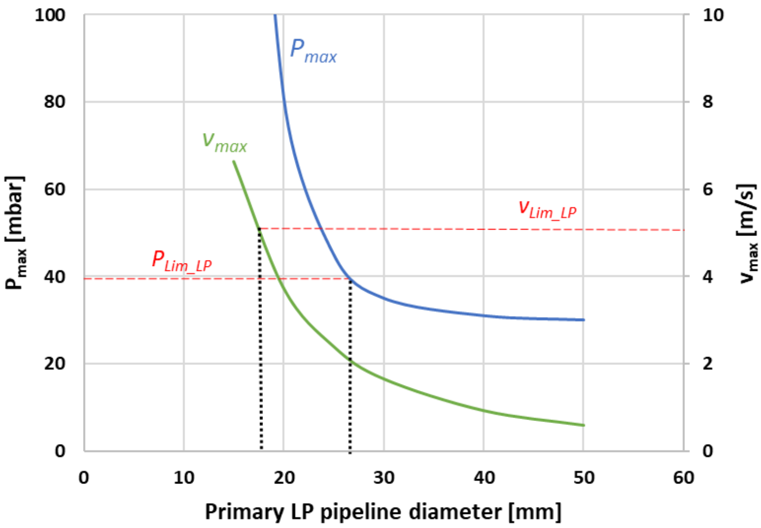


Figure 13: Maximum pressure and maximum velocity dependency on primary LP pipeline diameter

The figure shows that, considering the same mass flow rate, lowering the diameter, velocity increases and pressure drops increase too. The maximum allowable pressure value gives the strongest limitation because if the minimum diameter size to impose not to have velocity problems is 18 mm, the one to impose not to have pressure problems is 27 mm.

Finally, it even highlights that for a diameter size higher than 45mm, pressure remains always the same, thus not creating problems of linepack advantages exploitation even for higher nominal pressure values.

4.3 Linepack effect

The linepack effect is maximized when the nominal pressure downstream the PRG is the minimum allowable value. To exploit the linepack effect, the primary LP pipeline diameter must be greater than 45 mm to ensure the absence of pressure limits violations both at 10.00 (when the injection is maximum) and at 20.00 (when consumption is maximum). Figure 14 shows the pressure behavior inside the primary LP pipeline for a primary LP pipeline diameter size of 300 mm, a secondary LP pipeline diameter size of 150 mm and a nominal pressure downstream the PRG of 20 mbar.

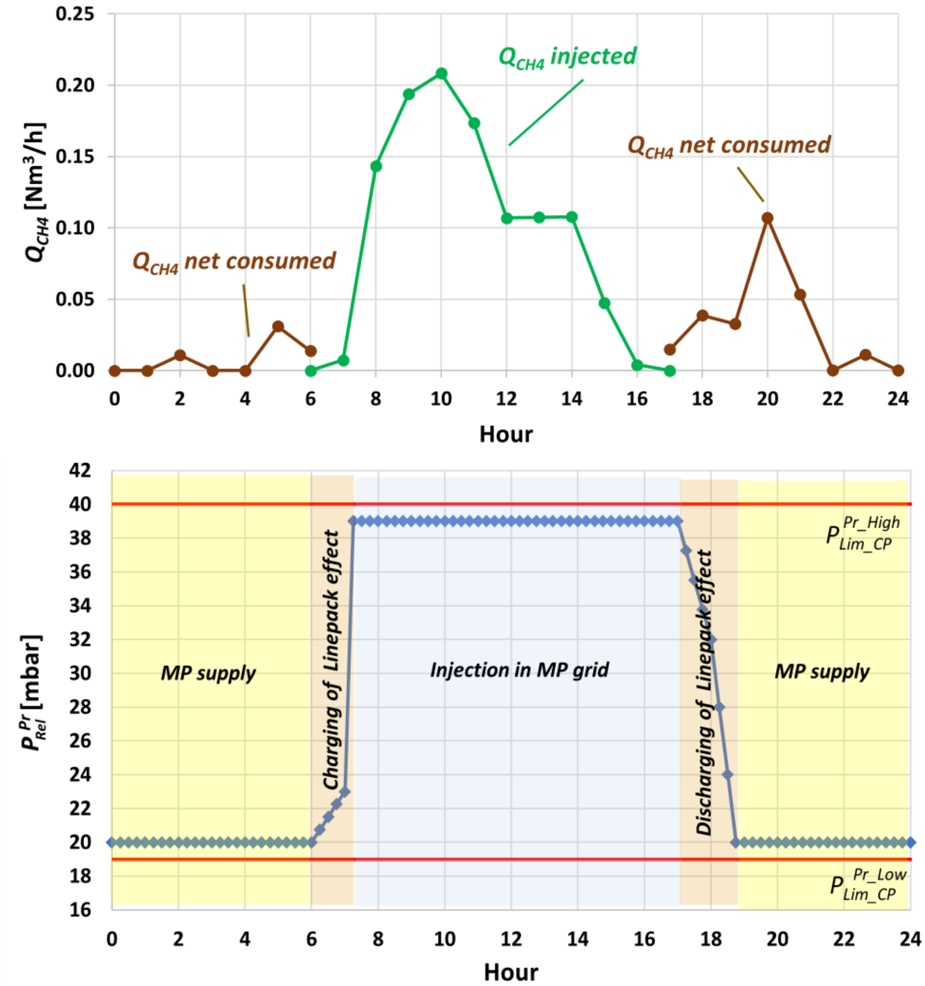


Figure 14: Linepack exploitation: daily pressure profile

Figure 14 shows that at 6:00, when SNG production prevails on NG consumption, it is injected back into the LP grid, exploiting the linepack effect until the maximum allowable pressure of

39 mbar is reached. Then the compressor in the PRG is activated, and NG is injected back into the MP grid. Once consumption prevails again on production, the linepack effect is exploited to cover the thermal load until nominal pressure of 20 mbar is reached again. From now on, the gas supply from MP to LP grid at PRG restarts. In this way, 0.81 Nm^3 of SNG can be stored, allowing a covered night load percentage of 13.5%.

5 Conclusions

The *LINK*- holistic architecture is crucial because it allows each grid level in electricity and gas systems to be approached similarly, allowing all consumers to become prosumers of electricity and gas. The technical limitations of rooftop PV integration at the Customer Plant level may be overcome by coupling the electricity and gas grids by exploiting coupling components to produce Synthetic Natural Gas and inject it back into the Natural Gas grid. For the analyzed study case, no problems appear for a minimum primary Low-Pressure pipeline diameter size of 27 mm; in this case, each Pressure Reduction Group should be upgraded with a compressor to allow the bidirectional gas transfer. The gas prosumer may exploit even the linepack effect. It allows covering a part of the thermal load even in the evening without incurring additional costs to buy a storage tank for each Customer Plant. The extent of this storage strongly depends on the diameter and length of the Low-Pressure pipelines. Still, it has the benefit of limiting the problem of non-contemporaneity between production and consumption and limiting the compressor's usage time, which is activated only when the pressure in the pipeline reaches the maximum allowable value.

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