Methodology for the evaluation of demand response strategies for the management of natural gas systems

Lina Montuori (*), Manuel Alcázar-Ortega, Carlos Álvarez-Bel

Universitat Politècnica de València, Institute for Energy Engineering, Camino de Vera, s/n, 5E, F, 5. 46022 Valencia (Spain), lmontuori@upvnet.upv.es, malcazar@iie.upv.es, calvarez@die.upv.es

[*] Corresponding Author: Lina Montuori (*), Universitat Politècnica de València, Camino de Vera, s/n, edificio 8E, acceso F, 5ª planta. 46022 Valencia (España), lmontuori@upvnet.upv.es

Abstract

The gradual increase in energy consumption that has been produced during the last years, together with the massive implementation of renewable generation technologies, has motivated a significant increment in the variability and unpredictability of power generation, along with the subsequent increment in the cost of grid management and higher probability of contingencies. As a result, the customers' participation in the solution of these problems by means of DR actions is more and more applied worldwide.

In this framework, the existing similarities between the electricity and natural gas systems permit to expect a successful application of DR concepts for a more efficient operation of natural gas systems by using the flexibility of consumers.

In order to develop DR products in the gas system, services that consumers may offer have been investigated. Therefore, the proposed methodology includes the analysis of the management actions that system operators must address in the daily management of the systems (such as balancing, pipeline congestion or reserve shortages in underground storages), the identification of DR products that have been successfully developed for power system operators or the metering and communication needs for the full exploitation of the flexibility in this sector.

Keywords: Demand Response, natural gas system, smart metering, methodology

Abbreviations

DR	Demand Response
DSO	Distribution System Operator
ESCO	Energy Service Company
GHG	Greenhouse gas
GSO	Gas System Operator
TSO	Transmission System Operator

Symbols

AF	Availability frame for a DR action (hours)
α_h^{NS}	Fix cost to by paid by the GSO in case of non-supply (€/h)
β_h^{NS}	Variable price to be paid by the GSO in case of non-supply (€/m^3)
B_h^{DRR}	Hourly benefit for the GSO when using DR resources (€/h)
CG_h^{Ba}	Hourly cost of natural gas for balancing purposes (€/h)
$C_{Ctr,h}^{DRP}$	Hourly cost of control equipment for DR purposes (€/h)
$C_{MtM,h}^{DRP}$	Hourly cost of metering and monitoring for DR purposes (€/h)
$C_{DS,h}^{DRP}$	Hourly cost of dual supply for DR purposes (€/h)
$C_{Am,h}^{DRP}$	Hourly cost of amortizations for DR purposes (€/h)
$C_{MP,h}^{DRP}$	Hourly cost of additional work force for DR purposes (€/h)
$C_{Ls,h}^{DRP}$	Hourly cost of service losses for DR purposes (€/h)
C_h^{DRP}	Hourly cost of implementation of a DR action (€/h)
CG_h^{St}	Hourly cost of natural gas for maintenance of the storage level (€/h)
C_h^{NS}	Hourly cost of natural gas in case of non-supply (€/h)
G_a	Amount of gas consumed during the recovery of a DR action (kWh)
G_b	Amount of gas consumed during the preparation of a DR action (kWh)
G_r	Amount of natural gas reduced during a DR action (kWh)
$G_{reduced}$	Net amount of natural gas saved during a DR action (kWh)
ΔHF_h^{DRP}	Impact of a DR action in the natural gas cost for a consumer (€/h)
HCV_{NG}	Higher calorific value for natural gas (kWh/m^3)
H_{firm}	Maximum hourly gas flow to be demanded by a consumer for a DR action (kWh/h)
HF_A	Additional hourly flow demand after a DR action (kWh/h)
HF_B	Additional hourly flow demand before a DR action (kWh/h)
HF_h^{Ba}	Hourly amount of gas used for operation purposes (m^3/h)
HF_h^{St}	Hourly amount of gas used for storage purposes (m^3/h)
HF_h^{NS}	Hourly amount of gas not supplied to consumers in case of shortage (m^3/h)
HFR	Hourly gas flow reduction (kWh/h)
π_{Ba}	Unitary cost of operation for balancing purposes (€/kWh)
π_{NG}	Price of natural gas for balancing purposes (€/kWh)
π^{St}_{NG}	Price of natural gas for storage purposes (€/kWh)
π^{St}_{Op}	Unitary cost of gas storage (€/kWh)
$\pi_h^{contract}$	Price paid by the consumer for the natural gas supply (€/kWh)
Pr^{bid}	Price offered by the GSO in exchange for a DR service (€/kWh)
Pr^{offer}	Price requested by a DR provider to deliver a DR service (€/kWh)
τ_{AD}	Notification in advance for a flexibility action (hours)

τ_{BA}	Minimum time between DR actions (hours)
τ_{D}	Duration of a flexibility action (hours)
τ_{PB}	Duration of the preparation period for a DR action (hours)
τ_{RA}	Duration of the recovery period for a DR action (hours)

1. Introduction

As one of the major energy sources, the natural gas covers in US the 24% of the total energy demand of the country [1] while in Europe represents the 30% of the primary energy consumption [2]. Together with renewable energies, natural gas results to be one of the most used energy sources worldwide and its utilization is predicted to grow [2] due to its low environmental impact. This resource emits much less CO_2 than other fuels due to the low carbon content of methane, so it is expected to be the most used fossil fuel internationally in the short and medium term [3]. Nowadays, natural gas is used in the residential and commercial sector included space heating, water heating, and cooking as well as in the industrial sector as fuel to generate heat and power or as feedstock. Due to its respectful environmental characteristics, the natural gas demand in residential, commercial and industrial sectors has grown substantially over the past few years [4], [5].

Storing and long distance of transportation are natural gas main limitations. Natural gas is essential in many countries where there are no gas deposits for the coverage of the energy needs. It makes these countries strongly dependent from foreign nations. On the other side, politically instability that affects the principal gas producer countries may determine interruption of the supply in the short terms and implies dependency on gas supply for many European countries [6].

In this uncertain and unstable scenario, flexible demand, together with the utilization of storage, results essential. Demand response (DR) products properly managed by means of interruptible contracts could help to overcome the natural gas limitations.

Demand response programs have been used by electrical system planners and operators as a significant resource for balancing supply and demand. DR provides an opportunity for consumers to play a significant role in the operation of the electric grid by reducing or shifting their electricity usage during peak periods in response to time-based rates or other forms of financial incentives. As DR has been a common practice in electricity systems for years, many successful examples of their applications exist around the world [7].

Electricity and natural gas systems present significant differences. The main difference is probably the impossibility to store significant amounts of electricity with an acceptable performance. This fact makes that the electricity that consumers demand from the power grid must be produced in real time by generators at the other side of the grid. Another significant difference is the wave nature of electricity. This nature provides electricity 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.

The existing similarity between the gas system and the electrical system may makes possible to adapt the current DR products used in the electric system for the design of DR program applications to the gas system. This is especially interesting in smart multi-energy systems, which is a trend in the current development of cities [8] . In this way, DR strategies should be applied to reduce imbalances in the natural gas network and reducing the need to pay large amounts of money in the short-term wholesale market. Furthermore, the design and deployment of more specific DR programs for gas applications need to be explored due to its potential together with the ability of consumers to offer the flexibility consumption to improve the efficiency of the system operation. In this framework, the emerging smart metering infrastructure may help in integrating DR programs in the gas distribution and transmission infrastructure, so that the different elements such “smart gas networks” may be able to adjust the consumption level to the real availability of the grid.

This article provides a novel methodology to be used for the design of DR programs applied to the natural gas network and the assessment of customer’s flexibility to participate actively in the operation of natural gas systems. This objective should be addressed by the design of a systematic procedure so as to determine the impact of the application of DR strategies under both the customer and the network operator perspectives. Demand side participation in energy markets does not happen spontaneously, so that new tools are required for such evaluation [9].

The article will be divided into the following sections: After a little introduction, a review of existing DR experiences in the natural gas systems of some countries is presented in section 2. After that, section 3 details the methodology designed for the evaluation of DR strategies applied to the management of the natural gas sector. Some discussions about the specific application of this methodology to balancing services in the natural gas system are presented in section 4. Finally, the most significant conclusions are presented in section 5.

2. DR applications in natural gas systems

DR programs have been used for years in different countries in the electrical sector according to the different level of their development. Thus, the management of the power system by DR programs offered by system operators or utilities has contributed to solve several issues for the habitual operation of the power grid [9].

In the latest years, more and more natural gas resources have been used for power generation due to environmental requirements to reduce power production with coal content. Despite that, the experience of the application of DR concepts in the gas sector are still poor.

Some examples can be found about research dealing with DR issues applied to the utilization of natural gas, but the proposed strategies are usually linked to the utilization of such gas for power production [10], [11], [12], [13].

DR products could represent an essential tool for the efficient operation of the natural gas system, mainly due to the following considerations [14]:

- The existing connection between the electrical and the natural gas markets as this last resource is more and more used for power generation.
- The tendency of regulation in different countries to reduce the environmental impact, which is making that natural gas replaces other fuels as coal [15].
- Power plants supplied by natural gas, especially those with combined cycle, have higher performance [16].
- The volatility of the natural gas market increases due to its utilization for power generation.
- The natural gas demand patterns, which have traditionally been seasonal and quite stable, are changing. Indeed, demand forecasting has been identified as a critical issue for natural gas consumers [17].
- The discontinuity that characterizes renewable energies requires de application of smart technology able to respond quickly in order to provide power reliability and supply guarantee.

The few pilot projects carried out in the natural gas sector demonstrate the potential of the application of DR programs in the natural gas sectors [18]. In Canada, a pilot project carried out in the residential sector demonstrated the potential savings that could be reached depending on the season and the external temperature of the considered period [5]. A similar experience was carried out in Massachusetts, where DR applications on the natural gas consumption determined savings of 20% during the winter season in commercial and residential consumers [18].

In the United States of America, the installation of gas smart meters was the first step approved by the California Public Utilities Commission for the development of demand response programs applicable to the natural gas sector [19]. Another representative experience involved Enernoc, which is one of the most active companies in DR applications. Enernoc has developed a platform (tested by National Grid in the state of New York) to optimize the use of fuel sources based on weather availability. This experience is focused on demonstrating as DR resources may help to solve in winter similar problems to those that the power system (closely linked to the gas consumption) has during peak periods in summer [20].

Regarding experiences in Europe, an interruptible program was approved in Spain in 2006, based on the need of establishing tools and mechanisms to make more flexible the natural gas system. This program enabled the gas system operator to interrupt the supply of large consumers willing to reduce their consumptions when emergencies happen. Enrolled consumers must completely interrupt their consumption after a notification of 24 hours. Interruptions may take between 6 and 10 hours. Nevertheless, this program is just eligible for large companies connected to a pipeline at a pressure higher than 4 bar whose annual consumption is, at least, equal to 10 GWh, and whose daily consumption higher than 26 MWh [21].

There is another experience in the United Kingdom, where an interruptible program at the distribution network level has been implemented, although just a small group of large industries can participate, depending upon the commercial arrangements they have agreed to [22], [23]. Participants receive rebates in the transmission charges in exchange for their gas consumption when demand is high (especially in winter peaks). In spite of that, the number of enrolled consumers is low [24].

In the Netherlands, the consortium Energy Delta Gas Research (EDGaR), composed of 11 entities, coordinates the development of research projects about natural gas under scientific, applied and technological approaches. However, even if their initiatives are done in the field of smart natural gas systems, DR applications are not considered [25].

Most of these experiences evidence the great interest that different entities worldwide have demonstrated in applications for a more efficient management of the natural gas systems by applying DR resources, similarly to the power system. However, most of them are just in pilot phase at present or, in the best case, only large consumers are enabled to participate. In this framework, the methodology here presented is aimed at increasing the participation of gas consumers in the provision of operating services to the manager of the network, which would increase the joint efficiency of the system and may reduce the cost associated to such services.

3. Methodology

The methodology developed in this article is aimed at evaluating the impact of the use of DR for operation purposes in the natural gas system. Based on the existing similarities between the electricity and natural gas systems, this methodology is expected to facilitate the successful application of DR concepts for a more efficient operation of natural gas systems by using the flexibility of customers to decrement or increment their consumption in specific periods.

3.1. Identification of the agents involved in the process

The different agents that would be involved in the provision or utilization of DR resources within each phase of the methodology are the following:

- The gas consumer, as “generator” of the DR resource. The consumer must be able to adapt and modify its consumption by reducing or increasing it if a lower or upper demand is required.
- The gas system operator (GSO), as the main user of DR resources. The GSO will use the ability of flexible consumers to manage their consumption to solve stability problems or contingencies that may affect the gas infrastructure.
- The aggregator. This agent will be in charge of managing the flexibility of smaller gas consumers, similarly to its role in the power system [26]. It is an intermediary between DR providers and DR users as, while large consumers might directly provide their flexibility, it is not operative in the case of residential consumers.

In addition to the GSO, the aggregator and the customer, there are other involved agents.

- Large consumers, which directly manage their flexibility and do not require an aggregator for the provision of DR resources.
- Energy Service Companies or ESCOs. They are specialized entities that also exist in the electricity sector and that support large consumers in their energy management. The participation of ESCOs is essential for the proper utilization of DR services as the providers of DR resources (consumers) are not usually familiar with this kind of specialized knowledge, which is frequently far away from the business they are devoted to. This lack of knowledge tends to make them reluctant to participate in DR services, so that ESCOs have here an essential role in order to convince them and to demonstrate the benefits that the use of flexibility would mean for their enterprises.
- Gas traders or suppliers. They may use DR resources to compensate the imbalances between the gas they purchase in the wholesale market and the real time consumption of consumers they have in their portfolio. Nevertheless, in order not to complicate too much this methodology, they have been left out of the scope of this work. Said that, it is important to take them into account for further research and a subsequent improvement and development of this methodology.

Relationships which may be stablished among the different natural gas system agents, configured as a smart grid, are schematically represented in Figure 1.

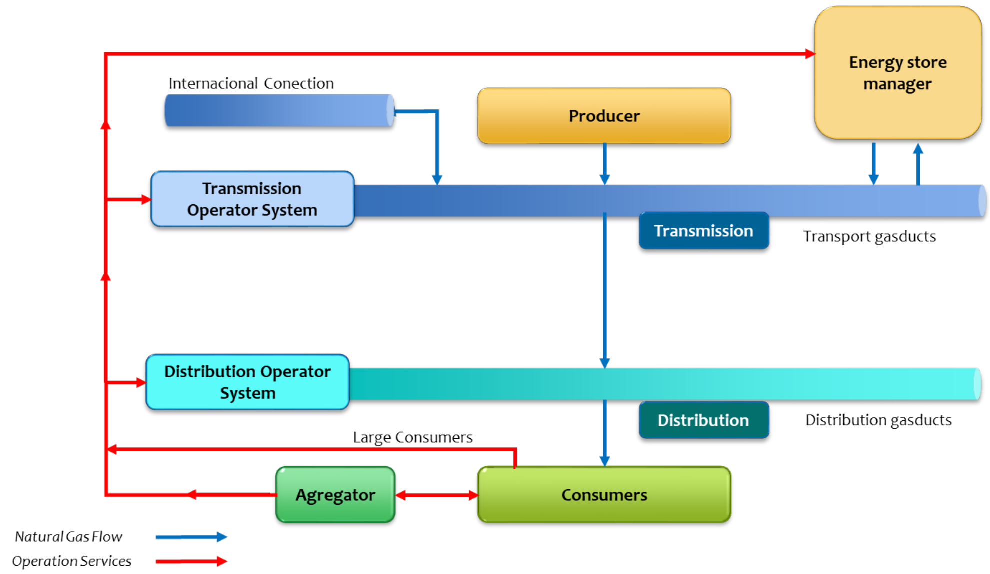

Figure 1. Relationships between the natural gas system agents organized as a smart grid

3.2. <u>General structure of the methodology</u>

The methodology is divided into six phases, which detail the different steps to be given for the proper design of suited DR products in the natural gas sector:

- Phase 1: Initial specification. In order to do a preliminary specification of the services to be based on customer's flexibility, the first step of the methodology is focused on the identification of the system operator needs and the customer abilities.
- Phase 2: Technical evaluation. After the identification of the technical characteristics that the system operator should have, the physical media (metering, communication and control requirements) that is necessary for the interchange of DR resources will be assessed.
- Phase 3: Economic evaluation. The benefit of the utilization of any DR product depends on the economic profitability that such product could provide to both the customer and the GSO. Therefore, in this phase, an economic evaluation based on a cost-benefit analysis will be carried out in order to demonstrate the economic advantages that a DR product could provide to all the involved agents in spite of the cost of its implementation or the use of any alternative solution.
- Phase 4: Environmental evaluation. In this phase, an environmental evaluation regarding the footprint reduction linked to the application of any considered DR product will be evaluated. The analysis of the avoided CO_2 emissions, but also the reduction of other greenhouse gases, will be carried out.

- Phase 5: Validation. After the mathematical evaluation of the proposed actions, a testing phase should be implemented in order to demonstrate with feasible evidence that the benefits theoretically evaluated can be actually achieved by all the involved agents.
- Phase 6: Final specification. In this final step, the DR products that have been designed and validated previously will be specified. In this way, the benefits when DR services are interchanged between DR providers (customers) and DR users (GSOs) would be guaranteed.

The methodology is schematically presented in Figure 2.

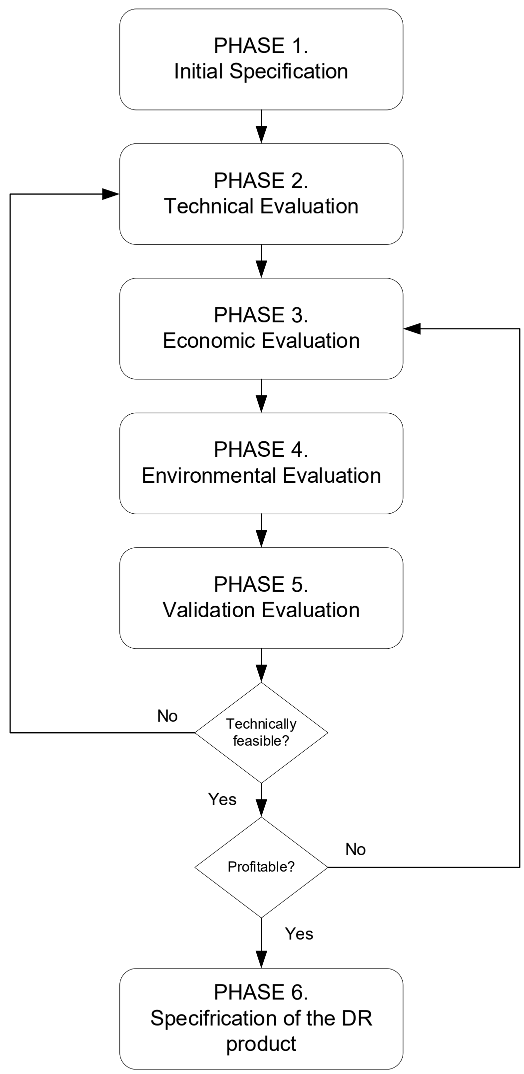

Figure 2. Methodology for the implementation of DR strategies in the natural gas sector

Following, each of the different phases of the methodology are further described in detail.

3.2.1. Phase 1: Initial specification of actions

The identification of the network problems that may be addressed by the demand side is the first step of this methodology. Therefore, in this phase, the different activities that will be required by the different agents of the process will be identified. They are classified depending on the involved agent (GSO, aggregator or consumer). Consumers are the providers of DR services, but the direct utilization of small demand packages is not operative for the GSO. For this reason, just large consumer may usually participate in this kind of services individually, being smaller providers aggregated so as to build significant products that could be useful for the GSO. Power plants are large consumers of natural gas whose consumption strongly depends on the electricity that is required by consumers connected to the power system. However, natural gas is also used by many different industrial consumers (fertilizers, chemical industry, oil refining) where the gas consumption is much more stable. Therefore, the application of demand response strategies requires a detailed energy study so as to determine the impact that such actions may have on their facilities, as well as the economic profit that the participation in demand response services may provide to them.

In this phase, which is schematically depicted in Figure 3, the external support of an Energy Services Company (ESCO) should be requested by large consumers in order to get some training to play with their flexibility, or to assess the impact of such flexibility on their processes. This is an important aspect, as the final decision to modify or not their consumption will depend on such impact. This support would be also required by smaller consumers but, in that case, the aggregator is who provides this support.

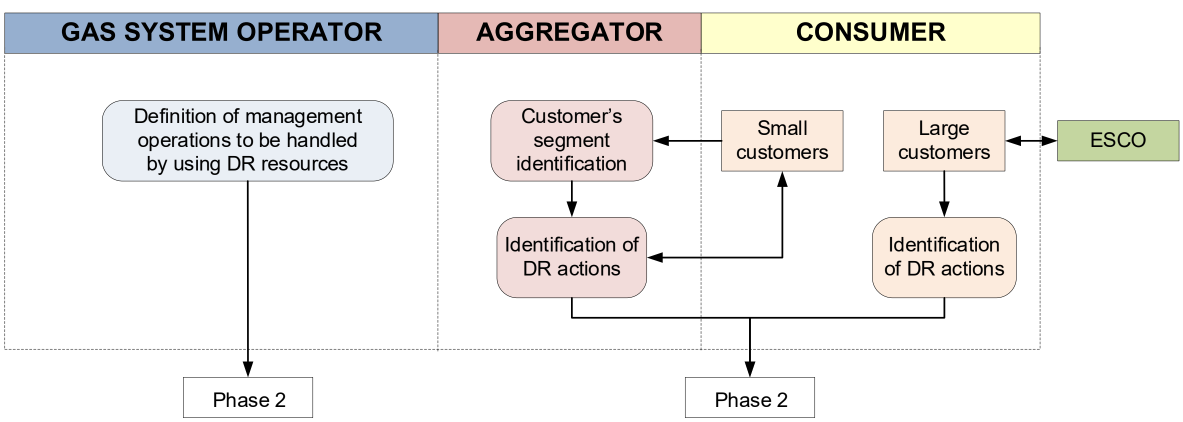

Figure 3. Phase 1. Initial Specification

3.2.2. Phase 2: Technical evaluation

<u>Standardization of DR actions</u>

The technical evaluation of the DR actions previously identified requires matching of the technical abilities of consumers and the technical requirements of the GSO. Therefore, a standardized definition of the DR actions is necessary to make actions understandable for all the involved parties.

Figure 4 shows the existing relation between the different parameters that would be used for a standard definition of a DR action that a flexible natural gas customer may implement. These parameters, based on [27] and taking into account the similarities between the electric and the natural gas systems, are the following:

a) Hourly gas flow reduction (*HFR*). Flexibility actions in the gas sector will be measured according to the maximum daily flow. In this methodology, a duration of 1 hour for a typical flexibility action will be considered. Consequently, the equivalent parameter to the flexible power in the power sector will be here the flexible hourly gas flow. HFR is measured in kWh/h. Complementarily to HFR, the factor H_{firm} is defined as the maximum hourly gas flow to be demanded by the customer during the flexibility action.

b) Duration of the flexibility action (τ_D). It is the total duration of a flexibility action (considering standard reductions of 1 hour), calculated as the number of consecutive reductions that may take place at the customer facility.

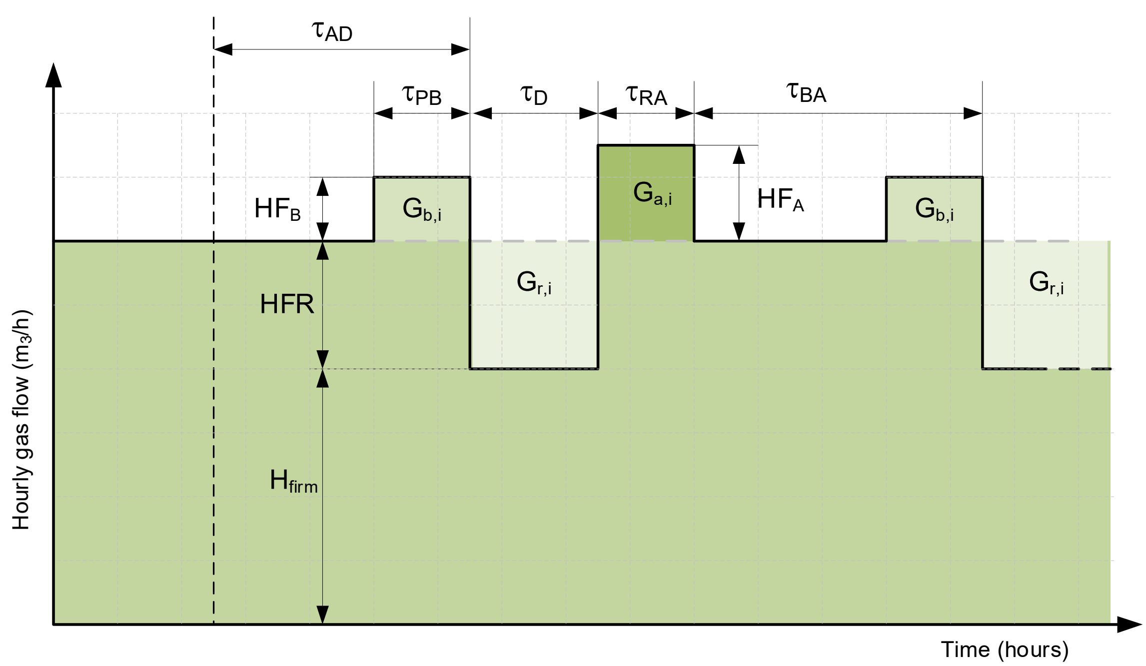

Figure 4. Standard definition of a DR action for a flexible gas consumer

c) Notification in advance (τ_{AD}). It is the time required by the customer to perform a flexibility action. It includes the time necessary for the adaptation of facilities and the physical management of the control devices.

d) Additional hourly flow demand before the DR action (*HF_B*). *HF_B* would be equal to the maximum hourly flow that is necessary for the adaptation of the facilities when an extra demand before the implementation of the DR action is required for the preparation of the processes to be managed. Similarly, to *HFR*, *HF_B* is measured in kWh/h.

e) Duration of the preparation period (τ_{PB}). This parameter represents the time during which the consumer demands the *HF_B* before the implementation of a DR action

f) Additional hourly flow demand after the DR action (*HF_A*). After the application of a DR action, an additional demand may be necessary in order to get back to the initial conditions (e.g. to reach the set point temperature). If this is the case, this demand overrun is considered by this parameter. *HF_A* is measured in kWh/h.

g) Duration of the recovery period (τ_{RA}). Similarly, to τ_{PB}, this parameter considers the duration of the recovery period, during which the consumer retakes the initial conditions.

h) Availability frame (*AF*). This parameter defines the period during which the flexibility action can be implemented (e.g. on working days).

i) Minimum time between actions τ_{BA}. This is the minimum requested time between the end of a flexibility action and the beginning of the next one.

Technical constraints in the natural gas system

The core of a natural gas system is an extensive frame of pipelines that transmit the gas from the production site to the consumption site. These pipelines are essential for the management of the natural gas system and their technical characteristics deeply influence its operation.

A constraint can be defined as a physical or commercial barrier that prevents the normal operation of the natural gas system, lowering the reliability of the continuity of the gas service. A detailed description of constraints that may appear in the natural gas system can be found in [28] but they may be classified into two types:

- A total interruption of the gas supply, if it is totally interrupted and the gas demand of the end user is not satisfied.
- A reduction of the gas supply, when the end user still receives gas but in a lower quantity compared to its actual needs.

In terms of lack of supply due to technical constraints, the concept of end user is applied to a significant consumption of gas from the grid (e.g. 40 m^3/h) which may be consumed by a district heating system, one or several industries or an entire town.

Interruptions of gas supply that could occur in the gas system determine a not continuity of the service. Traditionally, interruptions have been divided into short and long. Short interruptions are those whose duration is shorter than a standard value defined in regulation [29]. For example, the Italian regulation defines an interruption as short when the duration is less than or equal to 120 minutes. On the other hand, interruptions are considered as long when they exceed such standard duration.

The proper management of constraints in the gas system requires appropriate mechanism to forecast the dynamics of the whole system [30]. The performance of such mechanisms could be improved by applying demand response strategies, which may help the gas system operator to overcome such technical constraints. Therefore, the use of demand resources may promote the development of a reliable natural gas system, able to face quickly sudden network failures. Moreover, the implementation of DR programs could reduce the vulnerability to gas supply shocks, facilitating the development of an integrated gas market, reducing the import dependency and the variation of natural consumption due to the climate change issue.

<u>Assessment of the technical impact</u>

The amount of natural gas reduced by the consumer when applying a flexibility action "*i*" will be denoted by the variable $G_{r,i}$. If flexible demand packages have a standard duration of 1 hour, the total amount of energy reduced by the customer during the implementation of action "i" will be:

$$G_{r,i} = HCV_{NG} \cdot HFR_i \cdot \tau_{D,i} \quad \text{(kWh)} \tag{1}$$

where HFR_i is the hourly gas flow reduction related to the action "i", measured in m^3/h, and $\tau_{D,i}$ is the number of hours during which the action would take place. HCV_{NG} is the higher calorific value of natural gas, whose value depends on the quality and composition of the gas supplied to the consumers. Usually, it takes values from 37.5 to 43.0 MJ/m^3, equivalent to values from 10.42 to 11.94 kWh/m^3.

Similarly, the amounts of gas consumed before and after the application of the flexibility action in order to prepare the facilities or to get back the initial conditions would be calculated as follows:

$$G_{b,i} = HCV_{NG} \cdot HF_{B,i} \cdot \tau_{PB,i} \quad \text{(kWh)} \tag{2}$$

$$G_{a,i} = HCV_{NG} \cdot HF_{A,i} \cdot \tau_{RA,i} \quad \text{(kWh)} \tag{3}$$

According to the previous equations, the total amount of gas reduced during the application of action "*i*" will be:

$$G_{reduced} = HCV_{NG} \cdot \left[HFR_i \cdot \tau_{D,i} - HF_{B,i} \cdot \tau_{PB,i} - HF_{A,i} \cdot \tau_{RA,i} \right] \quad \text{(kWh)} \tag{4}$$

This phase of the methodology is represented in Figure 5.

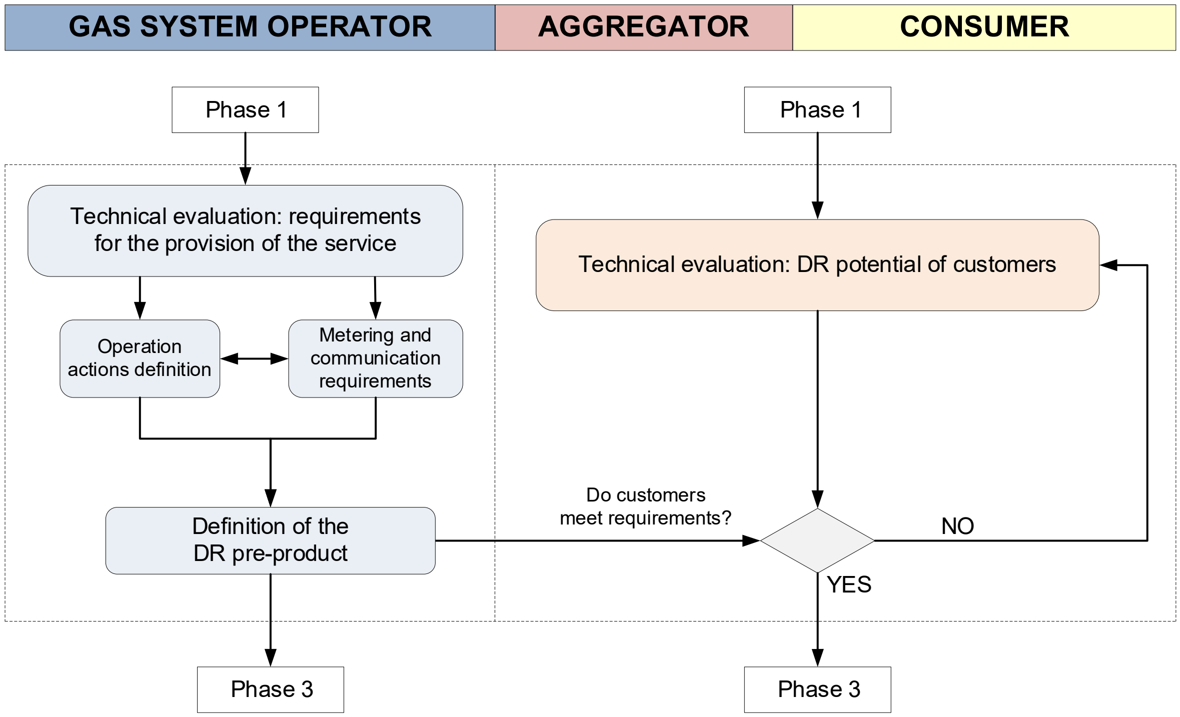

Figure 5. Phase 2. Technical evaluation

3.2.3. Phase 3: Economic evaluation

The success of a DR action will be based on the economic benefit that it may produce to all the parties involved in the transaction. From the DR provider perspective, the provision of DR services will be profitable when the incomes provided by the DR user are higher than the cost for the customer when performing such DR action. On the other hand, the GSO would use DR resources in order to solve some problem that may appear in the gas network if the cost of using DR is lower than the cost of solving such problem by means of traditional mechanisms. In both cases, the application of a DR action must benefit to both parties, so that in this phase, schematically represented in Figure 6, a cost-benefit analysis will be done to help the GSO to make a decision on using or not the flexibility that consumers may have. Similarly, the consumer should be able to determine the prices at which the flexibility can be offered to the GSO when this action also produces a benefit to him.

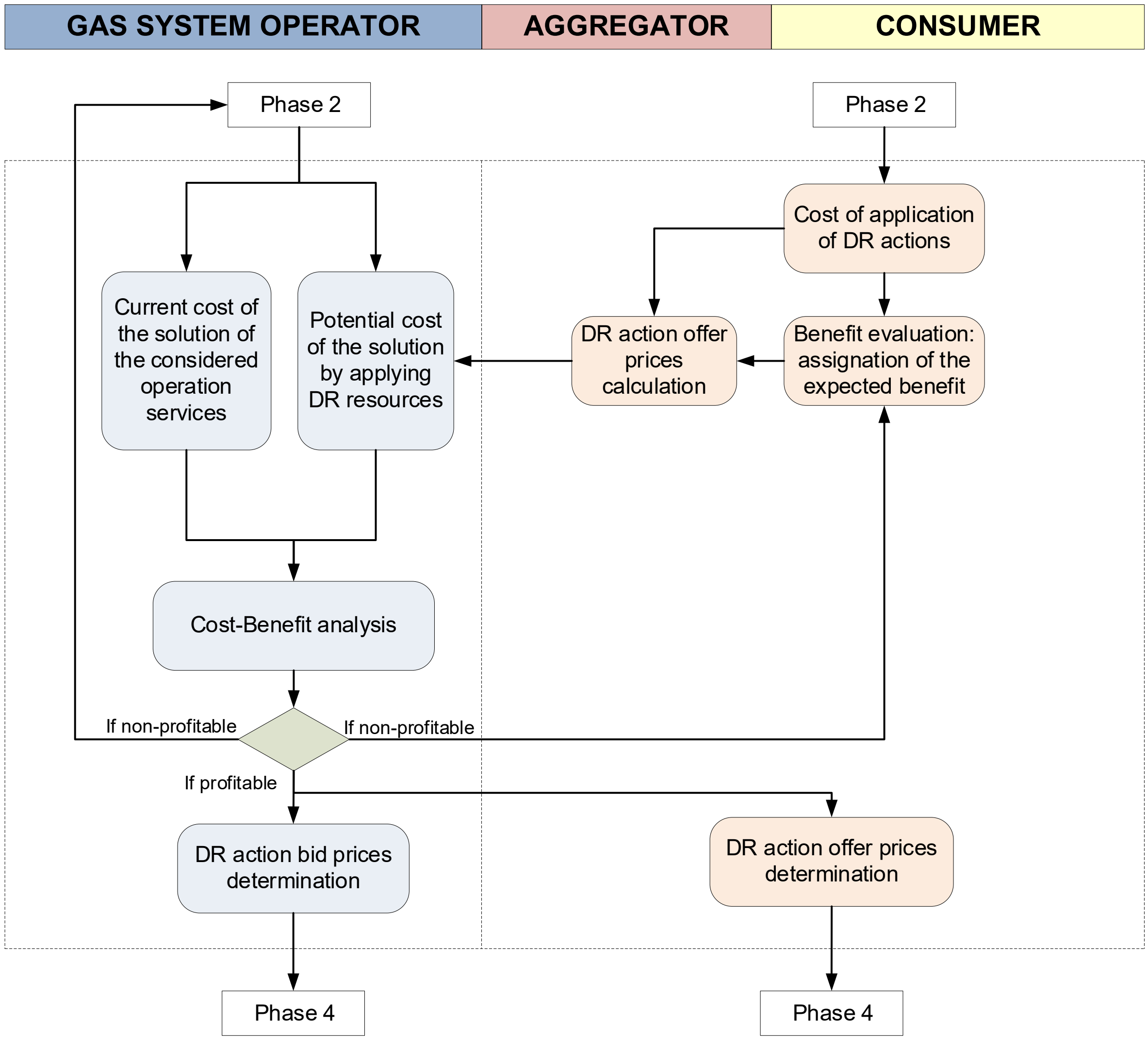

Figure 6. Phase 3. Economic evaluation

Costs evaluation on the GSO side

A cost-benefits analysis will compare the current operation costs that the GSO has to face so as to handle some kind of operation service and the cost that the utilization of DR resources provided by consumers may have. Depending on the nature of the considered service, the GSO costs may be evaluated as follows:

- Cost of natural gas for balancing purposes (CG_h^{Ba}). The provisioning of natural gas for operation purposes done in a daily basis will be calculated in terms of the hourly cost of natural gas as follows:

$$CG_h^{Ba} = \left(\pi_{Bal} + \pi_{NG,d}\right) \cdot HF_h^{Ba} \cdot HCV_{NG} \quad \text{(€/h)} \tag{5}$$

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. The origin of HF_h^{Ba} could be an interconnection pipeline to an external gas system, the facilities of an internal producer or a regasification plant. If the hourly value is unknown, it may be estimated as the daily value divided into 24. HCV_{NG} (kWh/m^3) is the higher calorific value of natural gas. On the other hand, $\pi_{NG,d}$ (€/kWh) is the price of the natural gas used for operation purposes which is incorporated to or extracted from the system. If the GSO needs more gas, $\pi_{NG,d}$ will be positive and it would represent the price of natural gas that the GSO must pay to the gas provider in the wholesale market. Otherwise, if there is an excess of gas, $\pi_{NG,d}$ will be negative and it would be the price at which the GSO sells the exceeding amount of gas to the wholesale market. Finally, π_{Bal} (€/kWh) is the hourly cost of operation of the network related to balancing operations.

- Maintenance of the storage level. The GSO must purchase from the wholesale market the amount of natural gas that is requested to restore the level of stored gas in case that the maximum admissible volume have been extracted during a day. The cost of this gas can be calculated as follows:

$$CG_h^{St} = \left(\pi_{NG,d}^{St} + \pi_{Op}^{St}\right) \cdot HCV_{NG} \cdot HF_h^{St} \quad (€/h) \tag{6}$$

where HF_h^{St} (m^3/h) is the hourly amount of natural gas purchased by the GSO to restore the daily level of stored gas. If the hourly value is unknown, it may be estimated as the daily value divided into 24. HCV_{NG} (kWh/m^3) is the higher calorific value of natural gas. On the other hand, $\pi_{NG,d}^{St}$ (€/kWh) is the price of the natural gas purchased by the GSO in the wholesale market for storage purposes and π_{Op}^{St} (€/kWh) is the hourly cost of storage (operation and maintenance).

- Cost of non-supply (C_{NS})**.** This is the cost in that the GSO incurs when there is a gas shortage due to some constraint, such as delay in the discharge of tankers or lack of capacity in the pipelines. This cost could be evaluated as follows:

$$C_h^{NS} = \alpha_h^{NS} + \beta_h^{NS} \cdot HF_h^{NS} \quad (€/h) \tag{7}$$

where α_h^{NS} (€/h) and β_h^{NS} (€/m^3) are, respectively, the fix and the variable price to be paid by the GSO to the customers not supplied during the hour h due to operational issues. These prices are usually given by the local regulation as they are considered as a compensation to customers as they are not delivered the committed amount of gas. Finally, NS_h^{NS} is the hourly flow that is not supplied to the consumers, measured in m^3/h.

Cost evaluation on the consumer/aggregator side

The costs related to the use of flexibility in the consumer/aggregator side can be structured according to the direct and indirect costs classification that can be found in [31], applied to the electricity sector.

According to this classification, direct hourly costs would include:

- The cost of control ($C_{Ctr,h}^{DRP}$), which includes the different management actions oriented to the application of flexibility in the customer side. This cost includes both the operational costs linked to control and the necessary investments for the control equipment acquisition and installation.
- The cost of metering and monitoring($C_{MtM,h}^{DRP}$), that is necessary in order to evaluate the potential of customers at any hour and to validate the fulfillment of a flexibility contract. Similarly, to the cost of control, this cost also includes the necessary investments for the metering and monitoring equipment that may be necessary.
- The cost of dual supply($C_{DS,h}^{DRP}$), which takes into account the possibility to use an alternative energy source when the main natural gas supply fails. It may include burners, supplied by different types of fuel (diesel, fuel) or electric heaters.
- Finally, the cost of amortizations($C_{Am,h}^{DRP}$), that considers the annual amortization related to the necessary investments to adapt the customer facilities for DR implementations.

Regarding indirect costs, the following concepts can be considered:

- The cost of additional work force ($C_{MP,h}^{DRP}$) that could be necessary in order to apply flexibility in the facility. It includes the extra working hours of related workers or even the hiring of some additional employee to be responsible of this new activity in the facility. In the case of small customers (residential or small commercial), this cost would include the payments to an external agent that may be necessary in order to manage the flexibility of the facilities.
- The cost of losses ($C_{Ls,h}^{DRP}$), which entail the loss of comfort for residential and commercial customers, or even the loss of productivity in the case if the industry. The evaluation of this cost is not easy, especially when considering the loss of comfort as it may be quite subjective. However, it is important to evaluate well this concept as it may have a strong influence in the final decision on activating or not some flexibility actions.

The hourly cost of implementation of a DR action will be thus calculated as follows:

$$C_h^{DRP} = \sum C_{k,h}^{DRP} = C_{Ctr,h}^{DRP} + C_{MtM,h}^{DRP} + C_{DS,h}^{DRP} + C_{Am,h}^{DRP} + C_{MP,h}^{DRP} + C_{Ls,h}^{DRP} \quad \text{(€/h)} \tag{8}$$

Cost-benefit balance

Once the different costs have been evaluated, the cost-benefit analysis of a DR action can be evaluated. A specific DR action will success when it provides a benefit to both sides: the GSO and the customer.

The benefit that is required for customers/aggregators in order to provide the DR Service would be established in advance, so that when a DR offer is sent to the GSO, either the costs that customers/aggregators incur in and the benefit margin they require to provide this service will be included in the offer. Therefore, the price required by the DR provider to deliver the service “i” to the GSO would be calculated as follows:

$$\Pr_i^{offer} = \tau_{D,i} \cdot \frac{\left(C_h^{DRP} - \Delta HF_h^{DRP}\right)}{G_{r,i}} + B_h^{DRP} \quad (€/kWh) \tag{9}$$

where $\tau_{D,i}$ (h) is the number or hours during which the action would take place; C_h^{DRP} (€/h) is the hourly cost for the consumer/aggregator when performing the DR action, as calculated in equation (8); $G_{r,i}$ (kWh) is the total amount of energy reduced by the customer during the implementation of action “*i*”, as calculated in equation (1); B_h^{DRP} (€/kWh) is the benefit margin required by the consumer to be willing to offer the flexibility it may have, and will be fixed according to the own strategy defined by the consumer or aggregator; finally, ΔHF_h^{DRP}(€/h) represents the impact of the DR action on the cost of the gas for the consumer, related to the cost when the DR action is not implemented. It would be calculated according to the following expression:

$$\Delta HF_h^{DRP} = \left(G_{r,i} - G_{b,i} - G_{a,i}\right) \cdot \pi_{i,h}^{contract} \quad (€/h) \tag{10}$$

$\pi_{i,h}^{contract}$(€/kWh) is the price that the consumer pays for the natural gas according to the contract of supply, and G_{ri}, G_{bi} and G_{ai} are calculated according to equations (1), (2) and (3).

The operation service “i” for which the GSO may require the participation of customer’s flexibility would be based on a price Pr_i^{bid}, which would depend on the benefit provided by such flexible action to the GSO. When the price required by the consumer/aggregator is lower than the price offered by the GSO, the transaction may be established. If this is the case, the consumer will obtain a benefit, given by the margin B_h^{DRP} used in the calculation of the offer price. Moreover, the GSO will obtain also a benefit, as it would receive from the demand side a service that is cheaper than other alternatives.

This methodology proposes a “pay as bid” settlement, so that the consumer/aggregator would receive the required price when offering the service, which already includes its own benefit. The hourly benefit B_h^{DRR} of the GSO would be calculated as the difference between the cost that the GSO has to face when solving the network service by means of traditional means and the payment to be given to the customer when providing such service:

$$B_h^{DRR} = \frac{G_{r,i} \cdot \left(\Pr_i^{bid} - \Pr_i^{offer}\right)}{\tau_{D,i}} \quad (€/h) \tag{11}$$

$G_{r,i}$ (kWh) and Pr_i^{offer} (€/kWh) are calculated by equations (1) and (9), and $\tau_{D,i}$ (h) is the number or hours during which the action would take place. Regarding Pr_i^{bid}, it would depend on the kind of service requested by the GSO, as it will be discussed in section 4.

If the proposed actions do not provide a net benefit to both stakeholders (the GSO as DR requester and the consumer/aggregator as DR provider), actions to be performed by the demand side should be redefined and adjusted (going back to the phase 2), as well as the service requested by the GSO. Otherwise, obtained prices may be accepted, which establishes a DR market between both parties.

3.2.4. Phase 4: Environmental evaluation

Natural gas is a fossil fuel. However, the global warming emissions produced during its combustion are much lower than those from coal or oil, not just at the utilization stage but also in the phase of extraction, production and transmission. According to Eurogas (www.eurogas.org), the high hydrogen-to-carbon ratio of natural gas results in a production of CO_2 a 30% lower than for oil and 50% less than for coal per unit of energy produced during combustion. Additionally, natural gas emits less nitrogen and sulphur oxides, as well as particles than any other fuel fossil.

The environmental impact of DR actions on the natural gas emissions can be evaluated by multiplying the emission factors of the different sub-products resulting from the gas combustion by the energy saved when flexibility is used. According to EPA (for USA) [32] and the British Government (for UK) [33], emission factors of the main combustion products of natural gas are given in Table 1. As it can be seen, the GHG emissions strongly depend on the composition of the natural gas used in each specific area:

Table 1. Greenhouse emission factors for natural gas. Sources: EPA and GOV.UK, 2021

Area	**CO_2**	**CH_4**	**N_2O**
	kg/Nm^3	**mg/Nm^3**	**mg/Nm^3**
USA	1.9225	36.3741	3.5315
UK	2.0189	2.7100	1.0700

If $G_{reduced}$ (kWh), calculated in equation (4), is the net amount of natural gas saved when applying a DR action, the greenhouse emissions related to that application for each type of emission is given in equation (12):

$$Greenhouse\ Emission = \begin{cases} G_{reduced} \cdot \dfrac{2.07}{HCV_{NG}} & \text{if } CO_2 \\ G_{reduced} \cdot \dfrac{39.16 \cdot 10^{-6}}{HCV_{NG}} & \text{if } CH_4 \\ G_{reduced} \cdot \dfrac{3.8 \cdot 10^{-6}}{HCV_{NG}} & \text{if } N_2O \end{cases} \quad \text{(kg)} \qquad (12)$$

HCV_{NG} is the higher calorific value of natural gas, which takes values from 10.42 to 11.94 kWh/m^3, depending on the quality and composition of the gas supplied to the consumers.

This phase of the methodology is represented in Figure 7.

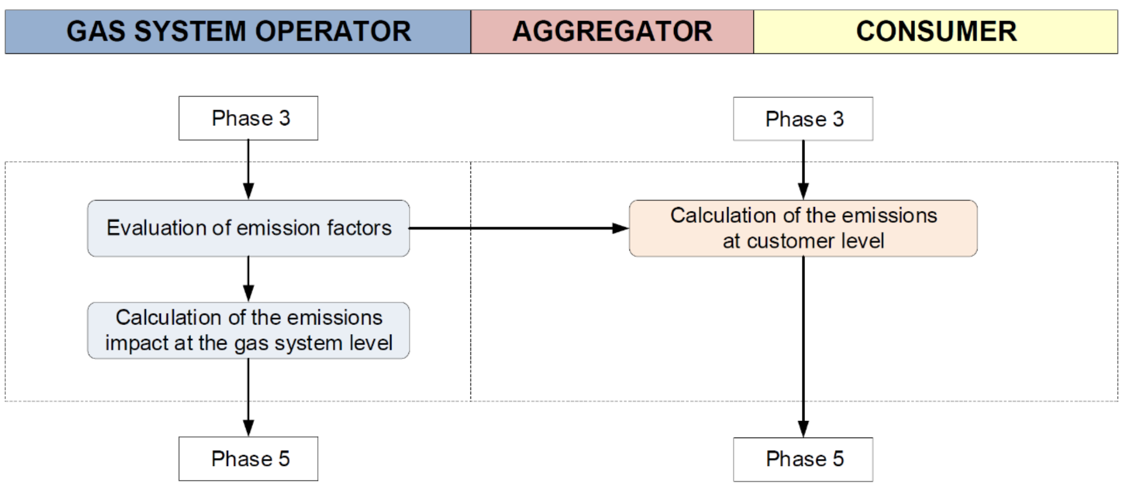

Figure 7. Phase 4. Environmental evaluation

3.2.5. Phase V: Validation

During this phase, that is the last one before launching a DR product into the market the different aspects theoretically evaluated in the previous steps will be demonstrated with a real application. The success of this validation resides in a proper design of a set of tests to be performed. It includes not just the technical or economic characteristics of the DR product, but also the metering and communications needs, which are essential for the implementation for the service and its proper settlement. Moreover, tests should specify the number of consumers that will be considered so as to get significant results which may be extrapolated for larger populations.

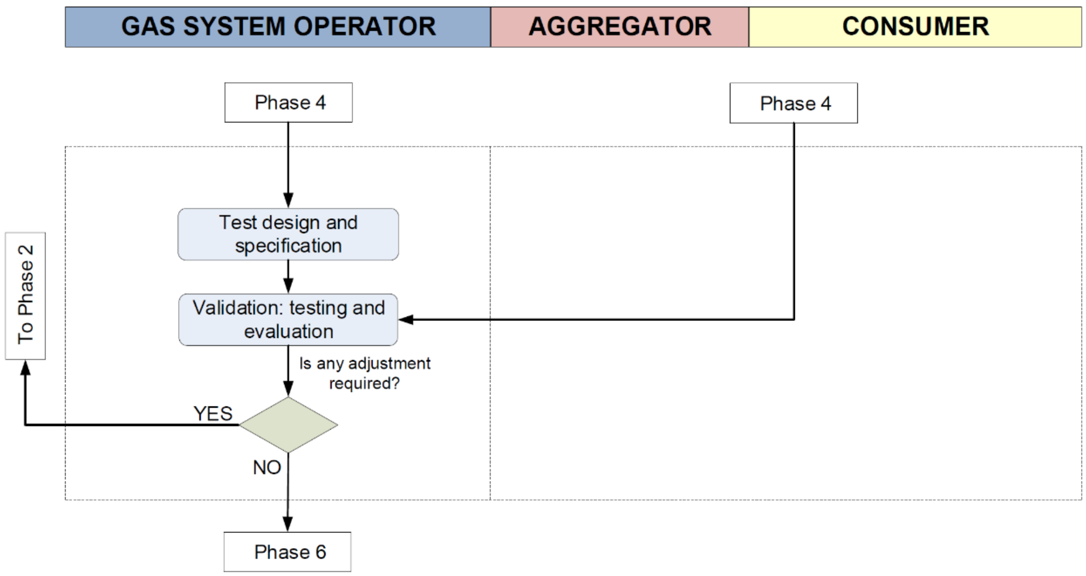

Figure 8. Phase 5. Validation

After the performance of tests, as shown in Figure 8, and once the required variables have been specified, the GSO will be responsible to verify the suitability of the DR product according to its specifications. If the obtained results do not success, some adjustments may be requested, so that going back to the Phase 2 of this methodology would be necessary. Otherwise, the DR product would be ready to be used for the provision of DR services into the market.

3.2.6. Phase VI: Final specification of DR products

The last phase of this methodology, represented in Figure 9, turns results into the final specification of DR products. Since a technical point of view, parameters used to define the DR product should be those detailed in Figure 4. Then, the economic evaluation should have demonstrated the profitability that the designed DR product means for the GSO and the consumer/aggregator. Additionally, a reduction in the GHG emissions may be obtained if the use of flexibility has achieved net reductions in the gas consumption of consumers. Finally, the specification of the DR product should include as well the requirements related to metering and communication devices, as well as the settlement mechanisms by means of which, consumers and/or aggregators would be paid by the GSO as DR user.

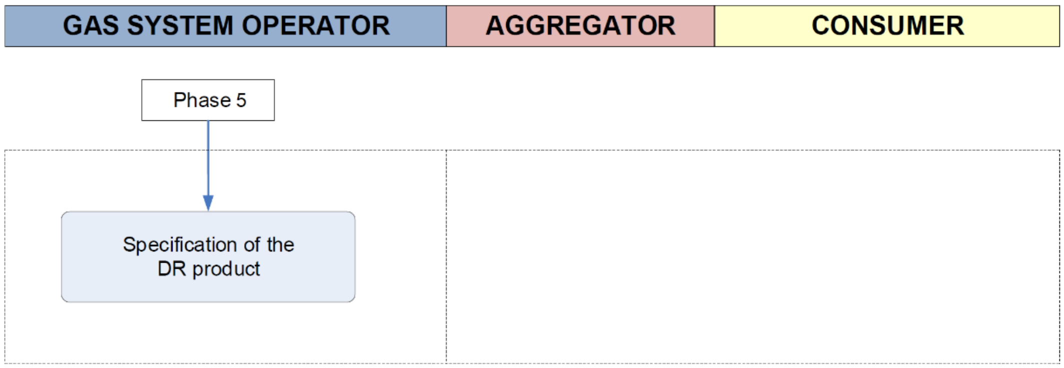

Figure 9. Phase 6. Final specification of DR products

4. Example of application

In order to illustrate the application of the proposed methodology, it has been partially applied to an industrial consumer that may provide its flexibility to the gas system for operation purposes. In particular, the standardization of DR actions described in Phase 2 has been applied to the gas consumption of a ceramic industry with a production of 3,500,000 m^2 of tiles a year. The hourly gas profile has been obtained by physical modeling, using the tools developed by the research group of the Institute for Energy Engineering of the Polytechnic University of Valencia during the project EU-DEEP [34], [35].

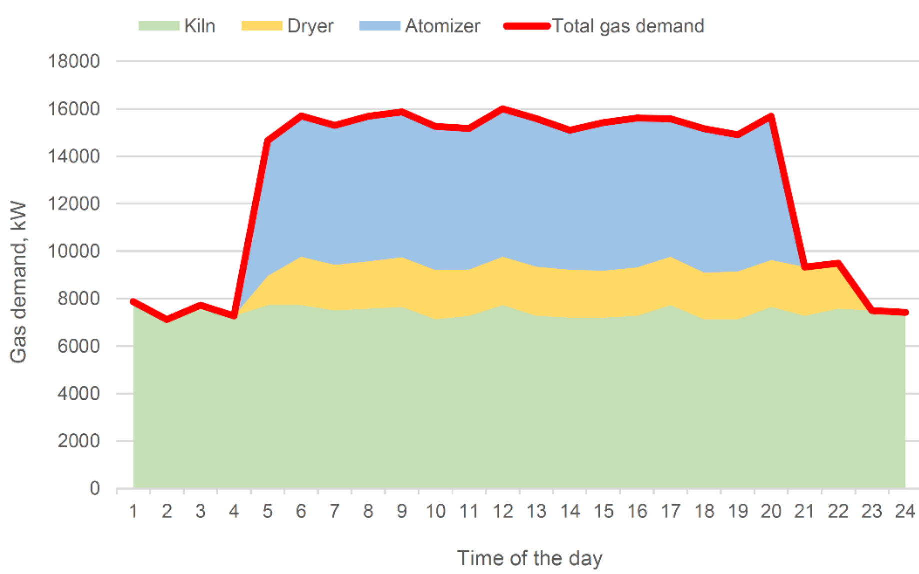

Figure 10. Typical hourly gas profile for a ceramic tiles factory

The hourly gas profile for a typical day of the aforementioned ceramic tile factory is represented in Figure 10. Natural gas is mainly used for three main processes: the atomizer, where the clay is prepared before starting the manufacturing of tiles; the dryer, where tiles undergo the first dehydration process after being molded; and the kiln, that is the mayor gas consumer of the factory, where tiles are heated at very high temperature so as to acquire resistance.

The kiln is the bottleneck of the factory as it is operating continuously and its schedule cannot be modified. However, the other two processes (even if they have been traditionally considered not manageable) may present some flexibility as they could be moved in advance or delayed for some hours (up to two hours may be acceptable, according to the experience of the authors in similar facilities). Assuming the hypothesis of moving in advance the atomizing process for one hour, the impact of this action in the total gas demand of the factory would be as represented in Figure 11.

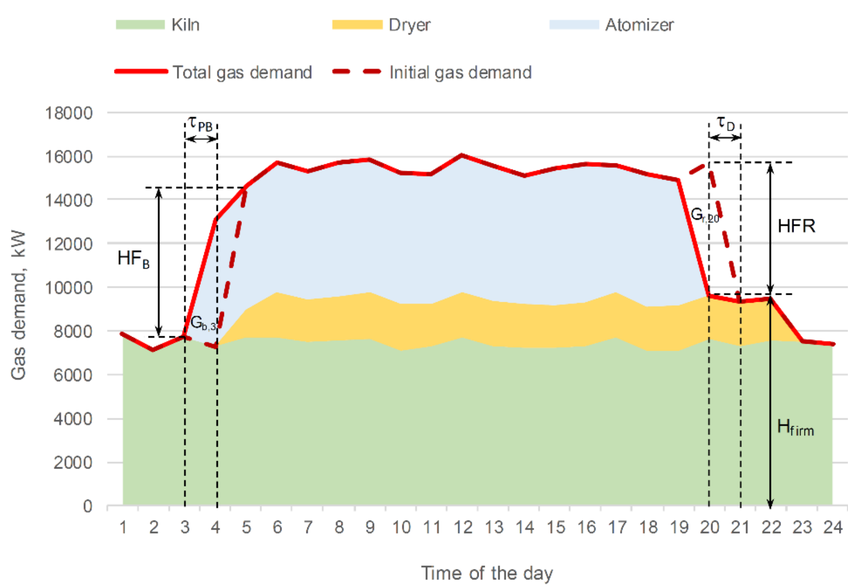

Figure 11. Gas profile for a ceramic tiles factory after applying flexibility

According to the parameters defined in the methodology, this DR action would be defined according to the parameters summarized in Table 2.

Table 2. Standard definition of DR action for a ceramic tile industry

Parameter	Symbol	Units	Amount
Hourly gas flow reduction	HFR	kWh/h	6,060
Duration of the flexibility action	τ_D	hours	1
Notification in advance	τ_{AD}	hours	24
Additional hourly flow demand before the DR action	HFB	kWh/h	5,824
Duration of the preparation period	τ_{PB}	hours	1
Additional hourly flow demand after the DR action	HFA	kWh/h	0
Duration of the recovery period	τ_{RA}	hours	0
Availability frame	AF	-	3 - 20
Minimum time between actions	τ_{BA}	hours	24

In the table, it has been assumed that this action could take place once a day (τ_{BA} = 24 hours). Similarly, it has been considered that the consumer should be notified one day in advance (τ_D = 24 hours). AF would correspond to the period during which the process of drying takes place.

This example just pretends to illustrate how a flexibility action could be parametrized according to the standard procedure defined in this methodology. This standardization of DR actions is essential in order to facilitate the communication between bidders and demanders of DR products. Said that, the authors are working out a detailed real application that will be presented in a coming publication, providing empirical evidence about the effect that the use of DR entails on existing gas infrastructures at system level.

5. Discussion

The methodology presented in this article allows to evaluate the impact when DR principles are used for operation purposes in the natural gas system due to the similarities existing with the power system, where DR concepts have been successfully applied for year. In the case of the natural gas system operation, the GSO may require DR for one or several of the following services:

- **Service 1: Balancing of natural gas in the transmission network.** This service guarantees that the minimum level of filling of the gas pipelines is maintained in the transmission network, where 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.

- **Service 2: Maintenance of the storage level**. The daily amount of natural gas injected to or extracted from an underground store must remain within the limits technically established. Therefore, the GSO has to buy in the wholesale market the required amount of gas to refill the store everyday up to the established limit. 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.** Technical constraints may produce in transmission and distribution infrastructures overload or even interruptions of supply to customers. Those interruptions of gas could determine a not continuity of supply, which jeopardizes the quality of the service provided to consumers. Here, DR programs may help to solve such problems similarly to the utilization that is made in power systems.

According to such services, the price of DR bids mentioned in section 3.2.3, that will be launched by the GSO to the market in order to acquire some DR services, may be calculated for each service as follows:

$$\Pr_i^{bid} = \begin{cases} \dfrac{\pi_{BA} + \pi_{NG,d}}{HCV_{NG}} & \text{if service 1} \\[2ex] \dfrac{\pi_{Op}^{St} + \pi_{NG}^{St}}{HCV_{NG}} & \text{if service 2} \\[2ex] \dfrac{1}{HCV_{NG}} \cdot \left[\dfrac{\alpha_h^{NS}}{HF_h^{NS}} + \beta_h^{NS} \right] & \text{if service 3} \end{cases} \quad (€/kWh) \qquad (13)$$

As presented in section 2, the participation of small customers in DR services has been historically neglected in both the electricity sector and in the few applications in gas sector, being just focused on very large consumers. In order to actually get the full potential that DR resources may have for the operation of the natural gas system, the role of the aggregator results to be strategic for the exploitation of the small customers potential. The aggregator may manage the flexibility of medium and small consumers in order to create more significant DR packages so as to be offered to the GSO. In this case, two different versions of the natural gas DR aggregator can be considered:

- The “traditional” aggregator, who represents and manage the flexibility of natural gas consumers, who directly uses this fuel in a boiler or a burning system for heating purposes.

- The manager of district heating systems (DHS). In this case, consumers do not directly use the natural gas, but steam or hot water supplied by the DHS, who is the actual consumer of the fuel. Therefore, this aggregator would be simultaneously the thermal energy supplier and the manager of the DR resources that may be offered by the supplied consumers within its portfolio.

In both cases, the objective would be the same: the utilization of the ability that consumers have to modify their usual patterns of consumption (direct natural gas or any other thermal fluid [36]) in response to the aggregator.

Regarding large consumers, who can participate directly (without aggregator), may also need some support in order to identify and manage the flexibility. The external agent that play this role is the Energy Services Company (ESCO). This figure is not necessary in the case of smaller customers that do not directly participate but aggregately, assuming that this role is played by the aggregator.

Some examples of DR actions that consumers could consider in order to offer their flexibility are the following:

- Similarly, to the use of flexibility of air conditioning devices for DR applications in the electricity sector, the installation of smart thermostats for the remote management of heating devices may open the gate for the exploitation of a very large potential. Sometimes, the same thermostats can be used for cooling and heating purposes (e.g. in the United States, the installation of smart thermostats in acclimation systems is being rapidly deployed across the country and are expected to replace the compressor switches that are used to control air conditioners [37]). Programmable thermostats might be remotely controlled by the own customer but also by a third party (such as the aggregator)
- In addition to heating space devices using natural gas, the management of other residential and commercial applications such as water heating or clothes drying may be very flexible [38].
- In large commercial and industrial applications, more specific processes would be considered, such as industrial washing machines, furnaces, boilers or air heaters. Direct control may be applied to those processes, which could be also related to some kind of interruptible gas contract.

In order to implement physically the proposed DR actions, the GSO needs to establish the metering and communication requirements that will be necessary. Metering and communication requirements will depend on the kind of service requested by the GSO and how DR will be used and verified. On the other side, customers will be economically settled according to the degree of fulfilment of the DR service that they are willing to provide to the GSO. At this point, smart meters could be used for many sophisticated applications, such as the implementation of DR initiatives. However, their utilization is limited at present to take remotely the monthly consumption reading for invoicing purposes. Regarding communication issues, it would be necessary to promote the interoperability between different types of smart meters and central acquisition systems able to remotely receive and transmit information registered by the smart meter.

Smart meters are being massively installed in some European countries to facilitate the data registration for billing purposes [39]. However, the potential of these devices is much higher as they can be used for enabling consumers to provide DR services by using the flexibility they may have.

6. Conclusions

In this article, a new methodology for the systematic design and evaluation of DR products to be used in the natural gas sector has been implemented. This methodology is one of the most significant contributions of this article, where the potential provision of operation services to the GSO is enhanced and evidenced.

The demonstrated value of the demand side participation in the power market permits expecting similar results if DR initiatives were implemented in the natural gas sector, whose development has taken place in parallel to the electricity market.

Both electricity and natural gas are the most significant energy vectors in the world. However, the participation of consumers for operation purposes has been traditionally left aside in the gas system. This methodology provides a systematic procedure for the design, evaluation and validation of DR products that can be used by the GSO in the daily operation of the grid, taking advantage of the flexibility of customers and reducing the operational costs of the whole natural gas network.

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