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Chapter

Demand Response Applications for the Operation of Smart Natural Gas Systems

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Abstract

This chapter discusses different aspects related to the operation of natural gas systems in the framework of the new configuration of energy systems based on the smart grid concept. First of all, different experiences performed worldwide regarding the application of demand response principles to increase the efficiency and operability of natural gas networks are presented. Next, the characteristics of the natural gas system to be configured according to the smart grid architecture are discussed, including the necessary agents for the proper functioning of such infrastructure. After that, the current state of installation of gas smart meters in some European countries is presented, according to the massive rollout process promoted by the European Union. Barriers that prevent the full exploitation of demand response resources related to natural gas systems are presented in the next section. After that, technical constraints which may be solved by using demand response are presented. Finally, last tendencies related to the development of natural gas systems, such as the injection of hydrogen, are considered.

Keywords: demand response, smart grid, smart city, energy management, natural gas infrastructure, consumer's flexibility, optimization, energy consumption, renewable energy

1. Introduction

The concepts of Smart Grid and Smart City have rapidly expanded worldwide with the objective to raise sustainability standards, quality of life, and economic dynamism of future cities. At present, cities are responsible for more than 75% of waste, 70% of greenhouse gas emissions, and 75% of energy consumption [1]. This trend is going to be more and more significant due to the increase in population of urban areas. By 2045, according to the World Bank[1], the number of people living in cities will increase by 1.5 times to 6 billion. This fact emphasizes the importance of increasing sustainability, reducing waste energy, and 'smart' management of the available resources. In this context, natural gas systems, similarly to the rest of energy systems, are evolving towards a highly technified structure, where the consumer is called to play a starring role. The implementation of a natural gas smart infrastructure requires the proper development of smart metering and communication protocols to be able to give real-time and remote consumption readings and provide advanced services to the users.

1 http://www.worldbank.org/en/topic/urbandevelopment.

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The implementation of this smart architecture is ongoing in some European countries and abroad as will be discussed in the following sections.

Demand response programs are the best candidates to promote the consumers' flexibility, empowering the smart natural gas infrastructure to be a resilient and feasible energy network. Future trends in the development of natural gas systems will be focused on, exploring the huge potential that remains unexplored on the natural gas demand side, which could be used by gas network operators for the solution of technical constraints, balance services, or optimization of programming of underground storage. This potential is especially interesting at this moment, when the massive rollout of gas smart meters is taking place [2, 3]. In this context, smart gas systems would facilitate the use of demand response resources for the better operation of gas networks, similarly to how it happens in power systems.

The chapter will be organized as follows: at first, the state of the art of the massive rollout of smart meters currently ongoing worldwide will be presented. Then, demand response programs currently used in natural gas systems around the world will be explored and analyzed, including a review of some international experiences on this matter. Before, the novel application of smart grid concepts, exclusively used up to now for power systems, will be proposed for the architecture of the smart natural gas system, including the analysis of existing barriers that prevent the implementation of demand response programs in this kind of networks. Finally, the future developments required to optimize the use of this energy resource and to improve the operation of natural gas systems will be presented, identifying new agents and new energy resources (such as hydrogen) that are expected to contribute to developing the natural gas systems in the coming years.

2. State of art of the smart metering infrastructure

The implementation of a smart city requires the proper development of a smart metering infrastructure, a system for the intelligent measurement of the energy consumption of each user, through smart meters able to give real-time and remote consumption readings of different services (electricity, water, gas, and district heating), providing advanced services to the users[2].

In order to reach the proper integration of different energy supplies, such as electricity, gas, water, district heating and energy produced by waste[3], and service systems such as the internet, video terminal, and e-cars, it is necessary to promote the use of different electronic meters (e.g. electric, water, heating, and gas meters) and different sensors integrated into a distributed architecture, able to gather and analyses heterogeneous data. So as to achieve this objective, the following subsystems should be implemented:

- Smart Grids: Intelligent interconnected networks, which have a bidirectional data flow between the service center and the end user.
- Smart Buildings: Commercial and residential buildings that respect the environment and have integrated energy production systems.
- Smart Sensors: Sensors with the function of collecting data from the necessary variables at the smart city. They are fundamental to managing energy and avoiding waste.

2 https://www.endesaeduca.com/Endesa_educa/recursos-interactivos/smart-city.

3 http://www.autorita.energia.it/it/com_stampa/14/140908cs.htm.

- Information and Communication Technology Infrastructure (ICT): ICT infrastructure must be able to control the different subsystems of the smart city, through which citizens and administrative operators can actively participate in the management of the different facilities and uses [4].

- Smart Citizens: They have to actively participate in smart solutions and smart programs. From the energy perspective, it is the energy consumer.

2.1 Pilots and cases of application

Smart city pilot projects have largely spread out in Europe (Spain, Germany, France, Finland, or Italy). In 2010, the Association "Genova Smart City" drew up a project to turn the capital city of Liguria into a smart city, meeting the requirements of the European Commission [5]. In 2015, into the framework of "Flexemeter project[4]—Flexible smart metering for multiple energy vectors with active prosumers", two pilot applications have been performed in Turin (Italy) and Malmo (Sweden). Both projects involved the local DSOs and volunteer "prosumers[5]" on real systems and were predominantly focused on the integration of the electricity and heating district supply. By 2030, supported by the European Commission, Geneva (Switzerland) will become a smart city for the electric, heating, and cooling networks, with the integration of renewable energies (wind turbines).

The diffusion of flexible multi-utilities and multiservice system is the crucial step to improve energy and market efficiency, to optimize the energy management during the peak periods, and to promote the integration of DR programs profiled on more efficient energy demand prediction [6]. In that framework, a fundamental role is played by the smart meters. At present, a smart metering infrastructure able to collect, aggregate, and analyze real-time data is essential to properly manage the different energy resources and to reduce greenhouse emissions as required by the COP21 [1].

The European Smart Metering Landscape report [7] has presented the best practices in the smart metering field. Different smart metering pilot projects have been successfully carried out in Europe: in Finland, the smart metering project was based on the monitoring of the cottage's electricity consumption in real time and its impact on the carbon footprint. Another example was carried out in Spain, where consumers equipped with smart meters received specific information to allow an evaluation on how to reduce their average electrical consumption. In Germany, a German start-up company created a Social Metering App that allows users to view and share smart metering data in terms of carbon emissions, kWh, or monetary costs for all energy carriers (electricity, gas, and oil), and water meters.

Under the Third Energy Package[6], Member States are required to ensure the implementation of smart metering for electricity, gas, water, and heating. In this framework, long-term cost benefits analysis (CBA) has been carried out so as to decide the implementation of a smart metering infrastructure [8].

In contrast with the Electricity Directive, which required that 80% of consumers should have smart electricity meters by 2020, the Gas Directive does not specify how many consumers should have smart meters or provide a deadline for deployments following a positive CBA. The following section will show the current situation of the rollout of smart meter gas in Europe.

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4 http://flexmeter.polito.it/index.php/project.

5 Prosumer is a neologism applied to consumers which also are able to produce electricity that can be delivered to the grid.

6 http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0072&from=en.

3. Architecture of the smart natural gas system

The main purpose of the gas system is to supply gas to consumers with the required safety and quality characteristics at a reasonable cost. In order to fulfill this target in a cost-effective manner, different agents are necessary; each of them will be assigned some specific role.

The gas transmission network is the physical medium through which consumers can obtain the amount of gas they need. Depending on the type of network (characterized, among other parameters, by the pressure level and its capacity), there are transmission and distribution networks. Distribution networks are structures connected to the transmission network and carry the gas to the final consumers. The owners of the network, which are in charge of maintenance and development of those infrastructures, will therefore be transmitters and distributors.

Distribution (low and medium pressure network) is the final link of the chain in delivering natural gas to customers. While some large industrial or commercial customers, as well as power generators fueled by gas, receive natural gas directly from high-capacity interstate and intrastate pipelines, most users receive natural gas from their local gas utility, also called local distribution company (LDC).

Unlike other energy sources, the gas can be stored in large amounts at different points of the grid. The network operator, whose mission is to ensure that the gas system remains balanced and stable so that energy transactions can be performed safely and reliably, can use these gas stores.

Depending on the type of network they manage, these operators may be transmission or distribution operators. The operation of the network is an activity that could be developed by agents different from the owners of the infrastructures, so that these operators would be different from the transmitters and distributors previously defined.

Other agents that should be established according to size and characteristics of the gas system, as well as the configurations that the network can adopt, are the aggregators, whose mission is grouping small distributed demand resources into larger packages that can provide significant value to the system as a whole.

Finally, the figure of the gas retailer appears as an intermediary of the retail market between the final consumers (small amounts of energy) and the mechanisms of the wholesale market and gas production (large amounts of energy). The different agents and the activities they would carry out within the new framework that smart grids offer to the natural gas market are further discussed subsequently.

3.1 Agents in a smart natural gas system

When the natural gas system is structured according to a smart grid architecture, the need for specific agents arises to make the whole network work properly. The different agents that would be involved in the proper performance of a smart natural gas system, including the provision or utilization of DR resources were identified in the research of Montuori et al. [2] and they could be summarized as follows:

- End users, who consume natural gas and pay the supplier the price requested. Moreover, end users in smart natural gas systems may provide the grid operator with demand response services.

- Producers, who explore, investigate, and exploit the gas deposits.

- Gas storage managers, who handle storage facilities to adapt the gas supply according to the end users' needs and the availability of resources in real time.

- Aggregators, who group small end users so as to create significant blocks of flexible demand that can be used by grid operators, as well as any other stakeholder needing demand response resources.

- Transmitters, who manage the gas network infrastructure at high pressure.

- Distributors, who, similarly to transmitters, manage the gas network to supply end users.

- Retailers, who behave as buyers in the wholesale market and sellers in retail markets to supply the natural gas to end users.

- Wholesale energy traders, who buy natural gas in international markets and incorporate it into the system, reselling it to retailers or to large end users, as well as to transmitters or distributors for operation purposes.

- Transmission System Operator (GSO), who operates the transmission gas network and guarantees the supply according to security standards and regulations in force.

- Distribution network operator, who operates a regional distribution network.

Market operator, who manages the necessary mechanism to exchange natural gas between the parties in the wholesale market (**Figure 1**).

The aforementioned activities refer to roles but not entities. Therefore, it is possible that some agent (for example, a distribution company) plays more than one role (distributor and distribution network operator).

3.2 New agents: aggregators

The role of the aggregator in smart natural gas system has been discussed in detail in previous research of Montuori et al. [2, 9]. This agent aggregates small and middle gas consumers, behaving as DR providers, and the stakeholders interested in using those services (such as transmission system operators, distribution network operators, retailers, etc.), who behave as DR requesters.

Aggregation in smart natural gas systems could be understood in two different ways:

- Traditional aggregation, which would be based on the joint management of gas consumptions of end users that actually use natural gas directly (similarly to what this agent does in power systems). This is the case of consumers using gas in a boiler or a burning system for heating purposes.

- District heating operators. This is a real novel approach, further detailed in [9], that considers the aggregation not of direct gas consumption, but of thermal energy that is produced in a centralized way by consuming natural gas. Therefore, the district heating operator, that is the actual gas consumer, may offer some kind of flexibility by managing the aggregated thermal consumption of the steam or hot water consumers within its portfolio.

One essential requirement for aggregators is to have appropriate monitoring and control equipment so as to offer reliable operation services to some particular stakeholders. Therefore, the massive rollout that is taking place in some countries, as mentioned earlier, will have a positive impact on this point since it will help to further develop the role of the aggregator in smart natural gas systems (**Figure 2**).

One of the main advantages of aggregation would be related to the balancing of natural gas, which would avoid the need for the transmission system operator to purchase natural gas in the wholesale market during high prices periods. In this case, aggregators may offer the same service by increasing or reducing the amount of gas of their consumers. Moreover, this aggregated service would make the system behave more efficiently since the activation of a demand response service when more gas is required is translated into a reduction of the gas level in the network, which also reduces the risk of congestion. Additionally, demand response reduces the greenhouse emissions when the amount of gas is reduced but not shifted to other periods.

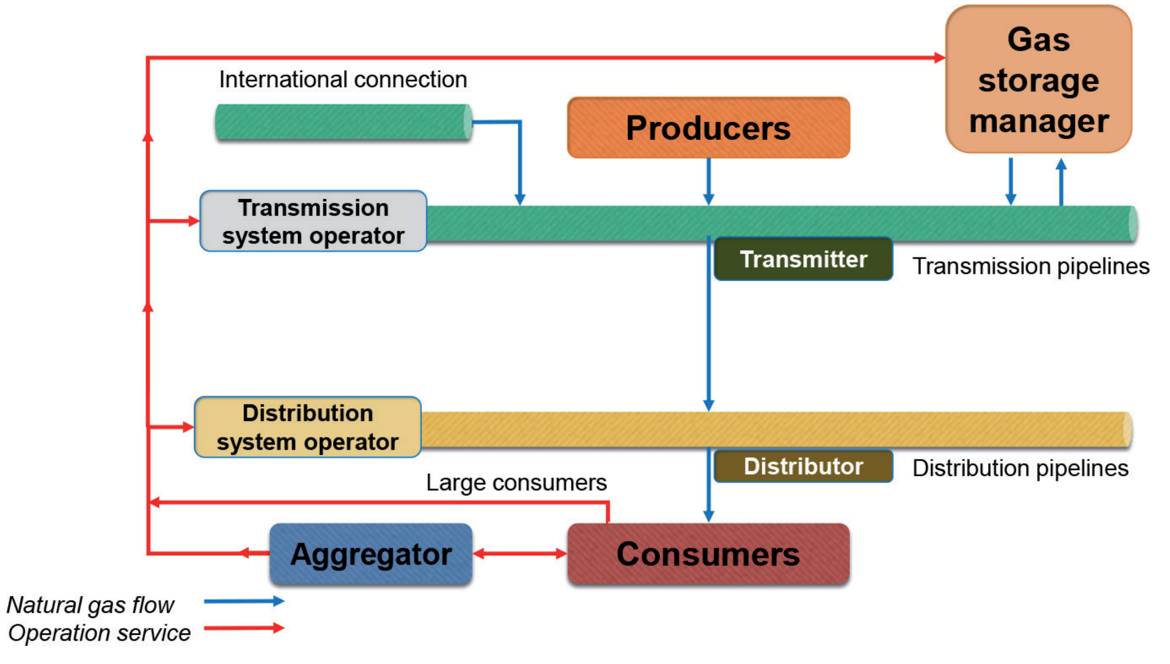

Figure 1.
Roles to be played in a smart natural gas system [2].

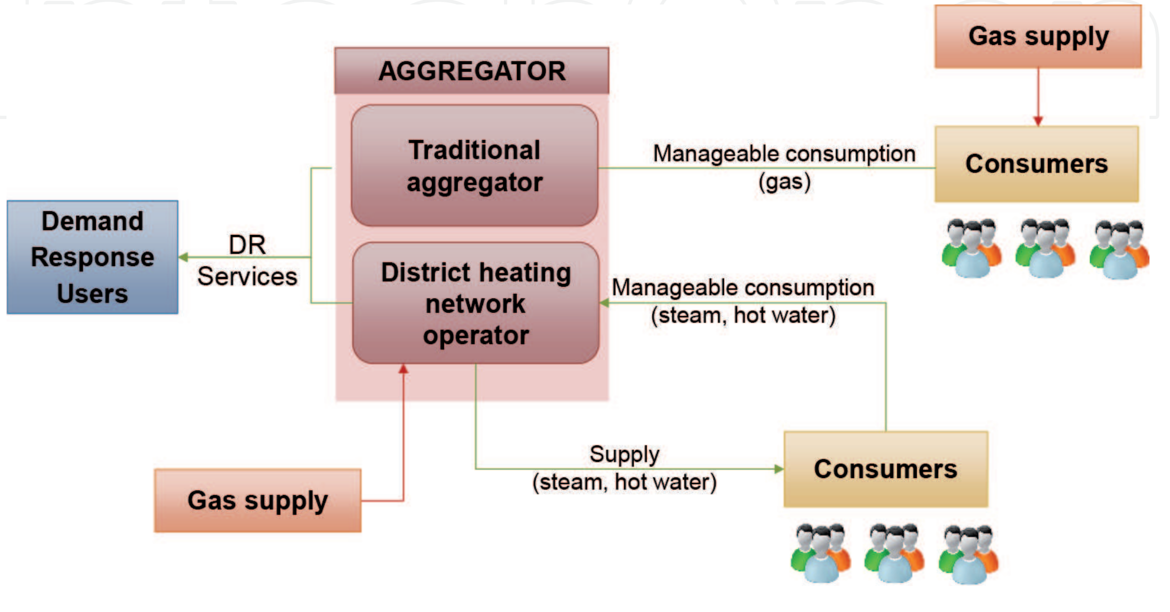

Figure 2.
Activities of the aggregator.

4. Massive rollout of smart gas meters in Europe

In recent years, the European Union has played a leading role in promoting the reduction of greenhouse gas emissions in line with the ambitious new targets that fix the GHG reduction emissions levels below at least 55% by 2030. In accordance with this de-carbonization process, deep changes are required to meet these standards and a new settlement of the gas retail market needs to be held.

In order to enforce the transition to a more efficient organization for the gas system, the introduction of gas smart meters and smart metering network concepts have to be promoted as it has been already done in the electrical sector. To support these innovative changes, a new concept of consumer like a more aware and active participant in the marketplace needs to be promoted [10]. Similarly, the role of aggregators also needs to be empowered as an intermediary between small customers and network operators willing to use customers' services (DR resources) so as to manage their infrastructures more efficiently. With regard to the metering instruments and in prospective to the development of multiservice smart cities, the European Directive MID 2014/32/UE defines the functionality of measuring instruments for the promotion of efficient consumer behavior and for their active participation in the energy market. In spite of that, the Directives on the Internal Market for Electricity and Gas (Directives 2009/72/EC and 2009/73/EC) included in the Third Energy Package does not oblige European countries to participate in the rollout of the smart meter gas and does not state a deadline to complete it either. This lack of a mandatory regulation on this matter derives into different behaviors in each European country.

Similarly, to that previously done in the electrical sector, European countries have carried out a CBA for participation in the smart meter gas rollout [11].

As shown in **Figure 3**, the results were dissimilar and a slower approach to the smart meters gas introduction was registered:

- In 2017, just five member states (Ireland, Italy, Netherlands, Luxembourg, and the United Kingdom) decided to introduce smart meters by 2020.

- In 2019, also France, Austria, Hungary, and Denmark set up a strategy for the massive smart gas meters rollout implementation.

In 2013, 19 European countries conducted a CBA with 12 countries showing negative CBA results (Germany, Spain, Portugal, Romania, Finland, Sweden, Poland, Czech Rep, Belgium, Greece, and Latvia). In 2018, eight Member States carried out a new CBA, obtaining coherent results with the previous one except for Austria and Ireland, where the first CBA was positive and this new one had a slightly negative result. Seven Member States did not conduct any CBA (Bulgaria, Croatia, Estonia, Greece, Hungary, Poland, and Portugal). Finally, states without natural gas networks have not been considered (Cyprus and Malta).

The latest conducted analysis among the State Members EU-28 has recognized different factors that push a country to install a gas smart meter. On one side, the two main driving factors are the digitalization of the distribution network and the optimization of the grid operation, together with the digitalization of the retail market that enables new services for private players [12]. Moreover, smart metering helps to reduce operating costs through savings in manual meter readings, theft protection, process improvement, better scheduling, and balancing processes, as well as consumer engagement opportunities. However, the participation in the massive rollout and the results of the CBA are also influenced by other factors, such as density of gas customers, gas customer expenditure, and competitiveness

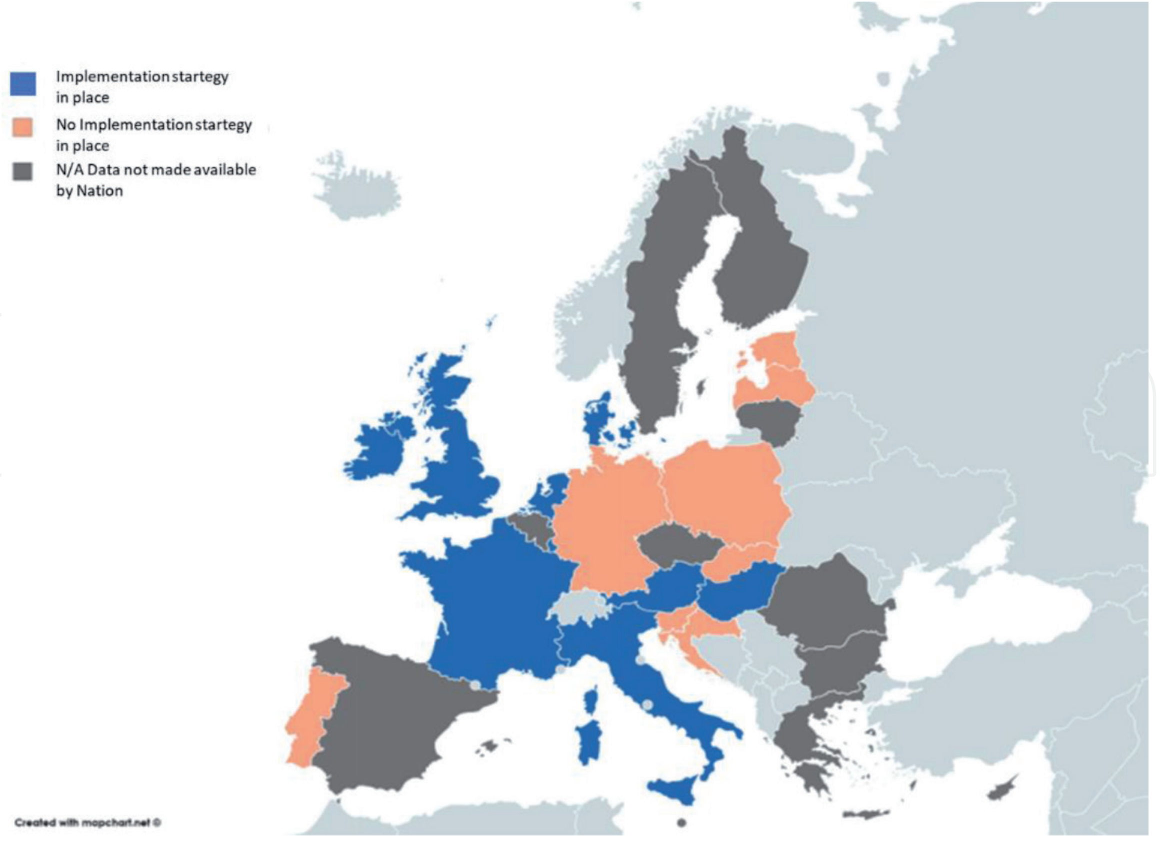

Figure 3.
Gas smart metering rollout in Europe (source: [12]).

of supply market and need for consumer engagement, meter location, and meter ownership [11]. Currently, countries with a high density of gas customers and a significant share of gas bills such as the UK and Italy were more favorable to the smart metering rollout. Additional benefits of taking part in the rollout of gas smart meters could be derived from the higher transparency and awareness about the gas consumption and from the reduction of GHG emissions improving energy efficiency. These social benefits, together with the introduction of DR programs, should be driving factors to enlarge the number of EU countries enrolled in this program.

Germany is the largest gas consumer country in the EU. However, it does not accept the mandatory rollout due to unclear costs-benefit ratio of the smart metering gas implementation, according to the report of Wissne and Stronzik [13]. In addition, the saving costs derived from theft protection were not as high in Germany as in the other countries, as this is not a frequent problem in that country. Similarly, Sweden rejected the participation in the rollout because the low number of gas consumers (around 40.000) made it not attractive, as highlighted by Brodin et al. [14]. On the other side, Spain has a much higher amount of gas customers (over 7 million) but, despite that, the CBA had negative results. The most significant results obtained in the countries which have adopted the rollout are described in the following sections.

4.1 Italy

The Italian CBA showed a positive net benefit, coming from the reduction of the operation costs mainly due to two reasons: the lower cost of metering compared to the manual reading and the reduction of energy theft. The CBA does not consider the installation of In-Home Display (IHD) as underlined Poletti et al. [15].

According to the Plan of the Authority for the Electric, Gas and Water, the mass market rollout started in Italy in 2013. The gas smart meter deployment target adopted was more ambitious than those set by other European countries pretending to end the mass-market stage of the rollout by the end of 2018. Conversely, the installation of electronic meters is still ongoing due to several disruptions (lack of funding and infrastructure) even if it shows a considerable growth, according to Bianchini et al. [16]. The new target period to complete the wide-scale rollout has been extended up to 2023 with the installation of 85% smart gas meters.

During 2020, almost three-quarters of domestic customers, 85% of condominiums, 75% of public service activities, and two-thirds of customers with other uses (**Figure 4**) were installed. By the end of 2020, the total number of gas smart meters installed was 23,854 thousand while the number of remaining traditional smart meters was 7432 thousand (comprising class from G4 up to G40) [17].

4.2 Luxembourg

Luxembourg is one of the EU countries, which had two positive CBAs, the first in 2013 and the second in 2018. At the first instance, the government chose to start a mandatory rollout with the introduction of gas smart meters and electrical smart meters by 2020 for at least 95% coverage. Now, the end of the massive rollout is expected by the end of 2021, reaching 90% of the total. The smart metering rollout started in 2015, and it included the development of an energy grid for the integration not just of electricity and natural gas consumptions but also distributed energy resources such as solar, wind, biogas, and heat pumps [7].

4.3 Ireland

In 2013, the CBA had in Ireland the strongest positive result, especially for the fast rollout scenario with the combination of energy statement with In-Home display (IHD) and variable tariff. Regarding the additional benefits from reduced emissions of greenhouse gases, all the considered scenarios were positive. However, in 2018 the trend changed and the CBA was reviewed with a slightly negative result that was considered neutral by the European Commission. The new deadline for the large-scale rollout has been set up in 2024 [12].

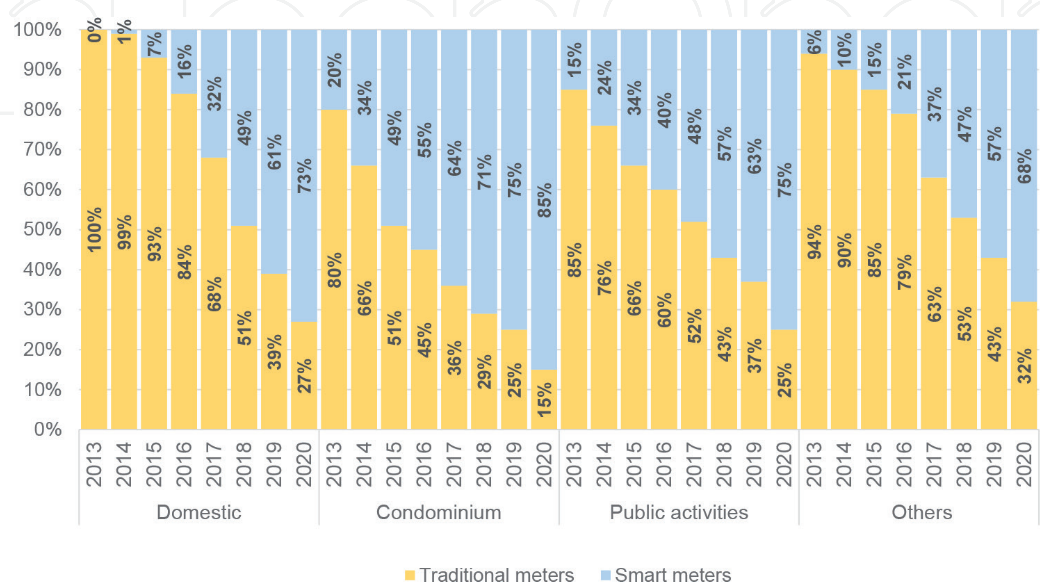

Figure 4.
Percentage of smart meter gas installed in Italy 2013-2020 (Source: [17]).

The company Gas Networks Ireland[7] (GNI) currently supports the National Smart Metering program, which is focused on both gas and electricity metering devices. The program includes the use of smart metering technology, variable time of use, and in-home displays according to the CBA results. A share communication infrastructure has been implemented for gas meters and electricity meters in order to leverage the costs. In future, the same infrastructure could be used also for water smart meters.

4.4 Netherlands

In 2009, due to privacy concerns, the mandatory rollout was not accepted by the Dutch Senate, so a voluntary rollout of 7 million consumers started. During 2012, the installation of smart meters was performed on a small scale and the company Oxxio (former Eneco Energie) provided over 200,000 smart meters using GPRS as the communication technology [18]. Considering that almost 100% of the households accepted the smart meter (with almost 100% standard readings), it would be expected a benefit of approximately 770 million euros, which is equivalent to 50 € per metering point according to the positive results of the CBA discussed by Bouw et al. [19]. In 2014, the Netherlands decided to implement a strategy for the smart meter gas rollout. In 2015, the rollout of smart meters in the Netherlands reached approximately 1.5 million domestic small meters installed. The target of the Dutch grid operator is to have at least 80% of all Dutch households connected to the network by a smart meter by the end of 2021.

4.5 United Kingdom

The CBA carried on by the UK Department of Energy and Climate Change in 2014 on the smart meters rollout was positive, with an estimation of net benefits equal to £6.2 billion (equivalent to 7.2 billion of euro) [20]. The UK's rollout is the largest project in the gas market, and it involves 30 million customers with a gas consumption equal to 50% of the household energy costs, as investigated by Segalotto [21]. Households can freely choose, if applying or not, for a smart meter of new generation, for the gas and electricity with an in-home display screen that shows in real time the exact amount of the energy consumption[8].

At the end of 2013, there were 295,700 smart meters already installed in domestic properties in the country. However, the British government started officially a smart meter rollout in 2016.

The home area network (HAN) implemented in the UK for the smart meters' remote reading uses a ZigBee Energy network. ZigBee Smart Energy is the network solution for electric meters, gas meters, and in-home displays, due to its maturity and popularity in Smart Energy application profile and its capability of ensuring robust communications architecture of a smart natural gas system [22]. At the end of 2020, there were 98,600 smart meters installed in non-domestic sites and, in spite of the delay due to the COVID-19 pandemic breakdown, smart meters installation showed the highest peak of the rollout (**Figure 5**).

On the other side, the installation in the domestic sites continued increasing in 2020 and reached a total of 3.1 million smart meters installed, as shown in **Figure 6** [23].

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[7] http://www.gasnetworks.ie/en-IE/About-Us/Our-commitment/Marketplace/Smart-meters.

[8] https://www.smartenergygb.org/en/about-smart-meters/what-is-a-smart-meter.

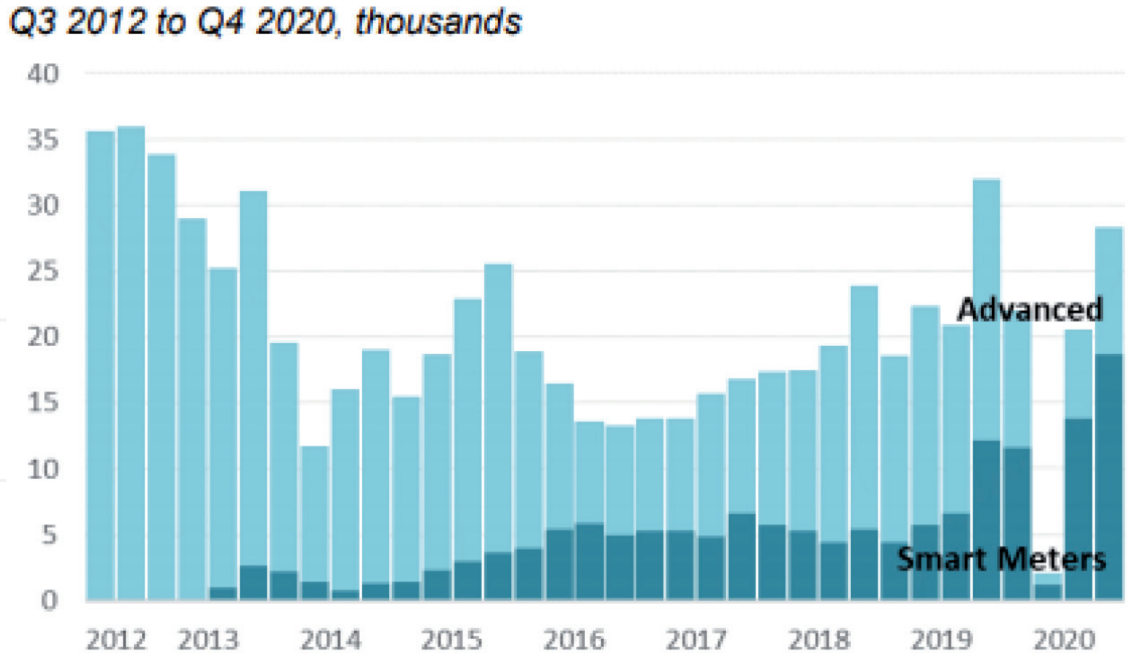

Figure 5.
Non-domestic smart meter gas installed in Great Britain from 3rd quarter 2012 to 4th quarter 2020 (source: [23]).

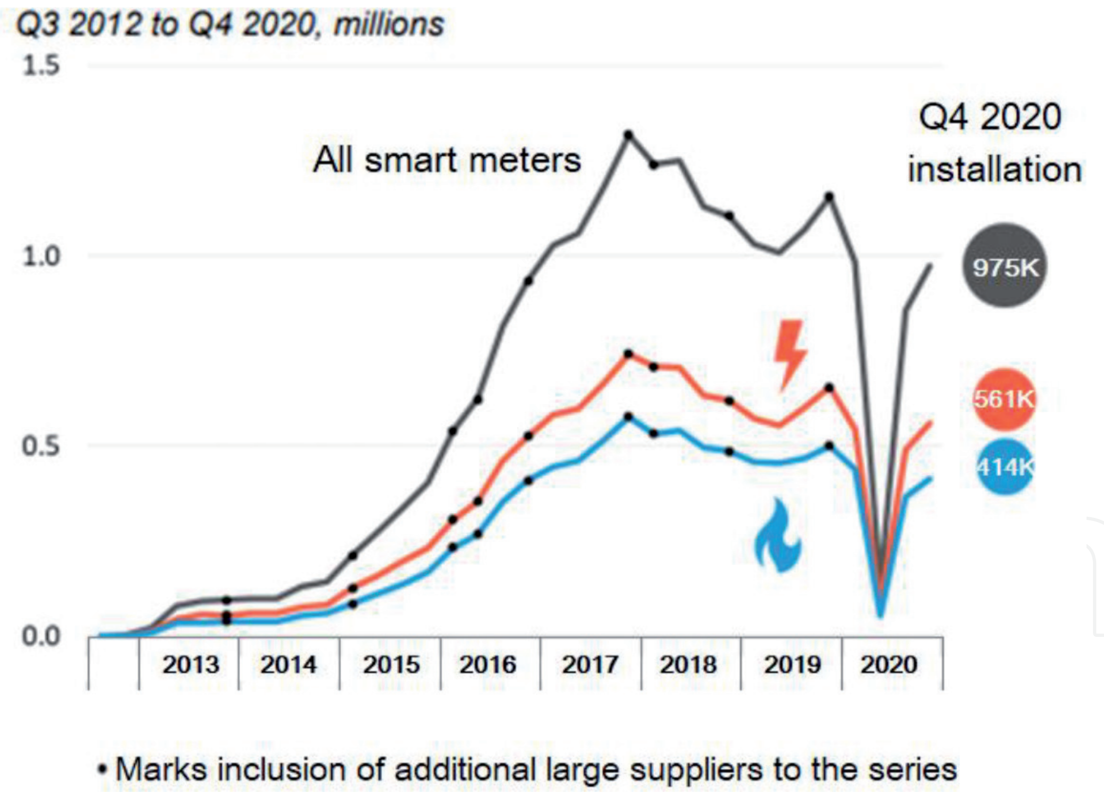

Figure 6.
Domestic smart meter gas installed in Britain from 3rd quarter 2012 to 4th quarter 2020 (source: [23]).

4.6 France

In France, Electricité Réseau Distribution France (ERDF) carried out an initial gas smart meter pilot project in 2011. From the start of 2010, the pilot project was carried out for 18 months in four regions (Auch, Saint-Omer, Laval and Pierre Bénite, and Etampes) with the installation of 18,500 meters. The obtained results support the idea that the smart meter is essential to achieve efficiency and reliable operation of the natural gas system. The utilization of smart meters made consumers aware of their consumption which, together with the use of demand response, resulted in savings of 0.9% in the gas consumption as gathered by Drozdowski and Vandamme [24].

In 2017, the French gas company GRDF started a huge smart gas meter rollout that should drive the replacement of 11 million traditional gas meters with an investment of 1 billion euros. To achieve this goal, the French gas infrastructure started an upgrade of the existing technological infrastructure to be able to meet the highest communication system standards. The full rollout of 11 million meters is expected to be complete by the end of 2022 [25]. Nowadays, the French rollout is ongoing according to the agreed planning. Six million meters had been already installed at the end of 2020, with an average value of 150,000 meters per month.

5. Demand response experiences in natural gas systems

DR concepts have been used for years (with different levels of development depending on countries) in the management of power systems [26]. Thus, DR programs, either offered by system operators or utilities, contribute to solving different matters that appear in the habitual operation of the power grid. Nevertheless, and in spite of the similarities existing between the power and natural gas systems, there are few successful experiences of DR applications in the natural gas system. However, as agreed by some researchers and professionals, DR concepts could be essential for the better and more efficient operation of natural gas systems, as can be deduced, among others, from the following factors highlighted by Srinivaspura [27]:

- Electricity and natural gas markets are closely related as this resource is more and more 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)

- The massive utilization of renewable energies, which makes necessary generation technologies able to quickly respond 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 the recent past, natural gas demand used to be quite stable and seasonal; however, this tendency is changing nowadays [29].

- Natural gas is replacing other fuels in hydrocarbon markets [28].

Until now, DR concepts have been applied worldwide as predominantly pilot projects, but results achieved have been promising [29]. In Canada, residential end-users have been asked to participate in DR programs based on the gas management through the regulation of the thermostat for heating applications. The energy savings estimated were influenced by the thermal oscillation (external Temperature) and the warmness of the season and could reach up to 21% [30].

Enernoc, the most active company 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 [31].

Regarding Europe, Spain was a pioneer in the approval of an interruptible program in 2006[9], based on the need of establishing tools and mechanisms so as 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 do 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 which may produce the lack of gas in the portfolio of such traders.

- 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 completely interrupt their consumption with a notification in advance of 24 h. The duration of the interruption may vary from 6 h up to 10 days. However, as mentioned earlier, 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 the distribution level and less developed than in Spain. Just a small group of large industrial consumers can participate, depending upon the commercial arrangements they have agreed to[10]. Interruptible customers receive discounted transportation charges when reducing their consumption in periods of high demand (especially in winter peaks). In 2010, just 27 customers participated in interruptible gas contracts in the UK [32].

In the Netherlands, a consortium of 11 entities called Energy Delta Gas Research (EDGaR)[11] 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 at the moment 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, as indicated in the research of Huitema et al. [33].

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

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

11 More information about this consortium is available at: http://www.edgar-program.com [Accessed: April 18, 2017].

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 the pilot phase at present or, in the best case, only large industrial customers are enabled to participate.

6. Constraints in the natural gas system

The present section has the aim to describe the technical constraints that may affect the natural gas system, highlighting the potential of demand response so as to overcome these limits and promote the development of a reliable natural gas system, able to quickly face sudden network failures.

Generally speaking, the physical/technical constraints of a gas network system are set by one or more of the following parameters:

- The capacity of the pipelines, which limits the quantity of gas that can be transmitted between two points.
- The pressure of the gas supply. Actually, a different reliability issue can derive from the natural gas operation. The gas network is characterized by variable flow for each arc, which determines a variable pressure at every node [34].
- The extension and meshing complexity of the network—areas not served by the pipelines cannot be supplied by gas.

Regarding the commercial constraints, they may be set by the following:

- Energy regulations. The energy regulations should be addressed to implement the efficiency of the gas network by providing incentives.
- Political stability. Sometimes, the presence of a large gas storage site or gas availability in countries defined as politically unstable could affect the trend of the natural gas market.
- Geographical position of a country. The geographical position of a country may facilitate more or less the connections with large gas reserves or with strategic gas transit hubs.
- Availability of other energy resources for thermal production. The presence of other energy resources guarantees energy independence from the natural gas network failure

Interruptions of gas supply that could occur in the gas system determine a non-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. For example, the Italian regulation defines an interruption as short when the duration is less than or equal to 120 min. However, interruptions are considered as long when exceeding such standard duration.

According to its nature, interruptions could be also classified as follows:

- Scheduled interruptions (also called interruptions with notice), which take place due to scheduled operations of maintenance of the system (transmission and distribution). Usually, operators notify the customers at least 24 h before a planned interruption occurs, specifying the date, time, and duration for the scheduled activities. Generally, among the activities considered as scheduled interruptions, the more relevant are the following:

- Ordinary/planned system maintenance, scheduled by the network operator (replacements of working parts of valves, of piping, etc.)
- Extraordinary maintenance, scheduled by the network operator (the rollout of the meters replacing)
- Extraordinary maintenance, requested by the customers (request for a metrological test, leakage test, etc.)
- Unscheduled interruptions (or without notice), which are unexpected events that occur on the gas system network and cannot be forecasted by the network operators. Among the reasons, those which can motivate an interruption without notice can be considered:
- Congestion of the pipelines in specific nodes of the network, defined as the impossibility of the system to meet the energy needs of end users. It could be of two types:
- Commercial congestion, due to the not commercial availability of the gas on the wholesale market
- Technical congestion, due to the non-physical presence of sufficient quantity of gas to meet the energy needs
- Extraordinary maintenance operations because one of the following events occurs:
- Detection of gas leakage from any part of the supply system (meters, pipelines, compression cabin, valves, etc.)
- Presence of water in the gas pipelines or in the meters
- Tampering of the network system (vandalism act, close of the meter valve, damage)
- Blocking of the pressure regulator in the compression cabin
- Pressure level out of the range of the proper operation of the system
- Political issue that determines unpredictable events such as acts of public authorities or such as the gas crisis of 2014 because of the political instability in the relationship with Russia.
- Natural catastrophe, unusual natural events for which has been declared a state of emergency by the competent authority, such as the heart quake in the center of Italy, which happened in the summer of 2016, which determined the damage of several pipelines and compression cabins.
- Strikes or rejection of the authorization documents by the competent authority (not taken into account in this book chapter)

- A gas accident, defined as an event involving any apparatus of the gas network that determines serious injuries or deaths of people, or damage to people's goods not lower than an economic value established by the law. For example, in Italy, this economic value is 1000 euros (Article 28, paragraph 28.1). The causes of a gas accident could be multiple, such as gas leakage (voluntary or not); an uncontrolled combustion caused by insufficient ventilation, etc.

- An emergency, defined as an event that can put into risk the safety and the continuity of supply in large proportions of the distribution/transmission network. An emergency can be caused by:

- Unplanned unavailability of service at delivery points or interconnection points.

- Unplanned out of service at the high, medium, or low-pressure networks that result in the interruption of the gas distribution without notice to one or more end users.

- Gas leakage on the pipelines.

- Damage caused by excess or defect of pressure in the network compared to the values provided by the current technical standards.

Depending on country-specific regulation, an emergency could be defined in different ways. For example, in Italy, and according to Article 27, paragraph 27.1, an emergency is considered an event that causes the interruption of the gas distribution without notice to at least a number of 250 end users and for the duration of 24 hours.

6.1 Gas network constraints in the United States of America

In the United States, the wide network of interstate and intrastate pipelines that runs throughout the country has several open issues to solve in order to strengthen the stability and reliability of the American gas network:

Implementation of existing pipelines and infrastructure. In spite of the growth in consumption, the US transmission infrastructure does not properly cover all the country and large areas suffer the lack of sufficient pipelines with the adequate capacity for gas delivery, such as the Northwest and New England [35]. In order to face this constraint, new upcoming projects are expected to increase the number and capacity of the existing pipelines in order to transmit natural gas from production centers to consuming markets or exports terminals. Recent projects intended to increase the reach of natural gas produced in the Marcellus and Utica regions of the Northeastern United States (see **Figure** 7). New infrastructures are expected to be built from the Appalachia production between 2015 and 2025.

Implementation of new pipelines and processing infrastructure. Forecast of energy needs beyond 2025 expects a significant impact of the growth in demand for gas-fired power generation on the existing pipeline system. In particular, to face the growth in electric demand, additional pipelines are needed in order to ensure the system's reliability. The gas demand for power generation will increase by 73% between 2014 and 2025, in comparison to the 39% increase between 2005 and 2014. New pipelines and processing infrastructure are required to face this growing demand and to connect the end user to new supply source [37].

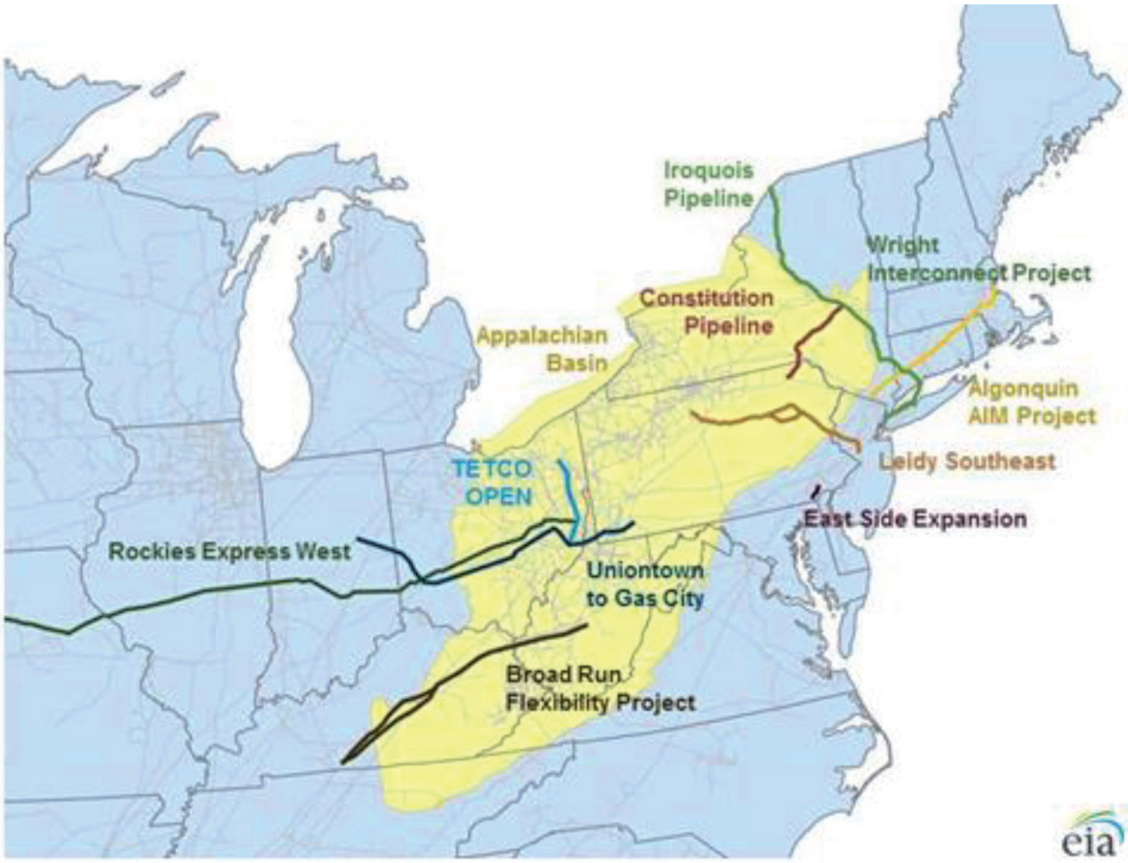

Figure 7.
Implementation of new pipelines in USA (source: [36]).

- Reduction of natural gas losses. Local distribution companies (LDCs) have been pursuing the replacement of leak-prone pipes in order to reduce natural gas losses from infrastructure systems, contributing to the increase in safety of the transmission system. Now, the mileage of cast iron distribution pipes has been reduced just for 25% between 2005 and 2014 [38].

- Increment in state incentives. New capital expenditures have to be provided by State legislators for building new pipelines and expanding or repurposing existing ones. Such investments should be applied also to other infrastructures, such as compressor and pumping stations [39]. In spite of the growing awareness of the stakeholders about the potential environmental benefits of reducing natural gas losses, many reforms are required on the natural gas infrastructure.

- Introduction of DR programs. The introduction of new DR programs for the management of the consumption could help to face the temporary lack of sufficient pipelines with the adequate capacity for the NG delivery (such as Northwest and New England). Indeed, putting in evidence the advantage of this kind of strategies is one of the main objectives of this book chapter.

6.2 Gas network constraints in Europe

Past gas supply disruptions as a result of the political turbulence between Russia and Ukraine increased EU dependency on gas imports and the risks of the security supply. Therefore, a reliable and interconnected system able to face the EU domestic

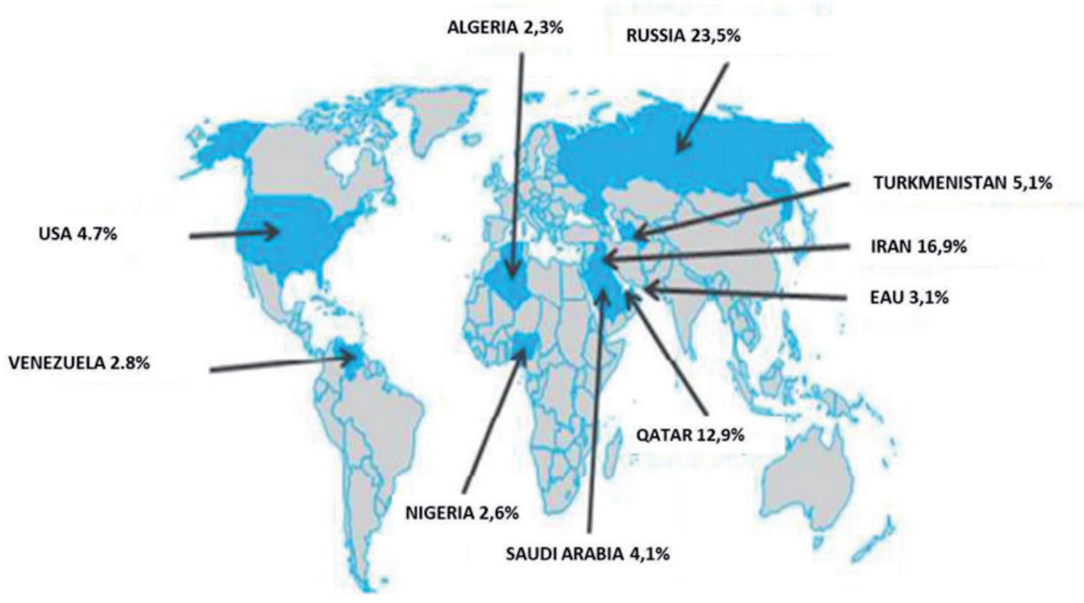

Figure 8.
Proven reserves of natural gas worldwide. Top 10 countries (source: [40]).

energy needs should be implemented. Depending on the duration and on the level of the demand, ENTSOG[12] shows that potential disruptions may directly affect the majority of EU Member States, except France, Spain, and Portugal, which may be supplied from the south interconnections. Indirect effects would include increases in the prices of LNG for the entire EU. The resilience of the gas infrastructure needs to get improved, carrying on the following implementations:

- Improvement of the existing pipelines. The increasing dependence on imports needs the improvement of the existing pipelines. The major issue is the limited connections between the Western pipeline and the Eastern infrastructures. In order to facilitate the creation of a reliable and robust gas system throughout Europe, the European Network of Transmission System Operators for Gas (ENTSOG), in cooperation with Gas Infrastructure Europe (GIE) implemented the Gas Infrastructure Map, which provides an overview of the existing gas infrastructures and establishes a reference for information of their trends over time.

- Diversification of supply routes. In order to reduce the dependency of imports from Russia (the owner of the 23% of the total proved reserves of natural worldwide, as shown in **Figure 8**) and unstable transit countries, new pipelines need to be built re-routing the Russian imports (i.e. Nord Stream, Yamal, and Blue Stream).

- Implementation of reverse flow pipelines. Even if establishing a reverse flow is relatively easy since a technical point of view, there are still many restrictions in the main pipelines, which both hinder competition and decrease the security of supply. The potential to operate pipelines in two directions increases the resilience in case of a supply disruption [41].

- Improvement of energy efficiency. It should be considered a potential in the energy-efficient design of the transmission system. These days, 5% of the energy is lost in the transmission grid.

[12] ENTSOG is the European Network of Transmission System Operators for gas. More information ca be found at: http://www.entsog.eu.

- Harmonization of the standards. The diversification and non-integration of the standards adopted by the different countries for technical building and daily operations do not favor the system management across the system borders. A higher degree of standardization is required. Efforts are required so as to regulate the third-party access to the grid (TPA) in free conditions, as well as to improve information requirements to ensure transparency.

- Improvement of the security of supply. After the physical breakdowns of energy transmission networks following the crises with transit countries (Ukraine in 2006 and 2008 and Belarus in 2007), EU has been forced to adopt the strategy of diversifying supply routes which would gradually reduce its dependence on such transit countries. An improvement in the energy network and strict cooperation between states is essential so as to ensure a timely response in case of crises.

- Introduction of DR programs. The implementation of the 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. Some of the most significant benefits of DR programs in the short term in European countries may be:

- Management of sudden supply disruption due to catastrophic events (heart quake) and/or to political issues such as in the case of disruption of all supplies from Russia.

- Management of the seasonal storage. The EU's gas storage, together with increased scope for reverse flows, can play a mitigating role in the event of supply disruption.

- Management of the growing variable trend of natural gas consumption and network congestion. The demand for natural gas has traditionally been characterized by a highly cyclic trend depending on the season and on the climatic changes. Generally speaking, gas demand is expected to be higher in January and February, and lower during the months of July and August. Correspondently, and in order to meet the cyclical demand, the base-load storage capacity is typically withdrawn in winter (to meet increased demand, while storage injection typically takes place in summer (to store excess gas in preparation for the next upcycle). The recent increase in the use of gas for power generation has resulted in an anomalous and variable behavior of the gas demand. Hence, the increasing use of natural gas so as to generate electricity results in a peak of demand during the warmest months, whose magnitude is as pronounced as the peak in electricity consumption for air conditioning and lighting systems.

7. Barriers to the implementation of demand response strategies in the natural gas system

Barriers and handicaps related to the implementation of DR in power systems have been discussed in many studies. One of the most recent examples can be found in Alcázar-Ortega et al. [42], which results from the European project DRIP. Among other results, this project produced a methodology for the systematic evaluation of handicaps, which prevents the implementation of DR strategies in the operation of power systems. Considering this work and based on the similarities previously identified between power and natural gas systems, a preliminary evaluation of barriers can be assessed or referred to the gas side.

One of the main barriers is the difficulty for customer's acceptance: customers are not willing to reduce their consumption. The first reason is that consumers are not aware of the potential they may have, and they do not know that someone could be willing to pay in exchange for such flexibility. Another reason is that, when being aware of this potential, customers perceive that the economic incentives they may receive are not attractive enough. This barrier can be faced by providing customers with evidence about the economic profitability that DR actions may provide to their energy bills. While this is a difficult task, there are some tools for this purpose (some examples are provided by the aforementioned DRIP project), developed in the last years for the electricity markets that may be used for this purpose but applied to the natural gas sector.

Tools are also necessary so as to jump barriers on the side of retailers or system operators, as the potential offered by customers is difficult to forecast, and the benefits that DR may mean for their business are not easy to assess. However, the benefits of DR have been also proved in power systems for these activities, so similar results can be expected in the natural gas sector. Retailers can find in DR resources a help for the optimization of their portfolio and the reduction of imbalances, with significant cost savings. Regarding the gas system operators, the most significant barrier for them is probably the utilization of small and medium flexible consumptions. In fact, the few examples that can be found about the utilization of DR in natural gas systems are just related to very large consumers (as discussed in Section 2.3). Therefore, the empowering of the figure of the aggregator in natural gas systems is essential for the proper integration of DR resources coming from the residential and commercial sectors, as well as medium and small industries. A significant role can be played here by the managers of district heating networks, as they can provide the system operator with flexible customers willing to play not only with their gas supply but also their hot water or steam utilization. The system operator can utilize the potential offered by flexible customers so as to solve technical constraints related to the maximum capacity of pipelines in periods of peak demand. Additionally, the usage of natural gas storage can be optimized, allowing the system operator to combine both storage and DR resources to guarantee the optimum management of the whole system.

The development of the concept of Smart Energy Systems in recent times, which provides a strong metering and communication structure of the natural gas network, is definitively enabling energy grids for the easier utilization of customer's flexibility. However, as indicated in [5], the impact of DR programs, most of which would be similar to those existing for power systems, has to be evaluated and validated. At present, except for the few examples mentioned in this section, there are no real experiences demonstrating this potential. Therefore, the implementation of pilots arises as one essential step to provide credibility for considering DR.

There are some opinions against the utilization of DR strategies in the natural gas sector since some experts think that DR programs for gas consumers may be alluring but impractical [43]. Nevertheless, this book chapter proves the suitability of DR strategies applied to the natural gas sector, where similar problems to those arising in power systems can be afforded by this media.

8. Novel resources: hydrogen

One of the most promising tendencies in clean energy sources is the utilization of hydrogen, which has been identified as the fuel for the energy transition of the

21st century by many institutions and scientists as remarked by Cheli et al. [44]. Indeed, mixing hydrogen with natural gas improves the utilization rate of this hydrocarbon while it also reduces greenhouse gas emissions and pollutants [45].

Natural gas and hydrogen may be mixed in the range from 10–20% in order to be compatible with existing natural gas infrastructures [46]. Indeed, in Italy, the gas system operator, Snam, has demonstrated the feasibility of introducing hydrogen into the natural gas pipelines at rates between 5% and 10% [47]. Some experiences have also taken place regarding the metering devices in the natural gas infrastructure, concluding that fractions of hydrogen up to 15% in the natural gas system do neither affect the reliability nor durability of diaphragm gas meters [48].

Hydrogen can be obtained by electrolysis, applying an electrical current. Therefore, this method can be used when renewable energy production is higher than demand during valley periods, which would increase the efficiency of the whole energy system [44]. Such efficiency increment could be maximized by allowing the participation of consumers by means of demand response services, as discussed in the previous sections.

9. Conclusions

Demand Response has been used for years in the operation and management of power systems. However, few experiences exist in the natural gas sector, where the application of DR strategies is almost non-existing.

The most significant experiences on DR utilization in the gas sector, as well as the main issues to take into account for the implementation of DR actions in gas networks, have been highlighted in this chapter. This kind of mechanisms offers many benefits either for customers and other stakeholders within the gas sector and may increase significantly the efficiency of the gas system when used in balance services by the gas system operator. Moreover, due to the similarities existing between the power and natural gas systems, the application of similar strategies used in electric systems for the gas sector should be considered as the natural evolution for a more efficient and operative management. Together with that, new strategies such as the injection of hydrogen in the gas network may also contribute to the higher efficiency of the whole system, reducing emissions and helping to integrate renewable resources.

The barriers that may prevent the utilization of DR resources in the natural gas system are also discussed here. However, many of them can be solved, thanks to the new structure that today is being given to the energy systems based on the concept of smart grid, which is discussed in this chapter. It is indeed in energy systems structured according to the smart grid configuration, where the application of DR is more useful and profitable.

Conflict of interest

The authors declare no conflict of interest.

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