Thermodynamic evaluations on the potential energy recovery from the Italian natural gas network

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Abstract:

A big amount of the pressure energy content of natural gas in the distribution network is wasted in the throttling valves of the pressure reduction stations (PRSs) to feed the final users at the required values. This paper presents an overview of the potential energy recovery from the 12000 monitored PRSs installed in the Italian natural gas distribution network. These PRSs are first split into three groups featuring high, medium and low inlet pressure (HP, MP, LP), to search then, for each group, specifically tailored expander-generators preheated by a geothermal heat pump in order to evaluate the amount of electricity that could really be generated by recovering the 3.17 TWh/year of energy presently wasted in the throttling valves. The 54.1% of this energy is available in the HP group while the 29.7% and 15.9% are available in the MP and LP groups, respectively. The total electricity generated by the expander-heat pump systems would be 1.526 TWh/year, 0.904 TWh/year of which from the HP-PRSs, 0.450 and 0.168 TWh/year from the MP and LP ones. The corresponding energy recovery efficiencies of these systems would be 52.7%, 47.7% and 33.2%. The highest efficiency is achieved in the HP-PRs because of the high efficiency of large radial turboexpanders and because of the enthalpy drop improvement that result from the preheating of the gas at high pressure.

Keywords:

Energy recovery, natural gas distribution network, natural gas expander, natural gas engineering

1. Introduction

The natural gas network is designed to achieve an acceptable compromise between cost of infrastructure and cost of the energy spent to pressurize the gas. To reduce the volume of pipelines and make the transportation efficient, the natural gas is compressed before the injection in the distribution network [1]. However, just a small fraction of the pressure energy of the natural gas is effectively utilized to keep it in motion while the rest is usually wasted in pressure reduction stations (PRSs). These stations subdivide the distribution network into subsystems --working at decreasing pressure levels as the gas gets closer to the final users. For instance, the maximum distribution pressure for domestic units is 0.04 barg, whereas it ranges from 8 barg to 0.04 barg for industrial users and energy conversion plants. To guarantee the availability of natural gas at the various extraction points and make the interaction possible between subsystems operating at different pressure levels, the natural gas network is equipped with various Pressure Reduction Stations (PRSs). In these stations, the pressure drop of the natural gas is obtained by means of simple and reliable throttling valves, which perform an isenthalpic process without any extraction of work. Alternatively, turbo-expander generators can be used to exploit the energy associated with the pressure drop for power generation. Real installations of radial-turboexpander generators have worked profitably for years in several countries (e.g. in the US [2], UK [3] and Italy [4-5]) however, the number of installed machines is still relatively modest. Recently, a few authors propose volumetric expanders instead of the traditional radial ones because of the lower cost and higher robustness. These features start to become increasingly important as the size of the energy system decreases, and for very small sizes, they may become necessary to pay off the investment costs in reasonably short periods. Diao et al. [18] developed a prototype of a screw expander working with natural gas between 8 barg and 2 barg, finding an isentropic efficiency of about 70%. Howard et al. [19] studied an energy recovery solution including a small size radial turboexpander coupled to fuel cells for preheating and working between 6 barg and 2 barg. They found an averaged isentropic efficiency of the expander of about 68%. Yao et al. [20] carried out a study on the performance of a twin-screw expander as power generation unit working with natural gas between average pressures of 8 barg and 2 barg. They found that the expander could reach isentropic efficiencies of about 70% at design conditions, which decrease to 35% at off-design conditions. Yaxuan et al. [21] considered the energy recovery from a natural gas network with a single screw expander coupled with a heat pump to provide the energy needed for preheating. The expander works both as power generation unit and pressure regulation device between 6 barg and 1 barg. They found an isentropic efficiency ranging between 90% and 40%. Tian et al. [22] developed a mathematical model to predict the performance of a single screw expander employed in steam pressure pipelines to recover energy from the pressure drop (7 barg – 1 barg) during intermitted operating conditions. They found that the maximum isentropic efficiency fluctuates between 73 and 83%. Barbarelli et al. [23] developed a prototype of an innovative volumetric expander to recover energy from natural gas from a pressure drop 3.5 - 1 barg. They found a maximum achievable isentropic efficiency of about 40%. As imposed by the Italian legislation, most of the expander installations require the preheating of natural gas upstream of the expansion process. This avoids the undesired condensation of gas hydrates that could damage pipelines and other components of the network but in contrast, it reduces the advantages of gas expanders in terms of energy efficiency. In many applications, thermal oil or water heaters are employed as gas preheaters because of their relatively low cost however, numerous works in the literature propose the utilization of different strategies to manage the preheating and increase the total efficiency of the system, such as:

a) Using a solar thermal storage [7] or low temperature thermal sources deriving from industrial processes and renewables [8, 9].

b) Coupling (e.g., [10]) heat pumps with the turboexpander electric generator to invest part of the electricity generated by recovery for preheating.

c) Utilizing the cold thermal energy available at the end of the expansion process for industrial or domestic users [11] or as a cold source for power plants [12].

In any case, the electricity generated by the expander-generator can be sent to the grid, used for preheating or stored in the gas network as hydrogen [13, 11, 14].

It is evident that this field represents an active research area in which authors propose a wide range of possible energy recovery solutions that could be applied to PRSs however, real applications are still very limited despite the stricter policies for energy saving adopted recently in several countries. In this context, some questions arise: why the energy recovery from PRSs in natural gas distribution network is rarely proposed? Is it a matter of costs or efficiency? Are there one or more energy recovery solutions that could be feasible for a diffuse application to a large number of PRSs? How much energy can be recovered with acceptable costs and efficiency?

The goal of this paper is to answer these questions by estimating the real amount of energy that is available from the pressure drops in the PRSs of the Italian natural gas network, and the power that could be generated if this energy were exploited by commercially available expander-generator systems. To this end, the complete Italian gas network is first described to provide a picture of its entire structure including its main subsystems. Secondly, a literature review is carried out to evaluate the real performance of expander-generator systems operating in accordance to the various operating conditions of the PRSs. Eventually, starting from the average annual values of mass-flow rates and inlet/outlet pressure of the 12000 monitored PRSs installed in Italy, the available energy and its recoverable fraction have been estimated. The economic wellfoundedness of the proposed intervention is also briefly discussed, although a complete economic evaluation is left to further works.

2. Description of the Italian natural gas distribution network

The following sub-sections describe: i) the general structure of the Italian gas distribution network and ii) the classification of the pipelines and pressure reduction units installed all over the country.

2.1 General description

Natural gas distribution networks are composed of three main components: pipelines, compression stations and pressure reduction stations (PRS). The Italian gas network features about 32.500 km of pipelines at various pressure levels, 11 recompression stations with a total installed power of about 877 MW and about 12.000 monitored pressure reduction stations. The entire network is divided into two main parts:

1) The "national pipeline network" including the systems involved in the transportation of natural gas from the injection points to the regional interconnections and storage sites;
2) The "regional pipelines network" including the systems required for the local transportation of natural gas and the supply of industrial/urban users and power plants.

Figure 1 shows the geographical location of the national (red) and regional (blue) pipeline networks and of the injection points from neighbouring and oversea countries.

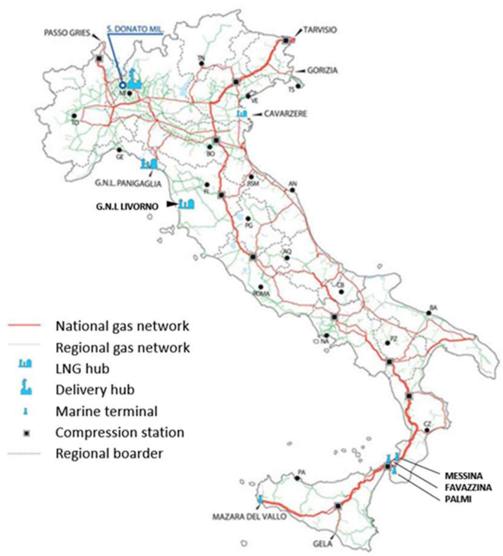


Fig. 1-Italian national (red) and regional (blue) pipeline gas network. Injection points from foreign suppliers [6].

The connection with Sicily Island is guaranteed by four Marine Terminals connecting the submarine pipelines to the onshore ones in Mazara del Vallo (Trapani), Messina, Favazzina (Reggio Calabria) and Palmi (Reggio Calabria).

National reserves cover only a small fraction of the natural gas consumption in Italy, the rest being supplied through five injection points (1-5 in the following) connected to international pipelines and three injection points (6-8 in the following) connected to LNG hubs:

1. Mazara del Vallo (Sicily), connected to the Algerian gas supply network by means of submarines pipelines;

2. Gela (Sicily), connected to the Libyan gas supply network by means of the submarine pipeline called "Greenstream";
3. Tarvisio (North-East), connected to the Austrian gas network by the TAG pipeline;
4. Gorizia (North-East), connected to the Slovenian gas network;
5. Gries Pass (North), connected to the Swiss gas network by the Transitgas pipeline;
6. Italia di Panigaglia, (North West coast), connected to LNG hub;
7. Cavarzere (North East coast), connected to LNG hub;
8. Livorno (North West coast), connected to LNG hub;

Natural gas storage sites are extremely important for the Italian market of natural gas because they highly improve the flexibility of the network and give a "safety margin" in a market strongly dependent from imports. The total storage capacity is about 16 billion of m^3 and it is realized in exhausted underground deposits. Both the storage capacity and the LNG injection points are planned to be increased in the next few years.

2.2 Pipelines and pressure reduction stations classification

Italian legislation provides a classification of gas pipelines based on their nominal operating pressure, indicating seven different "species", whereas an official classification of the pressure reduction stations (PRSs) does not exist yet. In this work, a classification of the PRSs based on the inlet pressure is proposed because of the high importance of pressure conditions on the performance characteristics of the energy recovery systems (expander-generator). Three inlet pressure ranges are used to identify high, medium and low-pressure stations (HP, MP, LP, respectively). Pipelines, PRSs groups and number of PRSs in each group are listed in Tab.1.

Table 1 – Pipelines and PRSs classifications.

Pipelines		Pressure Reduction Stations		
Species	Pressure	Group	Pressure	N° of PRSs
I	$p > 24$ barg	HP	$p_{in} > 24$ barg	9069
II	$24 \geq p > 12$ barg	MP	$24 \geq p_{in} > 8$ barg	2223
III	$12 \geq p > 5$ barg	LP	$8 \geq p_{in}$ barg	537
IV	$5 \geq p > 1.5$ barg			
V	$1.5 \geq p > 0.5$ barg			
VI	$0.5 \geq p > 0.04$ barg			
VII	$0.04 \geq p$ barg			

Detailed monitored data are available for the majority of the PRSs in the HP and MP groups while just a few information are available for LP-PRSs, i.e. those delivering gas to the domestic users. Gas distributors do not monitor the operation of these stations because of their secondary role in the distribution network. The number of LP-PRSs (537) is estimated considering that there is at least one LP-PRS downstream of the MP or HP PRSs having an exit pressure lower than 8 barg. Indeed, the real number of LP-PRSs is greater or equal to the number of these MP/HP PRSs because there might be more than one station downstream of such MP/HP PRSs. In any case, this hypothesis keeps the energy balances fulfilled, although pressure losses in the low-pressure pipelines are neglected.

3. Methods

The following sub-sections describe:

i) The method used to calculate the total energy dissipated in the pressure reduction stations of the Italian natural gas distribution network (i.e. the energy that is available for recovery);
ii) The criteria used to select the energy recovery system in HP, MP and LP reduction stations;
iii) The methodology employed to size the systems and calculate the annual producible electricity.

3.1. Calculation of the available energy

The energy available at each PRS is calculated using inlet pressure, mass-flowrate and inlet temperature data considering an adiabatic-isentropic expansion:

$$E_{av} = P_{av} * 8760 \quad (1)$$

$$P_{av} = \dot{m}_{gas} * (h_{in} - h_{is,out}) \quad (2)$$

$$h_{in} = f(p_{in}, T_{in}) \quad (3)$$

$$h_{is,out} = f(p_{out}, s_{in}) \quad (4)$$

where P_{av} [kW] is the available power, E_{av} [kWh] is the total annual available energy, $\dot{m}_{gas}$ [kg/s] is gas mass-flowrate, h_{in} [kJ/kgK] is the enthalpy of the gas at the inlet of the PRS and $h_{is,out}$ is the isentropic enthalpy of the gas at the outlet of the PRS.
The net available energy must take into consideration the thermal energy for preheating in the PRSs with high to medium pressure drops, which is required to avoid the formation of hydrates that could compromise the operation of valves and pipes. The Italian legislation does not impose a preheating system when a throttling valve is employed to perform the expansion process if the pressure drop or the inlet pressure is smaller or equal to 12 barg. In all the other cases, the Italian legislation suggests calculating the amount of thermal power required for preheating as:

$$M = \frac{\Delta h * \rho_s * Q}{\eta_h \eta_{ph}} = 0.00024 * \Delta h * Q \quad (5)$$

$$\Delta h = f(p_{in}, T_{in}) - f(p_{out}, T_{out}) \quad (6)$$

where M[kW] is the thermal power needed for the preheating process, Δh [kJ/kg] is the enthalpy drop between inlet and outlet conditions, T_{in} is the average annual inlet temperature (fixed at 10°C) T_{out} is the temperature after the pressure drop (fixed at 5°C to avoid hydrates formation), p_{in}, p_{out} [bar] are the inlet and outlet pressures, Q[Stm^3/h] is the standard volumetric flow rate of the gas, ρ_s is the gas density at standard conditions (0.7 kg/Stm^3), η_h and η_{ph} are the efficiencies of the heater and heat exchangers, respectively (90% for both components).
The net available energy from each PRS is calculated as follows:

$$E_{av,net} = 8760 * (P_{av} - M) \quad (7)$$

3.2. Selection of the energy recovery system

High and Medium pressure reduction stations

The literature review provided in the Introduction suggests that the production of electricity by means of turboexpander-generators in combination with a proper use of the associated thermal streams (cases a) and c) in the Introduction) is the most efficient energy recovery system when medium-to-high PRSs are considered. However, these solutions are "location dependent", because they depend on the features of the thermal sources and/or demands. Thus, the preheating solution that involves the utilization of geothermal heat pumps that consume part of the electricity produced by the turboexpander-generator (option b) in the Introduction) is considered here for all the HP/MP-PRSs. Independently of the efficiency, this solution does not involve the utilization of additional energy for preheating and so appears to be the most widely applicable.

Low pressure reduction stations

The low pressure drops available in the LP-PRSs are seldom considered as interesting opportunities to apply energy recovery technologies because of the increasingly intermittent nature of the gas mass-flowrate with decreasing pressure levels. To recover the pressure energy available in the group of LP-PRSs, volumetric Scroll expanders are considered instead of the traditional radial ones because of their lower cost and higher robustness. As suggested by the literature these features start to become increasingly important as the size of the energy system decreases, and for very small sizes, they may become necessary to pay off the investment costs in reasonably short periods. As per the HP and MP PRSs, geothermal heat pumps are considered as preheating systems (when needed) to be coupled to the Scroll expanders.

3.3. Electric consumption of the heat pump for preheating

The geothermal heat pump is fueled by the electric power generated by the expander connected to an electric generator having η_{el}=0.90. The electric power P_{el}[kW] required to provide the proper preheating is calculated as follows:

$$|P_{el}| = \frac{|Q_{th}|}{COP} = f(T_{evap}, T_{cond}) \tag{8}$$

where Q_{th} [kW] is the thermal power required for preheating. The coefficient of performance (COP) is strongly affected by the temperatures of the cold and hot source (T_{evap}, T_{cond}, respectively). In this work, a constant temperature of 15°C is considered for the cold source (ground) while the temperature of the hot source (T_{cond}) is calculated for each PRS in accordance to the temperature requested for the preheating before the expansion process (i.e. $T_{out,ph}$ in Eq. (11)):

$$Q_{th} = \frac{\dot{m}_{gas} * \Delta h_{ph}}{\eta_{HE}} \tag{9}$$

$$\Delta h_{ph} = f(p, T_{out,ph}) - f(p, T_{in,ph}) \tag{10}$$

$$T_{out,ph} = f(\Delta h_{is}, \eta_{is}) \tag{11}$$

where Δh_{ph} [kJ/kg] is the enthalpy increase resulting from preheating, $T_{in,ph}$ is the gas inlet temperature (depending to the season), p [bar] is the gas pressure and η_{HE} is the efficiency of heat exchangers (0.90). $T_{out,ph}$ is the gas temperature after preheating which depends to the expansion process in fact, this temperature is subject to the constraint that natural gas should not exit the PRS (after the expansion) at a temperature lower than 5°C. This constraint is imposed by the Italian legislation to avoid the condensation of hydrates in the gas network. To a first approximation, the evaporation temperature (T_{evap}) is set equal to the average annual ground temperature in Italy (as if the heat transfer area between ground and working fluid of the heat pump were infinite). The COP is evaluated using the commercial data [15] on the performance of geothermal heat pumps shown in Fig. 2.

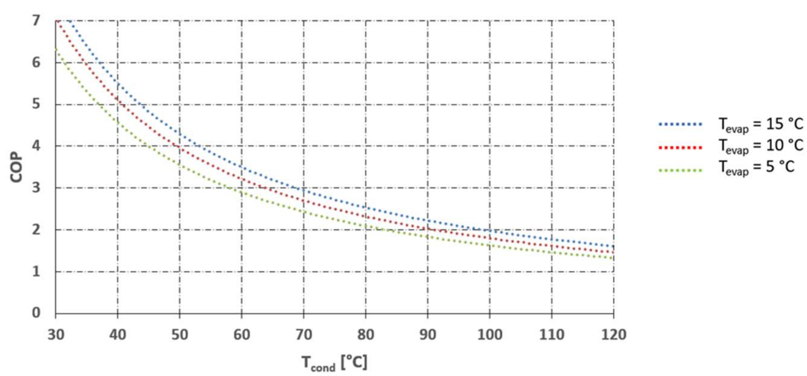


Fig. 2 - Geothermal heat pump performance map.

3.4. Sizing of the expanders and electricity generation from the available energy

The size of the expander (identified by the mass-flowrate (m_{DP}) at design point) should be selected for each PRS in accordance with the annual trend of the natural gas mass-flow rate, which is strongly affected by the seasonality of the consumptions. Figure 3 shows the dimensionless curve of the natural gas mass-flow rate derived from available data of a real MP-PRS installed in Padova. To simplify the calculations, this curve is substituted by a five-steps curve keeping the total area below the curve unchanged and is then used to reproduce the mass flow rate curves in all PRSs. This is done multiplying, for each PRSs, the dimensionless mass flow rate of each step in Fig. 3 by the known value of the annual average mass-flow rate through the PRS. Using the same trend for all the 12000 monitored PRSs reduces the accuracy of the calculation but strongly simplifies it. The loss in accuracy should not be very high because the trend of natural gas consumption in Padova (Fig. 3) is similar to that of the main cities in Italy where most of natural gas is consumed. Using the specific trends of every PRSs would enhance the accuracy especially in the LP-PRSs featuring larger fluctuations of the mass flow rates.

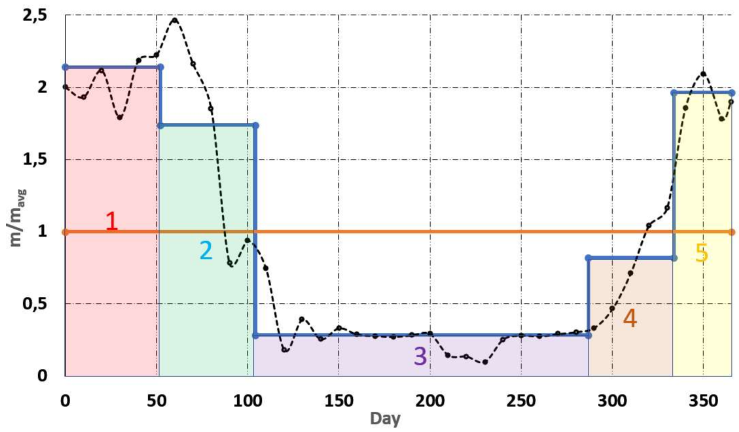


Fig. 3 - Dimensionless step (blue) and original (black dashed) function of the natural gas mass-flowrate flowing through a reference PRS.

The size of the expander is chosen to maximize the annual producible electricity, calculated as follows:

$$E_{el,net} = E_{el,exp} - E_{el,HP} = \sum_{step=1}^{5} (\dot{m}_{step} * \Delta h_{is,step} * \eta_{is,step} * \Delta t_{step} * \eta_{el} - \frac{|Q_{step}|}{COP_{step}} * \Delta t_{step}) \quad (12)$$

where $E_{el,exp}$ [kWh/y] is the annual electricity producible by the expander, $E_{el,HP}$ [kWh/y] is the annual electricity that is spent by the heat pump to provide the requested preheating, $\dot{m}_{step}$ [kg/s] is the expander mass-flow rate, $\Delta h_{is,step}$ [kJ/kg] is the isentropic enthalpy drop, $\eta_{is,step}$ [-] is the isentropic efficiency, Δt_{step} [h] is the time interval of each step. To choose the size of the expander, five different values of design-point mass-flow rates are selected in between the maximum ($m_{step=1,PRS}$) and minimum values ($m_{step=3,PRS}$) by dividing equally the operating field ($m_{step=1,PRS}$-$m_{step=3,PRS}$) in Fig. 3. For each of the selected values, the annual producible electric energy is calculated using Eq. (12) and eventually the best one is chosen. The sizing procedure is summarized in the following. It is slightly different for the two types (radial and volumetric) of expanders chosen for MP/HP and LP stations, respectively. The values of the performance parameters at design point are set in accordance to those normally adopted in the design of these types of expander (Tab. 2).

Table 2 – Design parameters of radial and scroll expanders.

	Radial turboexpander	***Scroll expander***
Design point isentropic enthalpy difference ($\Delta h_{is,DP}$)	$f(p_{in,PRS},T_{in,PRS})^*$	$f(p_{in,PRS},T_{in,PRS})^*$
Tip-speed-ratio ($u_2/\sqrt{2 * \Delta h_{is,DP}}$)	0.7	-
Isentropic efficiency ($\eta_{is,DP}$)	0.8	0.7
Rotational speed [rpm]	Constant	Variable

**T_{in} is imposed by the preheating*

The annual producible electricity is calculated using the following procedure:

1. When the selected expander size (m_{DP}) is lower than the mass flow rate in a step of Fig. 3 (i.e. $m_{DP} < m_{step,PRS}$), the expander operates at design point conditions and therefore a part of the mass-flowrate is by-passed. As a result, the operating parameters in Eq. (12) are set as follows;

$$m_{step} = m_{DP};\ \Delta h_{is,step} = \Delta h_{is,DP};\ \eta_{is,step} = \eta_{is,DP} \tag{10}$$

2. When the mass flow rate is lower than the expander size (i.e. $m_{step,PRS} < m_{DP}$) the expander works at partial load and the operating parameters required in Eq. (12) are calculated as follows:

Radial turboexpander

- $\dot{m}_{step} = \dot{m}_{step,PRS}$: the mass-flowrate of the expander is set equal to the PRS' one in the considered step;
- $\Delta h_{is,step} = f(m_{step,PRS}, T_{in,step}, c_{p,step})$: a variable geometry control system (e.g. Inlet Guide Vanes) regulates the partial load operation of the turbine. To a first approximation, the relationship between turbine mass-flowrate and Δh_{is} can be evaluated from Stodola's ellipse equation for unchoked flows.

$$\Phi_{step} = \Phi_{DP} * \sqrt{1 - \frac{\left(\frac{P_{out,step}}{P_{in,step}} - \left(\frac{P_{out}}{P_{in}}\right)_{cr}\right)^2}{\left(1 - \left(\frac{P_{out}}{P_{in}}\right)_{cr}\right)^2} * \left(1 - \frac{\left(\frac{P_{out,DP}}{P_{in,DP}} - \left(\frac{P_{out}}{P_{in}}\right)_{cr}\right)^2}{\left(1 - \left(\frac{P_{out}}{P_{in}}\right)_{cr}\right)^2}\right)^{-1}} \tag{12}$$

$$\Phi = \frac{\dot{m} * \sqrt{T_{in}}}{P_{in}} \tag{13}$$

$$\left(\frac{P_{out}}{P_{in}}\right)_{cr} = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma-1}} \tag{14}$$

Considering ideal gas properties:

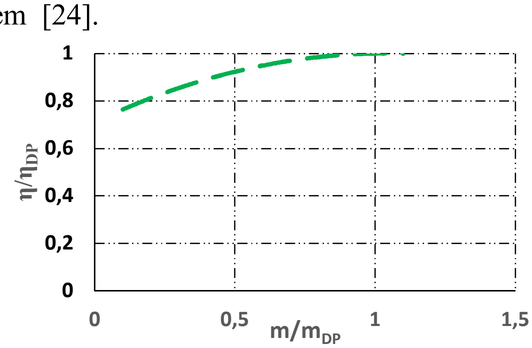
$$\left(\frac{P_{out}}{P_{in}}\right) = \left(\frac{\Delta h_{is}}{c_p T_{in}} + 1\right)^{\frac{\gamma}{\gamma-1}} \tag{15}$$

Sobstituting Eq. (13), (14) and (15) in Eq. (12), $\Delta h_{is,step}$ can be made explicit as a function of $m_{step,PRS}, T_{in,step}, c_{p,step}$.

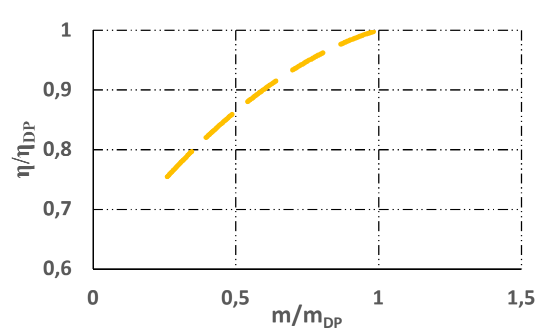
- $\eta_{is,step} = f(\dot{m}_{step})$: the partial load performance of the turbine is evaluated considering the dimensionless isentropic efficiency trend shown in Fig. 3a). Given the partial load mass flow rate $\dot{m}_{step}$, the corresponding isentropic efficiency can be evaluated. This trend is obtained by interpolation of experimental data of a radial turboexpander having a variable geometry control system [24].

Scroll expander

- $\dot{m}_{step} = \dot{m}_{step,PRS}$: The mass-flowrate of the expander is set equal to the PRS' one in the considered step.
- $\Delta h_{is,step} = \Delta h_{is,DP}$: The rotational speed of the expander can be varied, so the machine is able to work at partial load mass-flowrate keeping constant the enthalpy drop;
- $\eta_{is,step} = f(\dot{m}_{step,PRS})$: The isentropic efficiency at off-design operation is calculated considering the dimensionless efficiency curve shown in Fig. 3b). This trend is derived from experimental measurements (rotational speed vs η_{is} at constant Δh_{is}) provided in [25]. The results in [25] are made dimensionless and the rotational speed is substituted with the mass-flowrate by considering a linear relation between the two parameters.



a)



b)

Fig. 3 - a) trend of dimensionless isentropic efficiency vs tip-speed-ratio of radial turbine, b)trend of dimensionless isentropic efficiency vs dimensionless mass-flowrate of scroll expander.

The energy recovery efficiency is defined as:

$$\varepsilon = \frac{E_{el,net}}{E_{av,net}} \tag{15}$$

4. Results

Tables 3 shows the total available energy, the total thermal power needed for preheating and the net available energy in the three PRS groups without the energy recovery systems.

Table 3 - Available energy, preheating energy and net available energy at PRSs.

Group	E_{av} $[kWh_m/\text{y}]$	E_{ph} $[kWh_{th}/\text{y}]$	$E_{av,net}$[kWh/y]
HP	25.864*10^8	8.704*10^8	17.160*10^8
MP	9.717*10^8	0.290*10^8	9.427*10^8
LP	5.062*10^8	-	5.062*10^8
Total	40.643*10^8	8.994*10^8	31.649*10^8

The preheating energy is about 33%, 1% and 0% of the available energy in HP, MP and LP groups respectively. HP-PRSs perform the largest pressure drops. This is because most of these PRSs send the gas from the national network (i.e. from pipelines at 75 barg) to pipelines at 43 barg or lower. As a result, the available energy is always very high but, at the same time, a lot of energy must be spent for the preheating process. Conversely, only few MP-PRSs require a mandatory preheating because of the lower pressures and pressure drops while the LP-PRSs never require preheating since the maximum inlet pressure is lower than 12 barg.

Table 4 lists the total producible electric energy, the total thermal power needed for preheating, the average COP of the heat pumps and the net producible electrical energy using the expander-generator systems coupled to a heat pump. It is worth noting that the expanders sizing procedure indicates that the size (i.e. the design point mass-flowrate) that maximizes the annual energy production is always the maximum allowed by the PRSs.

Table 4 – Annual recoverable energy using expander-generator systems coupled to a geothermal heat pump.

Group	$E_{el,exp}$ $[kWh_{el}/\text{y}]$	E_{ph} $[kWh_{th}/\text{y}]$	$E_{el,HP}[kWh_{el}/\text{y}]$	COP_{avg}	$E_{el,net}$ $[kWh_{el}/\text{y}]$
HP	19.145*10^8	29.616*10^8	10.108*10^8	2.93	9.043*10^8
MP	8.345*10^8	10.376*10^8	3.805*10^8	2.73	4.540*10^8
LP	3.870*10^8	7.178*10^8	2.189*10^8	3.28	1.681*10^8
Total	31.360*10^8	47.170*10^8	16.102*10^8	2.93	15.264*10^8

It appears that the net producible electrical energy is about the 47%, 54% and 43% of the total producible electric energy that could be generated by the expander-generator systems in the HP, MP and LP groups, respectively. This trend was partially expected because of the increasing need of preheating at increasing pressure levels. However, the smaller amount of preheating needed by the LP stations is undermined by the lower efficiency of the volumetric expanders compared to the radial turboexpanders. It is interesting to note that a minimum average COP of 1.54, 1.24 and 1.85 (HP, MP and LP respectively) is needed to produce at least the energy required for preheating.

A comprehensive graphic representation of the results is given in Fig. 4.:

- Left: In Italy the total available pressure energy from natural gas during a reference year (3,17 TWh/year) is approximately the 0,42% of the total available energy (chemical plus pressure energy), which is 749,17 TWh/year.
- Center-left: The 54,1% (1,716 TWh/year), 29,7% (0,943 TWh/year) and 15,9% (0,506 TWh/year) of this pressure energy is available in the HP, MP and LP-PRSs respectively (see also Table 3);

- Center: Different fractions of these energies are recoverable in each group (52,7%, 47,7%, 33,2%, respectively. The highest energy recovery efficiency is found in the high-pressure stations because of the high efficiency of radial turboexpanders and the positive effect of preheating on the enthalpy drops at high pressure levels;
- (Center-right) the total recoverable energy is the 48,15% (1,526 TWh) of the total available pressure energy;
- Right: The HP-PRSs supply the highest contribution (59,3%) to the recoverable energy as a result of the large amount of available pressure energy (see the Center-left percentages) while the 29,7% and the 11% are provided by MP and LP-PRSs, respectively.

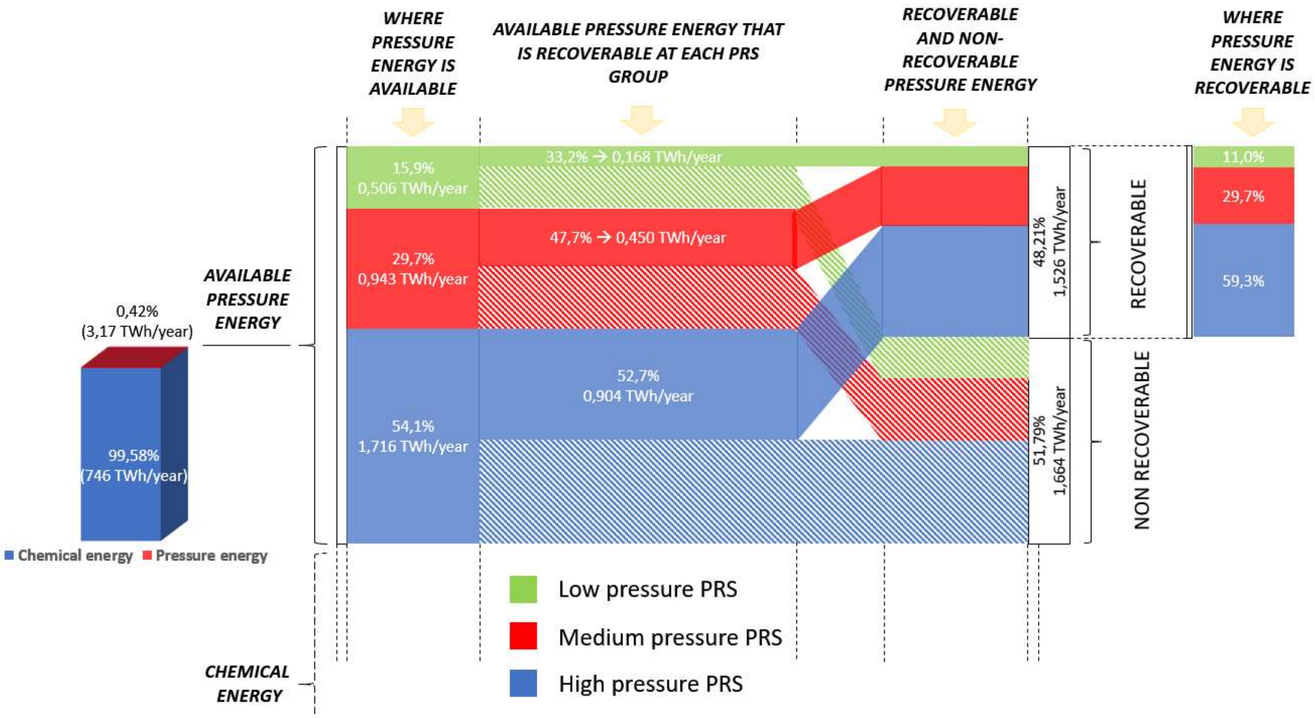


Fig. 4 – Graphic summary of the results.

Table 5 summarizes the most relevant results to highlight that, although the recoverable energy is higher in the HP PRSs, the cost for energy recovery could be lower in the LP PRSs because of the lower cost per kW of the volumetric expanders compared to the radial ones.

Table 5 – Results summary.

Group	Available energy [TWh_{el}/year]	ε	Recoverable energy [TWh_{el}/y]	Cost for recovered energy
HP	1.716	0.527	0.904	+
MP	0.943	0.477	0.450	
LP	0.506	0.332	0.168	-
Total	3.165	0.482	1.526	

5. Conclusions

In this work the potential energy recovery from the Italian natural gas distribution network is investigated from a thermodynamic point of view considering real data about the structure and operations of the pipelines and pressure reduction stations. Starting from available-monitored values of the average annual mass-flow rates and inlet/outlet pressure of the 12000 pressure reduction stations (PRSs), the available energy is calculated considering an isentropic expansion process. Then, the recoverable energy is evaluated considering a system composed of an expander-generator coupled to a geothermal heat pump that consumes part of the recovered energy to satisfy the preheating needed to avoid formation of natural gas hydrates downstream of the expander. A literature review about the energy recovery technologies from natural gas networks allowed identifying two different types of turbine with different performance to properly take into consideration the remarkable difference between the operating conditions of low-pressure stations and high-pressure ones. Results indicate that the expander-generator coupled with heat pump is more performing in the high-pressure ranges. In fact, the energy recovery efficiency in HP-PRSs reaches the highest value (52,7%) because of: i) the high efficiency of the radial turboexpanders and ii) the high pressure of the gas available at these stations takes a strong advantage from the preheating that results in improved enthalpy drops . The 59,3% of the total recoverable energy comes from the HP-PRSs group compared to the 29,7% and 11% from the MP and LP ones, respectively. Considering the economic aspects, it is opinion of the authors that the LP stations could be the most convenient location where to install the proposed energy recovery systems. In fact, the turbines proposed for the HP units are very efficient radial turbomachinery that need of ad-hoc designs, which could result in very high costs (involving higher risk investments, especially in case of system failures). In contrast, the expanders proposed for the LP units are standardized volumetric machines characterized by very low costs and low sensitivity to intermittent and off-design operations. These characteristics could make the energy recovery from natural gas network more attractive for LP-PRSs. In any case, exhaustive economic analyses should be conducted to confirm or not these indications.

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