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Demand response strategies for the balancing of natural gas systems: application to a local network located in The Marches (Italy)

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Abstract

During the last several decades, demand response programs have played a crucial role in the management of the electrical energy system worldwide. Thus, demand response programs, offered by either system operators or utilities, have contributed to solve different matters that appear in the habitual operation of the power grid. Currently, there are no successful experiences of demand response applications in the natural gas system. However, it seems natural that, in line with the current trends in the energy sector, demand response concepts will be eventually essential for the better and more efficient operation of natural gas systems. The research here presented leads with the analysis of demand response as a strategic tool for the gas system operator to manage better the natural gas network. Thus, this research demonstrates as demand response could represent a great opportunity for consumers to play an active role in the operation of the natural gas grid. In this paper, the ability of consumers to participate in the balancing of natural gas in the transmission network is assessed and the utilization of demand response resources to help reducing the imbalances in the natural gas system is demonstrated.

Keywords: Demand response, natural gas, balancing, gas smart grid, demand side management, Italy

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1. Introduction

The concept of demand response (DR) is not new in the electricity sector, where this kind of strategies have been used for more than 40 years, with different level of development, in several countries [1], [2]. Mainly in the US and Europe, DR implementation has been already successful in the electrical system. Based on that experiences, the ability of DR applications to reduce the management costs of electricity systems has been demonstrated, reducing the power consumption during peak periods and avoiding the costs of construction for new power plants and power delivery systems [3], [4]. In the US, this tendency has been promoted by a growing number of the emerging demand side initiatives offered by different American companies and institutions, taking into consideration the dynamics of pricing in the wholesale market [5], [6]. Utilities in European countries use demand response programs as a strategic resource for balancing supply and managing peak load shortages, as well as a less expensive alternative to fully meet demand of the electrical power infrastructure [7], [8].

There are no doubts that the expansion of DR programs is strictly related to the improving of intelligence communication technology and that it has been strongly driven by the emerging of newer smart metering infrastructures and smart meters [9], [10]. Furthermore, the application of smart systems such as in-home displays or home-area-networks has enabled consumers to easily change their behavior and reduce peak period consumption, giving them real time information on their power consumption and costs [11], [12].

Likewise, the modernization of the existing natural gas (NG) grid by the installation of smart meters and the conversion of the traditional network into a smart grid configuration is expected that strongly contributed to the diffusion of DR services for the NG management in the same way it has done it in the electrical sector [13], [14]. Smart sensors, able to perceive NG peak consumption problems, and automatic valves to reduce or divert NG source will allow customers to play a central role in assuring the feasibility of the grid by DR services. Advanced metering infrastructure, together with the application of DR programs, will reduce the probability of unbalancing of the NG network and the risk of dispatching failure [15], [16].

Natural gas and power systems present significant differences. The most significant difference is probably the impossibility to store large amounts of electric energy with an acceptable performance. This fact makes that generators must produce in real time the exact amount of energy that is consumed. Another significant difference is the wave nature of electricity, which provides it with an intrinsic characteristic such as the frequency, with no equivalency in the case of natural gas. Frequency must be constant through the whole power system, which can be only guaranteed if generation and demand are balanced at any time. However, in spite of the aforementioned differences, electric and natural gas systems share many other characteristics in terms of architecture, management and operability.

Based on the existing similarities between the electrical system and the natural gas network, the present research leads with the analysis of demand response programs as services for the improvement of the natural gas system operation [17], [18]. This aspect could be of especial interest in smart multi-energy systems that represents currently a trend in the development of cities [19].

This research proves that DR could represent a great opportunity for consumers to play a significant role in the operation of the natural gas grid in a similar way as they do in the electrical sector. An example where this kind of techniques was successfully applied was the DRIP project [20], focused on the assessment and exploitation of the potential flexibility within energy consuming processes of electricity customers that may be used for balancing purposes. The methodology that the authors have applied in this research, which is summarized in section 3 and further detailed in [21], is in part a consequence of the proved results of that project, in which the profits of DR initiatives for both the consumer and the system where properly validated [22]. The DRIP Project also analyzed the different barriers that may prevent the implementation of DR techniques [9], as well as a procedure to standardize the definition of DR actions in the electricity sector [14], which has been adapted to the natural gas case for this research. Previously, the ability of consumers to provide balancing services to the power system was also tested by the authors [23], [24]. In this work, we have used real data provided by the gas distributor *2i Rete Gas*, which is the second major company of this sector in Italy, as well as by other companies within the sector (*Snam rete gas* or *The Italian Regulatory Authority for Energy, Networks and Environment*). Such information allowed us to perform a realistic analysis based on the aforementioned methodology.

DR programs applied to the NG system by reducing or shifting consumers' usage during peak periods in response to time-based rates or other forms of financial incentives could represent a strategic tool for the gas system operator (GSO) to manage properly the NG system. In this paper, the ability of consumers to participate in the balancing of natural gas by using their flexibility is be assessed. Furthermore, the utilization of DR resources is demonstrated to help reducing the imbalances in the natural gas system, reducing also the cost related to the management of such imbalances, as well as the cost of purchasing additional amounts of gas in the wholesale market for balancing purposes. The provision of operation services in the natural gas network by means of demand resources represents a novel approach to this kind of systems, as the utilization of such mechanisms up to now has been marginal or inexistent. However, this situation may change due to the technification of the natural gas network, evidenced by measurements such as the massive rollout of smart meters in the natural gas system, which in some countries like Italy is taking place right now. This fact will enable consumers to provide the gas system operator with adequate operation services if the proper technical, economic and regulatory framework is developed.

The article is organized in six sections. After a short introduction about the objective of the investigation, section 2 is focused on the state of art of DR services applied to the NG system, including an overview on the latest developments in the implementation of smart metering systems applied to the NG systems. Then, the methodology applied to validate the benefits of the use of DR services in the natural gas network will be detailed in section 3. After that, the methodology is applied to a real gas network located in central Italy for validation purposes in section 4. Finally, the obtained results are discussed in section 5 and the most significant conclusions are stated in section 6.

2. State of the Art

DR concepts have been applied for years (with different level of development depending on countries) in the management of power systems. Indeed, DR programs have been used by utilities and system operators to manage different problems related to the operation of power systems. Currently, experiences of DR successfully applied to natural gas systems are rarely found. However, as agreed by some researchers and professionals, DR concepts will be sooner or later essential for the better and more efficient operation of natural gas systems, as can be deduced, among others, from the following factors [25] [26]:

- Electricity and natural gas markets are closely related, as this resource widely used for power generation. The main reasons are:

- Environmental issues related to the reduction of power production with such fuels as coal.
- The higher performance of natural gas power plants (especially in combined cycle facilities) [27]
- The massive utilization of renewable energies, which make necessary generation technologies able to respond quickly to the high variability of this kind of generation, providing power reliability and supply guarantee.
- The volatility of natural gas markets is increasing, especially due to the utilization of natural gas for power generation.

- Until recent past, natural gas demand used to be quite stable and seasonal; however, this tendency is changing nowadays [28]. In fact, demand forecasting is critical for NG consumers [29].
- Natural gas is replacing other fuels in hydrocarbon markets [28].

Natural gas and demand response are two concepts that do not usually appear in the same sentence and, when they do, they are just related to power stations supplied by natural gas that may provide flexibility to the power system. However, in this research, the flexibility concept is not applied to the power system but to the natural gas network, and consumers providing such flexibility are not necessarily large industries, but medium and small commercial and residential consumers that may provide their flexibility aggregately. Examples of DR concepts application with the direct participation of final consumers are exceptional and most of them are just pilots that, in fact, permit to estimate a promising future for this kind of developments [30] [31]. Some experiences have been driven in Canada and the US. In this first country, a pilot based on the management of thermostats for heating purposes in the residential sector demonstrated potential savings between 1.5% and 21%, depending on the season and the external temperature of the considered period [32]. Another experience took place in Massachusetts, where gas demand reductions up to 20% where obtained in residential and commercial applications in the winter season [30]. In addition, in the US, the California Public Utilities Commission has approved the installation of advanced gas meters for all the gas customers, providing opportunities for the development of demand response programs applicable to the natural gas sector [33].

Enernoc, one of the most active companies in DR applications for small and medium customers in the electricity sector, is also trying to develop some experiences in the natural gas sector. In particular, this company has developed a platform, which is being tested in customers from *National Grid* in the State of New York, in order to shift consumptions to optimize the use of fuel sources based on weather availability. Therefore, *Enernoc* will try to demonstrate that DR concepts may help in winter to solve the same kind of problems that the power system (closely linked to the gas consumption) has during peak periods in summer [34] .

Regarding Europe, Spain was a pioneer in the approval of an interruptible program in 2006[1], based on the need of establishing tools and mechanisms to make more flexible the natural gas system. By means of this program, the gas system operator has the possibility to interrupt the supply to large customers willing to that in case of emergencies. This advanced mechanism has two types or modes of interruptibility:

- Mode A: This mode can be used between the gas trader and the final consumer so that the consumer may help the trader in case of imbalance due to incidents that may produce the lack of gas in the portfolio of such trader.
- Mode B: Interruptible fee. The agreement is established between the final consumer, the gas trader and the gas system operator, so that the consumer is committed to reduce the consumption under requirement from the system operator due to the lack of gas in the system. In this case, a reduced access fee is applied to the consumer for using the infrastructures of the gas system.

Interruptible customers must be able to interrupt completely their consumption with a notification in advance of 24 hours. The duration of the interruption may vary from 6 hours up to 10 days. However, as mentioned above, only large customers with an annual consumption higher than 10 GWh and a daily consumption higher than 26 MWh and connected to a pipeline with a pressure higher than 4 bar can participate.

Another experience can be found in the United Kingdom, where there is a kind of interruptible program, but just at distribution level and less developed than in Spain. Just a small group of large industrial consumers can participate, depending upon the commercial

[1] The interruptibility program is regulated in the Resolution 25 July 2006 from the General Direction of Energy Policy and Mines. https://www.boe.es/diario_boe/txt.php?id=BOE-A-2006-14314

arrangements they have agreed to[2]. Interruptible customers receive discounted transportation charges when reducing their consumption in periods of high demand (especially in winter peaks) [35].

In the Netherlands, a consortium of 11 entities called Energy Delta Gas Research (EDGaR)[3] coordinates the development of different scientific, applied and technological research projects on natural gas. However, even if there are some research lines in the field of smart natural gas systems, none of them is dealing now with DR applications in the natural gas sector. Said that, it is true that for this consortium, customer's flexibility is a key value in smart grids and some ideas have arisen about the utilization of flexibility of electricity consumers for the management of power plants fueled by natural gas [36].

All these experiences demonstrate the promising application of DR resources for a more efficient management of the natural gas systems, similarly to the power grid. However, most of them are just in pilot phase at present or, in the best case, only large industrial customers are enabled to participate.

3. Methodology

The methodology designed in this research, presented in detail in [21] and schematically depicted in Figure 1, is divided into six phases.

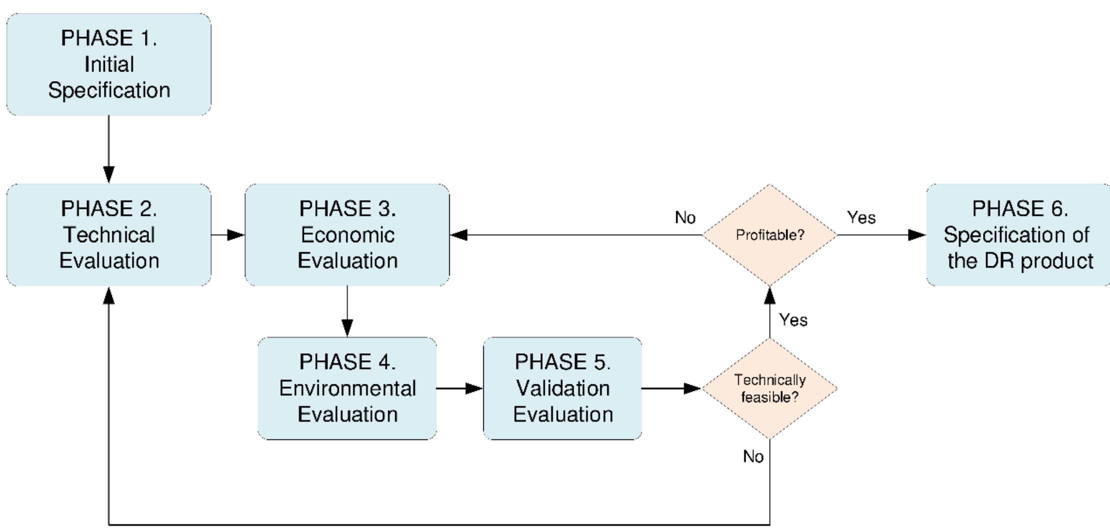

Figure 1. Methodology for the validation of DR strategies in the NG system

[2] The characteristics of interruptible supplies are described in: http://www2.nationalgrid.com/uk/Industry-information/Gas-transmission-system-operations/Interruptions-to-supply/

[3] More information about this consortium is available at: http://www.edgar-program.com.

The first phase deals with the identification of the system operator needs and the consumer abilities in order to make a preliminary specification of DR services. In phase 2, the identification of the technical characteristics of the DR services for both consumer (as provider) and system operator is done, including the characterization of the physical media (metering, communication and control requirements) that may be necessary for the interchange of DR resources. Phase 3 is focused on the economic evaluation (based on a cost-benefit analysis) to demonstrate the profitability that the considered DR products could provide to all the involved agents in spite of the cost of its implementation of the use of any alternative solution. After that, an economic evaluation is done in order to evaluate the carbon footprint reduction linked to the application of the considered DR products, considering the avoided CO_2 emissions but also the reduction of other greenhouse gases. After the theoretical evaluation, a testing phase is done in Phase 5 to demonstrate with feasible evidence that the forecasted benefits can be actually achieved by all the involved agents. Finally, after this validation stage, the designed DR products are specified in Phase 6. In this way, the benefits to be obtained by DR providers (consumers) and DR users (GSO) when interchanging DR services would be guaranteed.

4. Application case

The methodology summarized in the previous section has been applied to the real case of the natural gas network of a town located in the region of The Marches. In this town, the evaluation of the DR potential has been done considering natural gas consumers participation in the provision of balancing services. Notice that the Phase 4 of the methodology will be out of scope of the investigation. The reason must be found in the balancing services for the management of the NG system. The combustion of natural gas produces several greenhouse gases and, in general, the activation of DR programs should activate a reduction in GHG emissions. However, in the specific DR services of balancing, the NG consumption will be shifted but not reduced. Therefore, the environmental analysis will have no impact on the investigation.

4.1. Specification of services to be provided by consumers

The following DR strategies have been initially considered for the utilization of gas consumers' potential:

- Service 1: Balancing of natural gas in the transmission network. The amount of natural gas must be daily balanced in order to guarantee that the daily amount of natural gas consumed from and injected to the network is balanced. Therefore, the flexibility of consumers may be used to reduce the imbalances in the natural gas network, reducing the daily difference between the gas extracted and injected.
- Service 2: Maintenance of the storage level. The daily amount of natural gas inject to or extracted from an underground store must remain within the limits technically established. The use of DR resources may avoid exceeding such limit, reducing the consumption of customers when the daily storage limit is achieved.
- Service 3: Solution of technical constraints, which may produce transmission and distribution infrastructures overload or even interruption of supply to customers.

Among the possible DR services identified above, the present investigation will be focused on the analysis of the consumers in Service 1. Every day, the GSO has to balance the amount of natural gas in the network to balance the system. According to the difference between the amount of natural gas in the network and the net demand of customers during the day, the system can be in three different states:

- If the gas consumed by customers is higher than the amount purchased in the wholesale market, the system is said to be short. Therefore, when the system is short, the GSO has to purchase an additional amount of gas in order to balance the network.
- If the gas consumed by customers is lower than the amount purchased in the wholesale market, the system is said to be long. Consequently, the GSO has to sell to the wholesale market the gas excess to balance the network.
- When customers consume exactly the amount of gas purchased in advance in the wholesale market, the system is said in equilibrium and the GSO does not need neither purchase nor sell any amount of gas for balancing purposes. Nevertheless, it is hardly difficult if not impossible that the system remains in equilibrium, as there is always some difference between the energy pre-purchased and actually consumed.

Therefore, practically speaking, the system would be actually long or short, so that the GSO should buy or sell some amount of gas for balancing purposes at the end of the day.

As the provisioning of natural gas for balancing purposes is usually done in a daily basis, the hourly cost of natural gas (CG_h^{Ba}) for operation could be calculated as follows:

$$CG_h^{Ba} = \left(\pi_{Bal} + \pi_{NG,d}\right) \cdot HF_h^{Ba} \cdot HCV_{NG} \quad (€/h) \qquad (1)$$

Where HF_h^{Ba} (m^3/h) represents the hourly amount of natural gas used for operation purposes that is incorporated to or extracted from the network.

4.2. Characterization of the consumers

4.2.1. Location and size of consumers

The DR strategy of balancing of natural gas in the transmission network will be applied to a town of 16,000 inhabitants, located in the region of The Marches, in the central area of Italy. This region is especially interesting due to the high risk of earthquakes, which may damage the natural gas infrastructures [37]. Therefore, the utilization of customers' flexibility may help in the solution of some of the technical constrains that may appear because of the lack of some pipelines or ancillary facilities.

Figure 2 shows the number of towns in the region of The Marches, grouped according to the number of inhabitants. The town chosen for the application of the methodology belongs to the group marked in red, which includes the towns with a population between 10,000 and 20,000 inhabitants. This group is composed of 20 towns with a total population of 269,721 inhabitants (2017), which represents the 18% of the total population of this region.

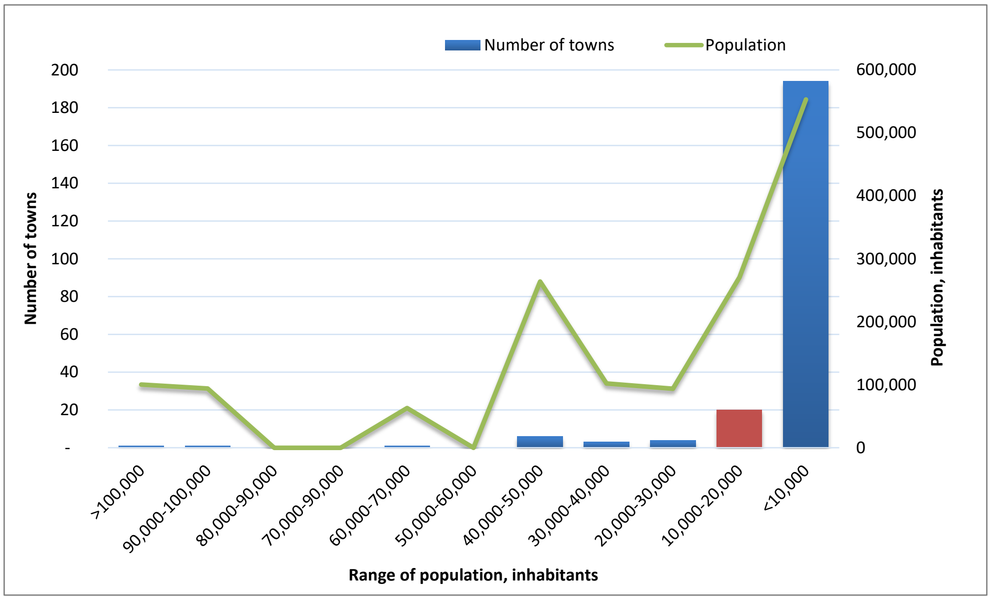

Figure 2. Towns' classification in the region of The Marches, Italy (2017)

The distributor of natural gas for this town is the company *2i Rete Gas S.p.A.* [38], the second major natural distributor of Italy, who has provided the consumption data on which is based the investigation.

The considered town has 557 points of supply (388 residential and 169 non-residential), with a total annual consumption of 1,704,400 Nm^3/year.

4.2.2. Classification of consumers

According to the data provided by the distributor, gas consumers have been divided into two blocks:

- Residential: It includes domestic consumers that use natural gas for homes.
- Non-Residential: It includes commercial and industrial applications, others than domestic uses.

Non-residential consumers are divided into six categories, according to the standard classification of gas consumers in Italy based on the final use that is given to the natural gas [39]:

- C1: The natural gas is mainly used for space heating
- C2: The natural gas is mainly used for cooking and hot water production
- C3: The natural gas is used for space heating, cooking and hot water production
- C5: The natural gas is used for space heating and cooling
- T1: The natural gas is used for industrial processes

- T2: The natural gas is used for industrial processes and space heating

Another category (C4) also exists in the Italian regulation, including consumers that use natural gas for space cooling. However, this category is not considered here, as there are not customers under this classification in the studied town. Moreover, the presence of consumers using natural gas for space cooling in the whole country is residual and not significant when compared to the rest of end-uses.

4.2.3. Gas consumptions per category

The period under analysis covers one whole year, from 1st October 2015 to 30th September 2016 and the daily consumption of consumers under each category has been accounted for this period. Figure 3 shows the gas daily load curve for the mentioned period, where the consumption of customers under each category has been plotted in different colors. As it can be seen in the figure, the largest gas consumption corresponds to category C1 (space heating). Due to the use of gas for this purpose, the profile shows a deep seasonality, being much higher during the winter season (from November to March). In contrast, the summer consumption is flat, with an average consumption of almost 2,000 Nm^3/day.

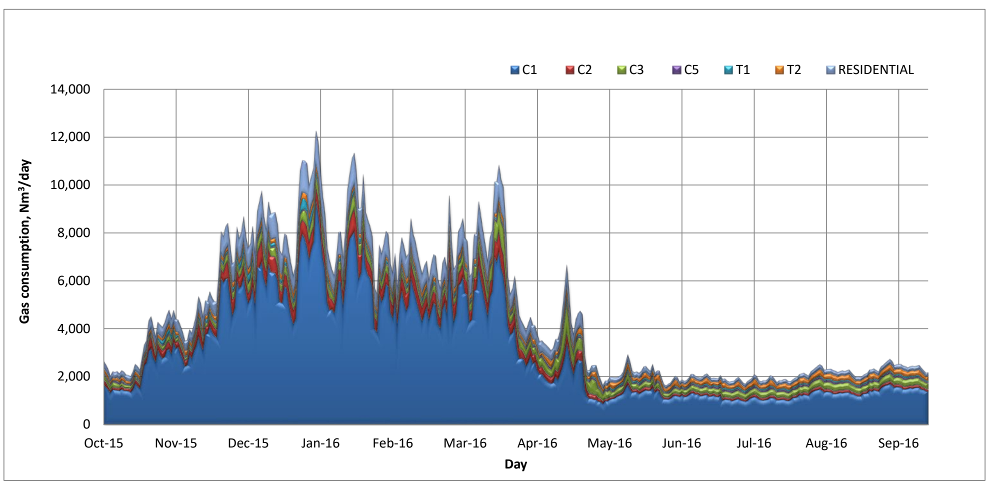

Figure 3. Natural gas load curve profile of consumers in a town of 16,000 inhabitants. Data *source: 2i Rete Gas S.p.A.*

A mean high calorific value (HCV) of 10.74 kWh/Nm^3 has been considered for the natural gas, according to the standard value considered by the distributor (*2i Rete Gas S.p.A.*). By means of this factor, the energy consumption of natural gas per category has been obtained, as it is shown in Table 1.

The total monthly consumption per category is finally represented in Figure 4. As it may be expected, the highest consumption takes place during the winter months (from November to March) while demand is lower in summer as the heating requirements are lower.

Table 1.Annual consumption of gas per category

	Nm^3/year	MWh/year
C1	1,154,437.94	12,398.66
C2	116,718.77	1,253.56
C3	112,436.08	1,207.56
C5	15,934.59	171.14
T1	37,693.04	404.82
T2	66,581.22	715.08
Residential	200,592.67	2,154.37
TOTAL	**1,704,394.30**	**18,305.19**

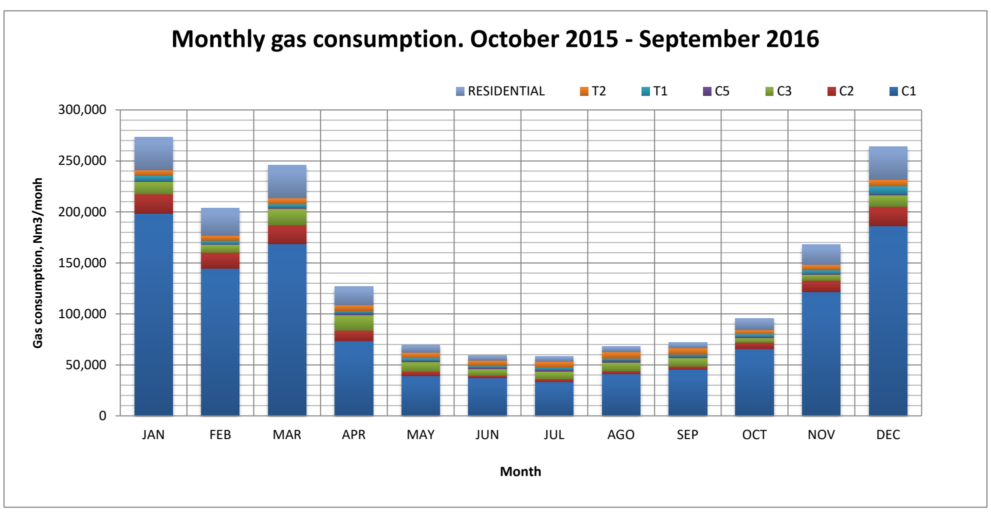

Figure 4. Monthly gas consumption for the considered town of 16,000 inhabitants. October 2015 – September 2016

If the monthly rate of consumption of this town is compared to the total amount of natural gas supply in the whole country by the distributor (Figure 5), the obtained profile for both cases is very similar, being the standard deviation lower than 1.7% in all the months. Therefore, it can be concluded that gas consumers in the selected town behave according to the usual patterns and, therefore, the obtained results may be extrapolated to the whole country. It should be considered that the most consuming category is C1, which will actually mark the tendency of consumption for this town and for the whole country.

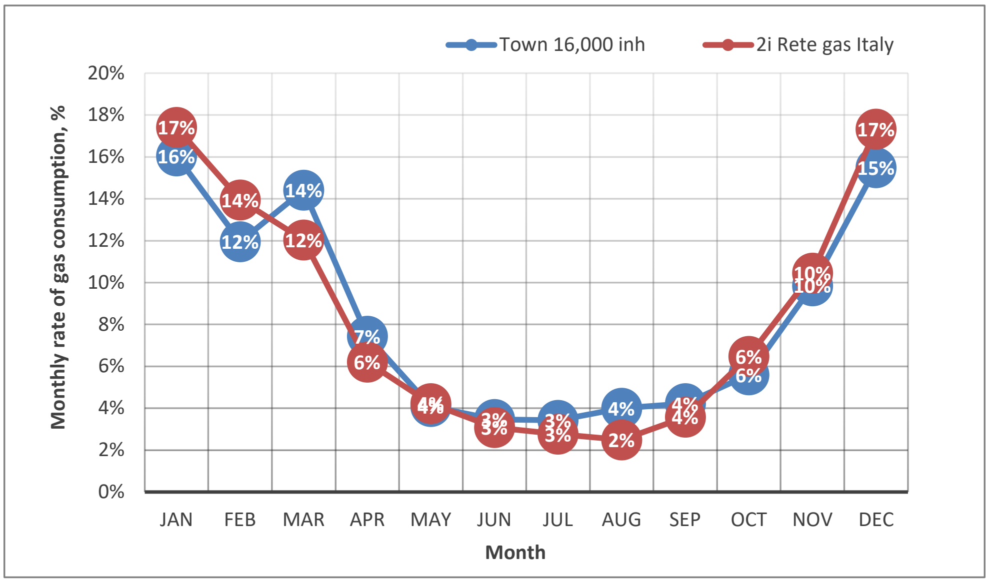

Figure 5. Comparison between the monthly rate of consumption for the considered rate and the whole distribution area of 2i Rete gas in Italy

4.3. Prices of the natural gas balancing service

The information related to prices of imbalances and amounts of energy extracted from and injected to the gas network has been obtained from the Italian GSO *Snam Rete Gas S.p.A.* According to (1), there are two prices, which have to be defined:

- The hourly cost of operation of the network related to balancing operations π_{Bal}. According to the annual report of *Snam*, the annual cost of balancing operations for 2015 was 1,800 million of euros [40]. As the annual amount of energy involved in balancing services was 29,586,788 MWh, an average value of 60.84 €/MWh has been considered for this concept.

- The price of the natural gas in the wholesale market for balancing purposes $\pi_{NG,d}$. This price is published monthly by *Snam* and it is available on the website of the GSO. The prices considered for the evaluation, together with the daily amounts of natural gas purchased and sold in the wholesale market from October 2015 to September 2016 are shown in Figure 6.

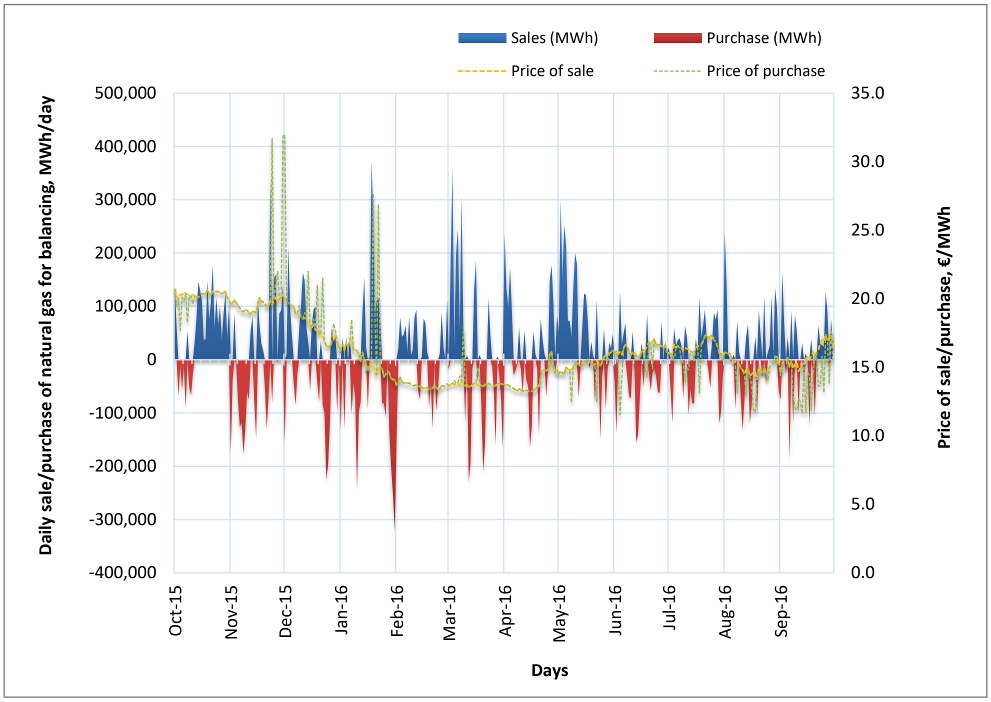

Figure 6. Prices and amounts of gas for balancing in Italy 2015-2016 (source: Snam)

The price of sale is the amount received by the GSO in days when the gas system is long (there is a surplus of natural gas that the GSO has to sell in the wholesale market because the demand has been lower than the amount of gas purchased the day before). Conversely, the price of purchase is the amount to be paid by the GSO in the wholesale market for gas that needs to be incorporated to the network in short days (when the demand exceeds the amount of gas purchased the day before).

4.4. Technical analysis

4.4.1. Evaluation of the NG flexibility potential

As shown in the previous section, most of the consumption is related to space heating (category C1). It means that most of flexibility of gas customers would be coming from the modification of the temperature set point of devices used for acclimatization. Therefore, the flexibility potential has to be evaluated according to the amount of energy that consumers may reduce or shift from one specific period to another one. The evaluation of flexibility is not an easy task and it requires detailed energy audits at the customer side where energy patterns are identified, by the time that the potential manageability of such consumptions is evaluated.

The mentioned detailed evaluation of flexibility is out of the scope of this research, so that in this case, the consumers' potential has been assessed by means of simulations of Monte Carlo, considering that the flexibility of customers for each category may take random values from 0 to 50% of the daily consumption every hour. This percentage also takes into account the participation of customers under each category in the DR program that may be established. The hypothesis here considered is moderately conservative, so that a detailed evaluation at customer's facilities may show a higher potential. Consequently, 3,000 simulations have been done for each hour of the year, considering different random participation factors for each category. After that, results have been analyzed according to the Monte Carlo method in order to assess the most frequent values within each hour.

The flexible power of each group of consumers have been then aggregated in blocks of 500 kWh of manageable power (from 500 to 69,000 kWh), obtaining the probability of each block within the 3,000 hourly simulations. The flexible gas consumption per simulation has been obtained as follows:

$$G_{s,h}^{red} = \sum_{i=1}^{7} \xi_{s,h}^{Cat} \cdot G_h^{Cat} \quad \text{(kWh/h)} \qquad (1)$$

where $G_{s,h}^{red}$ (kWh/h) is the amount of energy which may be reduced in the hour *h* according to the simulation *s*; $\xi_{s,h}^{Cat}$ (%) is an aleatory variable taking values from 0% to 50% which represents the rate of flexible consumption of consumers in category *Cat* (C1, C2, C3, C5, T1, T2 or Residential), in the hour *h* according to the simulation *s*; and G_h^{Cat} (%) is the total consumption of gas of consumers in category *Cat* during the hour *h*.. Then, the flexible gas consumption has been calculated in each hour according to this expression:

$$G_h^{red} = \sum_{i=1}^{3000} \psi_{s,h}^{Cat} \cdot G_{s,h}^{red} \quad \text{(kWh/h)} \qquad (2)$$

where G_h^{red} (kWh/h) is the amount of energy which may be reduced in the hour *h* for the whole town; $\psi_{s,h}^{Cat}$ (%) is the probability factor for simulation *s* according to the Monte Carlo method, which takes values from 0 to 1; and $G_{s,h}^{red}$ (kWh/h) is the amount of energy which may be reduced in the hour h according to the simulation s.

4.5. *Economic analysis*

The economic evaluation is based on a cost-benefit analysis, so that customers would be willing to modify their usual pattern of consumption when the cost of applying flexibility is lower than the payment they receive from the GSO. On the other hand, the GSO would be willing to use DR resources when payments required by customers are lower than the cost of solution of the considered service by other means. Therefore, the cost that the application of flexibility may entail for customers is evaluated firstly.

4.5.1. Costs of flexibility for consumers

The estimated cost for consumers when applying a DR action is summarized in Table 2.

Table 2. Estimated cost of flexibility for customers

	Cost of smart meter	*Residential*	*Non-residential*	
	Capital cost	85.00	336.00	€
	Expected lifetime	15.00	15.00	years
	Days/year	100.00	100.00	days/year
DIRECT COSTS	Amortization	0.06	0.22	€/day
	Cost of control equipment	*Residential*	*Non-residential*	
	Capital cost	400.00	1,000.00	€
	Expected lifetime	15.00	15.00	years
	Days/year	100.00	100.00	days/year
	Amortization	0.27	0.67	€/day
	Annual personnel costs	*Residential*	*Non-residential*	
	Hours/week	-	30,000.00	€/employee
	Weeks/year	-	40.00	hours/week
INDIRECT COSTS	Cost of working hour	-	50.00	weeks/year
	Time used for a flexibility action	-	15.00	€/hour
	Labor cost	-	10.00	min/action
	Labor cost of implementing DR	-	0.10	€/day
	Total AVG daily cost per customer	0.32	0.99	€/day

Source: 2i Rete Gas, [8]

The considered smart meters correspond to those chosen by the distributor *2i Rete gas* for the considered town, according to the following models:

- G4 Ultrasonic GPRS for residential customers
- G10 Diaphragm, G16 Diaphragm and G25 Diaphragm for non-residential customers, depending on the flow capacity.

According to the technical evaluation of flexibility done in section 4.2, the average flexible consumption of residential and non-residential customers in the considered town is equal to 2,154 and 16,151 MWh/year, respectively. Considering these figures, together with the average daily cost indicated in Table 2, the mean cost of flexibility for customers results in 6.43 €/MWh, estimating a total of 100 hours of participation in the DR service per customer. According to the methodology, customers may provide their flexibility when they cover their cost while obtaining an additional benefit. This benefit would be determined according to the strategy defined by each customer. In order to establish a criteria for the calculation of this case of application, and according to the criteria proposed by [41] for the estimation of the price requested by consumers in DR services for electricity systems, an additional benefit equal to the cost of applying flexibility would be considered. Therefore, the price required by customers to activate their flexibility in this analysis will be equal to 12.87 €/MWh.

5. Discussion and Results

5.1. Technical analysis results

Based on the method discussed in the section 4.1, the flexible consumption has been estimated on a daily basis, depending on the type of day (short of long) since the balancing point of view. It is important to take into account that this flexibility has been evaluated aggregately for a group of many different consumers. It means that not all the customers would be reducing their consumption every day, but the aggregator, similarly to the case of power systems [42], would achieve a global reduction of the magnitude here presented by activating the flexibility of different consumers in different days. In residential and commercial applications, flexibility could be provided not only by heating space devices using natural gas, but also by water heating devices or clothes dryers [43]

Flexibility is not always related to reductions of consumption, as some days it would be necessary to increment demand when the gas system is long. Consequently, the evaluation here presented considers that consumers would reduce their consumptions according to the potential evaluated and shown in Figure 7 when the system is short, shifting such consumptions to the days when the system is long and increasing consumptions is necessary.

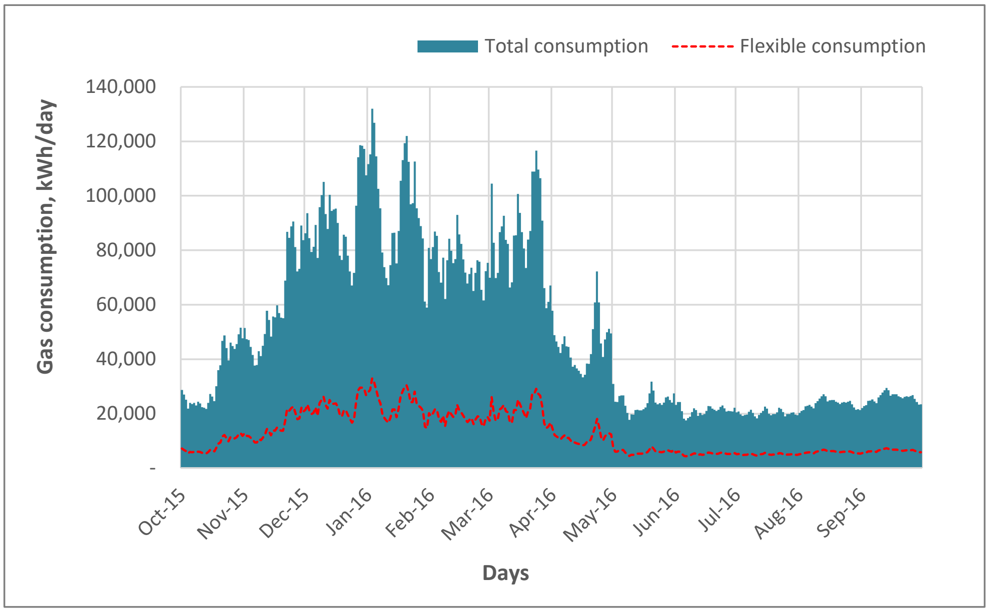

Figure 7. Estimated flexibility potential of gas customers in a town of 16,000 inhabitants.

In order to verify the viability of this option, the number of consecutive days during which reductions may be required has been accounted. The results are shown in Figure 8.

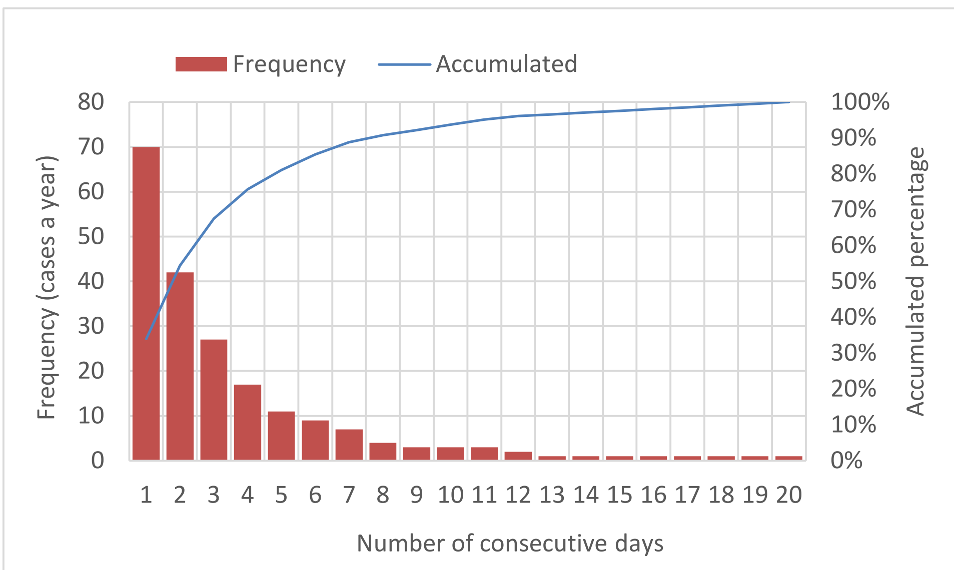

Figure 8. Histogram on the number of consecutive days of gas reduction for balances

As it is shown in the histogram, the 90% of energy reductions takes place for 6 consecutive days or less (65% of cases is just for 1 day of energy reduction), while the longest reduction was for 20 days and took place just one time during the year. Therefore, it is reasonable to plan energy shifting from days during which the system was short to days where the system was long. It means that customers may be asked not to purely reduce consumptions neatly (with the subsequent loss of service) but to shift this consumption to other period.

On the other hand, the aggregator could plan the recovery of consumptions not to make customers recover their consumptions some days later, but the day after. Thus, a different group of customers may reduce the consumption to allow the group that reduced the consumption the day before to recover their set point (see Figure 9). In this way, the aggregator may manage the consumptions in order to implement the recoveries when the system is long, contributing also to the balancing service during those days.

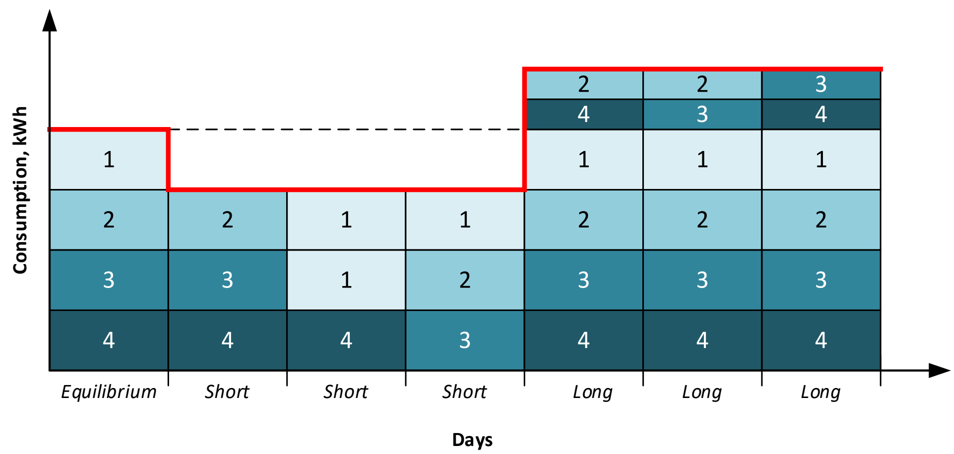

Figure 9. Sample of gas demand packages managed by an aggregator for balancing purposes

In Figure 9, the total number of customers has been divided into four groups with a similar amount of flexible gas consumption. For the first short day, the aggregator can activate the flexibility of group 1, which will recover the reduced energy during the next day. As the following day is also short, the aggregator may order a reduction to groups 2 and 3, which may be able to recover such energy some days later. After three short days, part of the energy reduced by groups 2 and 4 in the short days can be recovered, helping the GSO to reduce the excess of gas in the network. During the following days, the energy reduced during the short days by groups 2, 3 and 4 would be recovered, so that three long days after, the consumption set point would be restored. According to this idea, the case presented considers that customer would reduce their consumption according to the evaluated potential, being recovered during the following days where the GSO may require from customers to increase their consumption. Regarding the gas distribution in long days, it has been considered that the consumption reduced in short days would be recovered during the following days when the system is long. To do this, it has been considered that the total amount of energy reduced during a group of consecutive short days is recovered during the following group of long days, recovering each day this total amount of energy divided into the number of long days during which such consumption will be recovered.

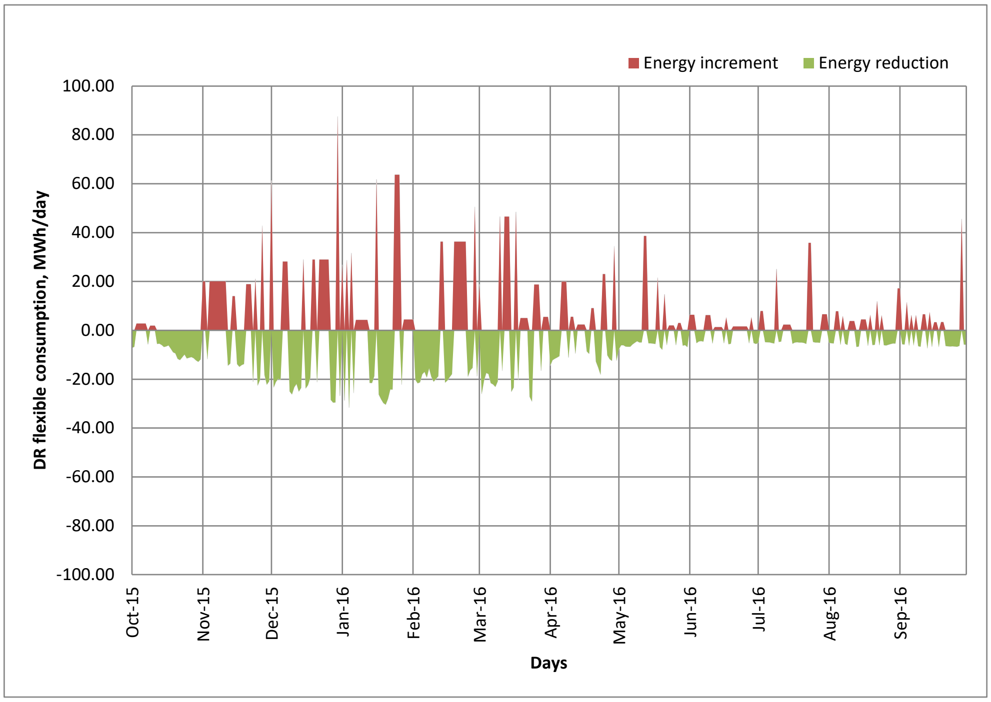

Figure 10. Daily schedule of DR resources to be used for balancing purposes

Because of the previous considerations, the daily schedule of flexible energy to reduce or increment is shown in Figure 10. Since energy reduced is later recovered, the DR actions here considered are energy shifts but not net reductions, so that the annual energy savings are equal to zero. It implies a manageable energy of 2,627 MWh a year. In the figure, the green area represents the hours in which an energy reduction has been requested to consumers participating in the DR program. Complementarily, the energy recovered by flexible consumers during the subsequent days is represented in red.

5.2. Economic analysis results

As stated in section 4.3, the cost of balancing for the GSO takes into account two different prices: the hourly cost of operation of the network related to balancing operations, evaluated in 60.84 €/MWh, and the price of natural gas in the wholesale market for operation purposes. This price, published by *Snam*, could be referred to the price that the GSO has to pay if the system is short, or the price at which the GSO is paid for the excess of gas when the system is long.

The price of gas when the system is short during the considered period (October 2015-September 2016) varies between 11.6 and 32.0 €/MWh. Therefore, the specific cost for the GSO, also considering the cost of operation, would take values from 72.4 and 92.8 €/MWh. On the other hand, when the system is long and the GSO has to resell the excess of gas in the wholesale market, the participation of customers in order to reduce this excess would mean a reduction in the incomes that the GSO would have. It means that the GSO would save the corresponding specific cost for operation (60.8 €/MWh) but the incomes for selling energy would be lower. The net benefit for the GSO when the system is long could be calculated as the difference between the reductions in cost of operation minus the benefit of reselling the excess of energy. The price at which the GSO is pays in the wholesale market takes values from 13.2 and 20.7 €/MWh Therefore, the specific cost for the GSO when the system is long would vary from 40.1 and 47.6 €/MWh. These specific costs represent the maximum price that the GSO would be willing to pay to customers when providing operation services by using their flexibility. When customers can provide this service at a lower price, it would mean that the GSO would be obtaining an additional benefit, equal to the difference between those specific costs and the amount paid to the customers.

As it was calculated in section 4.3, the average price requested by customers would be equal to 12.87 €/MWh, including the additional benefit in exchange for their participation. As this price is lower to the specific cost of the GSO in all of cases, it means that the utilization of DR resources would be profitable for the GSO every day for the considered period.

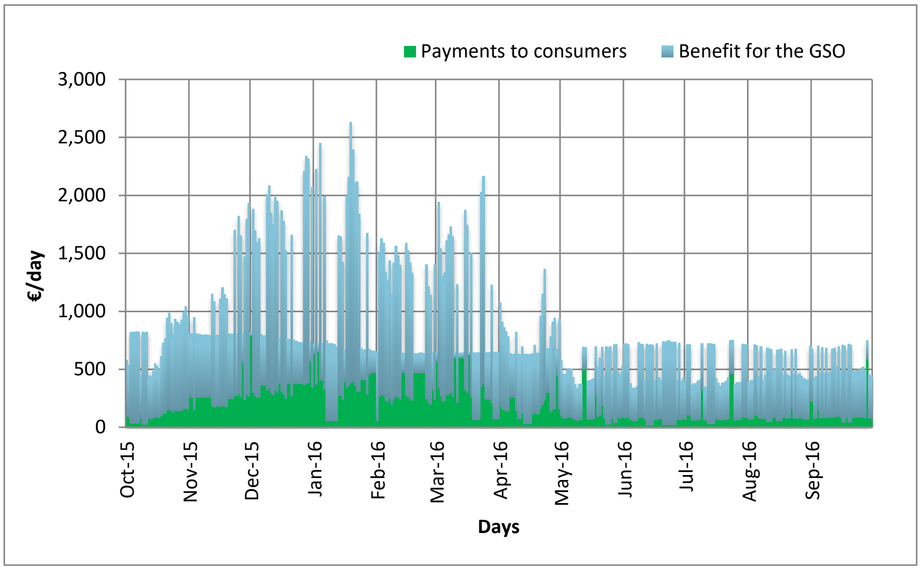

Figure 11. Economic evaluation of DR participation in balancing of the gas network

Figure 11 shows the economic impact of DR participation in balancing of the natural gas network for the considered annual period. The green area represents the daily payment to customers, which includes the incurred costs and the required benefit for participation. The blue area is the benefit for the GSO, compared to the traditional solution of imbalances by using the negotiation in the wholesale market. This benefit is equal to the difference between the cost of balances without DR participation and the cost required for customers when providing this service.

As it can be seen, the benefit for the GSO is, in most of days, much higher than the payment required by customers, which demonstrates the high profitability of using DR resources for operation purposes. Table 3 summarizes the monthly economic result for all the parties.

Table 3. Monthly summary of DR participation in gas balancing services

Month	Payment to customers €	Cost for the GSO without DR €	Benefit for the GSO €
Oct-15	2,934	23,483	20,549
Nov-15	7,341	31,777	24,436
Dec-15	10,959	44,121	33,162
Jan-16	10,137	40,186	30,049
Feb-16	8,746	33,224	24,478
Mar-16	8,994	34,870	25,876
Apr-16	4,765	23,380	18,615
May-16	3,318	16,328	13,010
Jun-16	1,556	18,103	16,547
Jul-16	3,045	16,018	12,973
Aug-16	2,474	16,807	14,333
Sep-16	3,027	17,049	14,022
Annual	67,297	315,347	248,050

According to these results, it can be seen as the payments to customers involve the 21% of the total cost of balancing for the GSO for the related amount of managed energy. It means that the GSO would save about 79% of the cost when using DR resources.

In order to compare the benefit for customers to the annual cost they have to face for their gas supply, the average prices for residential and non-residential customers included in Table 4 have been taken into account. These prices are applicable to Italy for 2015, as provided by the Italian regulator AEEGSI (*Autorità per l'energia elettrica il gas e il sistema idrico*). According to these prices and the annual consumption of gas of final customers summarized in Table 3, the total cost of gas to be paid by final customers would be equal to 894,200 €. It means that the incomes received by customers when participating in the balancing service would represent the 7.5% of their annual cost. A half of this rate would be destined to pay their self-cost of using their flexibility, which implies a net benefit of 3.8% over the total cost of gas for the customer.

Table 4. Price of natural gas in the Italian retail market

	Annual consumption *m^3/year*	Price (excl. taxes) *cts€/m^3*
Residential	< 525	89.94
	525 - 5,254	57.52
	> 5,254	46.27
Non-residential	< 26,000	51.79
	26,000 - 263,000	42.35
	263,000 - 2,627,000	33.25
	2,627,000 - 26,268,000	29.41
	> 26,268,000	28.02

Source: AEEGSI, 2015

An economic benefit of 3.8% may not be attractive to customers to provide their flexibility, so that a higher price should be probably considered. Moreover, the benefit for the GSO is 78.7% of the cost of solution of the involved imbalances by traditional mechanisms. Therefore, a sensitivity analysis is done in the next section in order to evaluate the impact of increasing the price paid to customers, shifting part of the benefit from the GSO to the customers' side.

5.3. Sensitivity analysis

A price equal to twice the cost of flexibility was considered in the cost-benefit analysis for the calculation of the price payable to customers when they offer their flexibility to the GSO for balancing purposes. However, a higher price could be considered, as the benefit of using DR for the GSO is much higher than the benefit provided to customers. According to this premise, the sensitivity of the economic benefit receiver by both customers and the GSO to the variation of the price paid to customers has been evaluated.

The results of the sensitivity analysis are presented in Table 5. As it is shown in this table, as the price paid to customers increases, the number of days during which the application of flexibility is profitable decreases, as the amount required by customers is higher than the solution of imbalances by traditional mechanisms.

Table 5. Sensitivity analysis: economic benefits of DR for different offer prices

Price paid to consumers €/MWh	Payment to consumers €/year	Benefit for the GSO €/year	Participating days a year days/year
6.43	33,622	281,725	365
12.86	67,245	248,102	365
19.29	82,146	231,242	347
25.72	92,848	218,193	324
32.15	100,256	210,306	308
38.58	114,347	195,740	300
45.01	119,416	192,600	292
51.44	135,309	177,256	290
57.87	148,790	164,891	285
64.30	164,214	150,213	283
70.73	173,942	139,374	278
77.16	74,974	269,194	102
83.59	2,485	373,107	-

The considered step for increasing the price has been the cost of flexibility, so that the different prices that have been evaluated are multiples of this cost. The first evaluated case is that in which the price is exactly the cost of implementing flexibility for the customer side, so that the benefit for the customer is zero. As the price required by customers increases, the benefit received by customers is higher while the benefit for the GSO is lower.

According to the table, the total benefit is shared in equal parts between customers and the GSO for a price equal to 10 times the cost of flexibility. For this price, the benefit for customers would be equal to 164,214 €/year, which is equivalent to the 18.4% of the annual cost of the gas supply. It means that if the costs of flexibility were 3.8%, the net benefit for customers would be equal to 14.6% of the annual cost of gas.

The relative benefit for customers compared to the total cost of supply of natural gas in an annual basis, once the cost of implementing the flexibility has been discounted is shown in Table 6. Similarly, the benefit for the GSO is also represented referred to the cost of balancing the amount of gas that may be managed by customers if customers were not providing their flexibility.

Table 6. Sensitivity analysis: relative benefits of stakeholders

Price paid to consumers €/MWh	Energy involved MWh/year	Benefit of customers compared to the cost of gas supply %	Benefit for the GSO compared to the cost of balances %
6.43	5,229	0.0	89.3
12.86	5,229	3.8	78.7
19.29	4,258	5.4	73.8
25.72	3,609	6.6	70.1
32.15	3,118	7.5	67.7
38.58	2,963	9.0	63.1
45.01	2,653	9.6	61.7
51.44	2,630	11.4	56.7
57.87	2,571	12.9	52.6
64.30	2,553	14.6	47.8
70.73	2,459	15.7	44.5
77.16	971	4.6	78.2

As it is shown, the benefit of customers increases until the price is 70.73 €/MWh, equivalent to 11 times the cost of flexibility. For this price, the incomes for customers would be equal to 173,942 €/year (19.5% of the annual cost of gas) while the benefit for the GSO may reach 139,374 €/year (44.5% of the cost of solution of imbalances by traditional means). From this point, the number of hours when flexibility can be applied reduces dramatically, so that the customers' benefit also reduces.

In any case, the benefits of using DR resources for the solution of imbalances in the natural gas system results evident for all the stakeholders. Therefore, the need of applying the DR principles to the natural gas system arises as the natural solution for reducing the operational costs related to the management of the whole network, similar to how this kind of strategies has been applied to the electricity sector.

5.4. Risks and limitations

In the Phase 5 of the proposed methodology, that is devoted to the validation of the preliminary specified DR products, a set of field tests have been considered so as to demonstrate the consistency and validity of a DR product. Therefore, the technical success of such product, once it has been launched, is guaranteed since it has been specified according to the network operator requirements and the actual flexibility that consumers are able to offer. In spite of that, there would be two potential sources of risk that may jeopardize the success of some particular action: the first one would be that the consumer committed to participate fails and does not execute the action. In that case, a penalty could minimize such risk and, in the worst case, would allow the GSO to compensate the economic lost. The second risk is related to the capacity of the aggregator in case of insufficient consumers providing flexibility for some specific action. This risk has been properly addressed in the case of power systems and it may be easily overcome with adequate tools to provide the aggregator with accurate forecasting and allow the aggregator managing their flexible consumers' portfolio [22].

Since the economic point of view, there is a risk inherent to the prices of flexibility according to the market performance, which may affect the profit obtained by consumers, making it lower than expected. To limit this risk, the sensitivity analysis performed in section 5.3 has shown that adequate prices (which may be calculated by means of such tools such as described in [22] or [44], already tested in power systems) would provide attractive enough incentives to consumers while the GSO reduces system costs.

Finally, it should be take into account that the price of natural gas can vary in case of some consumers change this energy source by an alternative supply (e.g. electricity or hydrogen). In this case, if the price changes, it may have a significant impact in the economic evaluation of DR that should be considered more in detail.

6. Conclusions

The research here presented deals with the evaluation of DR applications for the balancing of the natural gas system, where a real evaluation applied to the Italian NG network has been done. The flexibility potential of gas consumers located in a town of 16,000 inhabitants in central Italy has been evaluated, as well as the impact of using this potential to help the GSO to solve the imbalances that appear in the grid daily. The economic profitability of DR applications has been demonstrated, reaching a benefit for customers between 15% and 20% of the annual cost of the gas supply. At the same time, the GSO may obtain a significant reduction in the cost of balancing the system, which takes values around the 50% of the annual cost of balances for the involved amount of gas.

These results should drive regulators to incentivize the utilization of the flexibility of customers in order to increment the efficiency of the natural gas system as a whole. As it has proven, these techniques may reduce the total cost of operation while favoring the involvement of customers in a more dynamic energy infrastructure. This customers' participation is essential for the proper management of smart energy systems (power and gas), which are called to be energy networks of the future. The case of application also includes a sensitivity analysis by means of which different strategies related to the price required by DR providers have been simulated. It allows to compare the distribution of the welfare produced between DR providers (consumers or aggregators) and DR requesters (in this case, the gas system operator) so as to better adjust the prices generated for the bids and offers of flexible demand packages.

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