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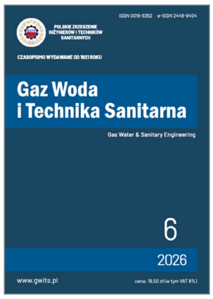

Gas balancing problems in transmission systems

Problemy bilansowania gazu w systemach przesyłowych

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Abstract:
This paper examines gas balancing challenges in transmission networks, focusing on the dual role of pipelines as transport and storage systems. Particular attention is given to line-pack flexibility, enabling short-term balancing of supply and demand through pressure management. The study discusses technical constraints, economic trade-offs, and market implications, including impacts on transport capacity and investment efficiency. It also analyzes balancing mechanisms in liberalized gas markets, supported by a case study of the UK system, highlighting regulatory frameworks and incentives for system operators and shippers.
Keywords: gas balancing, line-pack flexibility, gas pipelines, transmission systems, energy markets

Streszczenie:
Artykuł analizuje problemy bilansowania gazu w sieciach przesyłowych, koncentrując się na podwójnej funkcji gazociągów jako systemów transportu i magazynowania. Szczególną uwagę poświęcono elastyczności line-pack, umożliwiającej krótkoterminowe bilansowanie podaży i popytu poprzez zarządzanie ciśnieniem. Omówiono ograniczenia techniczne, kompromisy ekonomiczne oraz konsekwencje rynkowe, w tym wpływ na przepustowość i efektywność inwestycji. Przedstawiono także mechanizmy bilansowania na rynkach liberalizowanych wraz z analizą przypadku Wielkiej Brytanii, uwzględniając regulacje i bodźce dla operatorów i uczestników rynku.
Słowa kluczowe: bilansowanie gazu, elastyczność line-pack, gazociągi, systemy przesyłowe, rynki energii

1. Introduction

Gas pipelines and compressors are the physical backbone of natural gas market, and they can be used to make gas flow and store it. There are, however, important trade-off between these two possibilities to engage the gas infrastructure. If this dual functionality, which is embodied by line-pack flexibility, is neglected, negative effects are carried into the gas commodity and the gas transport market. Yet, almost no reference to the problems with line pack flexibility can be found in the literature. The problem is complicated because aspects of investments, network operations and balancing markets have to be dealt with simultaneously. The pipeline flexibility can be seen as a positive externality of the transport network design, on the one hand; the right to use this flexibility decreases the available transport capacity, on the other hand. So, the benefit of flexibility in the timing of injections and withdrawals that is possible because of line-pack flexibility should be weighed against the harm of reducing available transport capacity in order to assure the flexibility [1, 2, 5].

The cost of line-pack flexibility, which is a main tool for balancing operations, should not only reflect the commodity price, but also the infrastructure costs, such as the use of the pipeline and the compressors. The cost decomposition of pipelines between its two functions of transport and flexibility is complex. The supply function of pipeline storage and pipeline transport can be classified by the classic microeconomics theory as a multi-product monopoly with the demand for each product independent (as both have different substitutes) but the costs dependent. Moreover, in Europe gas transport is a regulated monopoly, whereas the pipeline flexibility is competing with other sources of flexibility such as contract flexibility and other storage mechanisms. Because of this complexity, the understanding of the trade-offs between the transport function and the storage function of the infrastructure is important. The ability of gas networks to store natural gas inside its pipelines is a consequence of the physical properties of the transport network where the volume gas flow can vary according to the pressure differential. The transport operator can decide how much gas to transport and how much

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gas to store taking into account some technical limits. These technical limits determine the line-pack flexibility. We clearly distinguish between the concepts of "line-pack", which is the total volun1e of gas present in a pipeline section, and "line-pack flexibility", which is the amount of gas that can be managed flexibly by controlling the operation pressure levels between a minimal and a maximal level [1, 3, 4].

2. Line-pack flexibility

The ability of gas networks to store natural gas inside its pipelines is a consequence of the physical properties of the transport network where the volume gas flow can vary according to the pressure differential. The transport operator can decide how much gas to transport and how much gas to store taking into account some technical limits. These technical limits determine the line-pack flexibility. We clearly distinguish between the concepts of "line-pack", which is the total volume of gas present in a pipeline section, and "line-pack flexibility", which is the amount of gas that can be managed flexibly by controlling the operation pressure levels between a minimal and a maximal level. The following sections explain how this flexibility is produced in the network as a consequence of the gas transport dynamics, and how this flexibility is useful for managing a gas network system [2, 5].

3. Production of line-pack flexibility

The steady-state gas flow through the network is described by Eq. 1 in which Q stands for the volumetric flow rate (m^3/s), D represents the diameter (m) of the pipeline section of length L (m), and Pin and Pout are the pressure (Pa) at the inlet of the pipeline and at the outlet of the pipeline, respectively. The constant c represents material and gas characteristics such as pipeline roughness and gas density, and is also dependent on the units chosen for the other parameters.

$$\dot{Q} = cD^{2,5}\sqrt{\frac{p_{in}^2 - p_{out}^2}{L}} \qquad (1)$$

$$V_{LPflex} = w\left(\frac{p_m}{K_m} - \frac{p'_m}{K'_m}\right) \qquad (2)$$

$$p_m = \frac{2}{3}\left(\frac{p_1^3 - p_2^3}{p_1^2 - p_2^2}\right) \qquad (3)$$

Basically, the gas flow rate is related to the difference of the quadratic pressures at both ends of the pipeline section, and not the absolute levels of the pressures. Pipelines can be operated at a range of pressures that are limited at the upper bound by a maximal operating pressure (p_{emax}), which is determined by the material characteristics and at the lower bound by a minimal operating pressure (p_{dmin}). This lower bound is the pressure that ensures flow by compensating friction or it can be determined by contractual arrangements for a certain delivery pressure [6, 7].

The system operator can ensure the safe operation of the pipeline network by operating within a pressure band defined by the maximal and the minimal pressures. This operational flexibility in gas transport networks results in the ability to store gas in the pipelines by using line-pack flexibility.

The available line-pack flexibility, expressed in standard cubic meters, is determined by Eq. 2 in which w is a constant that is dependent on the geometric volume of the pipeline and the chosen reference conditions. Basically, the storage potential is dependent on the difference between the higher average pressure p_m (Pa) and the lower average pressure p'_m, which are calculated according to Eq. 3. K_m and K'_m > are the compressibility numbers (dimensionless) corresponding to p_m and p'_m, respectively. The lower average pressure depends on the entry pressure and the delivery pressure that correspond to the desired transport flow. If the full pressure differential is required to make the gas flow, there remains no storage potential, whereas if there is no flow the full geometric volume of the pipe can be used to store compressed gas.

4. Use of line-pack flexibility

Line-pack flexibility is produced by exerting the still available pressure difference and results in the storage of gas inside the pipeline. The basic principle of storage is that one can only withdraw what has been injected before. Therefore, line-pack flexibility operates like a buffer that is filled first, and emptied at a later time. This buffer concept has been defined as the part of the line-packing, meaning the total volume of gas in the pipeline, that can be used without any safety problem [3, 8].

5. Managing a set of pipelines

So, the line-pack flexibility enables the network operator to store gas inside the pipelines to facilitate the matching of gas supply and demand over time. The line-pack flexibility is particularly suited to immediately accommodate short lived imbalances between demand and supply. Physically, an imbalance occurs whenever the amount of gas injected in the system (m_{in}) is not equal to the gas taken from the system (m_{out}), disregarding losses such as gas consumption in compressors along the pipeline. The correct equation reads:

$$\dot{m}_{in} - \dot{m}_{in} = \frac{\partial (pV)_{storage}}{\partial t} \qquad (4)$$

The right hand side term in Eq. 4 reflects the change over time of the gas mass stored inside the pipeline by means of line-pack flexibility. The imbalance is then reflected in that storage term, in which V represents the geometrical volume (m^3) of the pipeline section and p the gas density (kg/m^3). Therefore, line-pack flexibility makes balancing gas networks an intertemporal problem because the short term storage in pipelines allows matching demand and supply over a time interval, rather than instantaneously. Although the system operator is ultimately responsible for the safe operation of the network, the shippers should balance their gas injections and withdrawals themselves [4, 9].

6. The technical aspects of line-pack flexibility

Technically, line-pack flexibility is available in any pipeline with a non-flat transport demand profile. To use the pipeline flexibility, the line-pack buffer has to be produced first, though. This buffer is basically just local pipeline storage, which is very useful to manage a gas network. However, as the flexibility needs to be produced and can be applied for different uses there are real economic values and costs involved, which are further discussed in the next sections [12].

7. The economic value of line-pack flexibility

The fundamental value of line-pack flexibility can be attributed to its buffer function to quickly cover temporal imbalances between supply and demand. Technically, pipeline storage reflects physical „imbalances". Therefore, the economic definition of a gas imbalance depends on the balancing period, which is the time interval over which nominated gas injections and withdrawals should match and this interval can theoretically last from a second to an hour or even a day or a month. Taking into account that the value of gas demand varies in time, and that the production or import of gas is often less costly when it is fiat, there is a value to facilitate the matching of gas demand and gas supply over time [3, 4].

Moreover, the economic value created by the flexibility to store gas inside the pipeline and to transport gas through a full or empty pipeline can be appropriated by different players: the system operator can use this property to minimize its pipeline investments, whereas shippers can use it for price arbitrage and load management [10].

8. Line-pack value for a system operator

The system operator is responsible for the network investment and thus for the dimensioning of the network. Therefore, an efficient TSO maximizes the sale of transport capacity while minimizing the capacity that it builds. Line-pack flexibility helps the TSO to avoid overinvestment, meaning an investment in capacity that will not be used during the pipeline deprecation horizon [1, 4].

9. Line-pack value for a shipper

In a liberalized gas market, the shippers, who can be any gas buyer or seller, are profit maximizing market players. They buy their gas as cheap as possible and sell it as expensive as possible (or use it when it has a bigger economic value). This means that in a market context shippers prefer to buy gas on a flat-rate basis, avoiding additional costs associated with volatile production, or when prices are lower due to lower demand in that period. The gas is then preferably sold in peak periods, which have higher prices [3].

In Europe the line-pack costs are usually socialized by means of the transport tariffs and in part allocated to shippers through the balancing rules, charges and tariffs.

A typical balancing mechanism specifies time and space boundaries in which the shipper has to balance. Furthermore, the balancing mechanism specifies imbalance charges that should reflect the costs incurred by the system operator to balance the transport system. In actual EU balancing regimes, however, line-pack costs are not included in an efficient way as the allocation of line-pack costs is dependent on the balancing period, the tolerance levels, and the way balancing prices are determined.

10. Balancing mechanism definitions

First, the definition of the balancing period, which is the time interval over which to balance gas injection and withdrawal, is a key issue because this definition determines how long the network is obliged to guarantee free storage to shippers. If the balancing period is an hour, the shippers need to balance injections and withdrawals every hour; whereas in a daily balancing mechanism the shippers should only balance every 24 hours. Inside the balancing interval, the operator should balance the system at no cost for the shippers. Therefore, the system operator needs to provide gas from (pipeline) storage in case a shipper withdraws gas before he injects, and needs to keep gas in storage that was injected for withdrawal at a later time [4, 5].

Imbalances within the balancing period have no financial consequences for the unbalanced shipper. In other words, flexibility costs within the balancing period are socialized. Some countries, however, have added rules to limit the free flexibility inside the balancing period (e.g. hourly limits in a daily balancing system). These rules are meant to discourage huge differences between injections and withdrawals over smaller periods [4].

Second, the definition of the imbalances that are subject to balancing charges and the size of these charges is not homogenous in Europe. Balancing rules have very different approaches to dealing with tolerance levels and penalty charges. For instance, in some balancing mechanisms there are different prices according to the size of the imbalance. Imbalances below a certain level are charged a price Pref or even no price at all, whereas larger imbalances are considered excessive and are subject to a price Pref plus a penalty x. The small imbalance that is less expensive or free is defined by the tolerance levels. The balancing interval and the tolerances actually are reflected in the availability of line-pack flexibility. By offering tolerances the system operator commits to keeping a certain level of line-pack flexibility for storage services at the cost of selling this capacity for the purpose of transport. In systems that have a smaller balancing interval or do not offer tolerances, the system operator can sell more capacity for transport services. Therefore, the cost of different balancing rules can be calculated based on the opportunity cost of pipeline transport capacity.

Third, different systems exist to set up a price structure for balancing charges. The Italian balancing charges are based on the tariffs for underground storage, but most European balancing mechanisms base the balancing charges solely on gas prices. In other words, by the end of the balancing period a shipper should not have any remaining imbalances. If the shipper has imbalances, he will be subject to pay the cost for the equivalent amount of gas as if that gas had been bought or sold on the market.

11. Case study – evolution of the UK gas market

Context on the problem of gas balancing is provided by using the UK market as a case study. The story of the evolution of the UK market from a monopoly to full competition, it illustrates how natural monopoly assets are regulated to promote efficiency, including the tools that are available to those assets to ensure shippers contribute positively to the mechanism [13].

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Prior to the Gas Act of 1986, the whole Gas industry in the UK was monopolised by British Gas (BG). Slow progress was made to manage the monopoly advantage of BG until the Gas Act of 1995, which truly enforced liberalisation of the market, establishing competition and defining pipeline operators and shippers. The Network Code (1996) set out rules and procedures for third party access to the British transmission grid and introduced the concept of the National Balancing Point (NBP)9. The NBP is a theoretical, as in non-specific location, place where the grid is balanced by the TSO as a factor of multiple entry and exit points. It is an assessment of an individual shipper ' s imports vs. exports to/from the grid [1, 5].

It is important to understand that the UK grid is very complex. A description from 2010 states that it incorporates 6,600 km of pipeline at a range of pressure between 45 and 85 bar, employs 28 compressor stations, has over 140 offtake points and approximately 60 Direct Connect customers, including power stations.

Gas in the UK, at the inception of the network code, was generally traded through medium to long- term bilateral contracts. Trading developed, initially, at the UK import terminals at Bacton (south-east) and St. Fergus (northern Scotland) for short-term gas in response to long-term take or pay arrangements. This quickly developed into trading at the NBP with the implementation of the Network Code.

The introduction of standard short-term contracts, with physical delivery to the grid or from the grid and financial settlement between the delivering /taking parties, enabled the tightening up of the UK balancing regime. Balancing was executed on a monthly basis, 15 days in arrears, and now shippers were obliged to start balancing on a daily basis (Fig. 1).

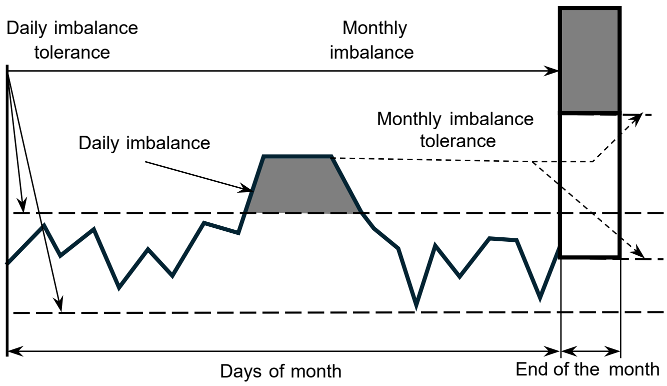

Fig. 1. Balancing on a daily basis
Rys. 1. Bilansowanie w cyklu dobowym

Key principles from the European Regulators Group for Electricity and Gas (ERGEG – guidelines for good practice for gas Balancing) guiding principles on gas balancing:

- "Market participants should have access to appropriate information, adequate re- nomination procedures and flexibility tools/services so that they can manage their imbalance positions (and therefore risk) efficiently, taking into account the relevant characteristics of the balancing system, in particular the balancing period and/or the width of the tolerance margins." Para 1.9.
- "Where a TSO's balancing regime permits the acceptance of bids and offers for balancing gas as a means to balance the system it should procure flexibility (including gas) in a transparent and non-discriminatory manner using market based mechanisms." Para 1.27.
- "In relation to balancing costs TSOs should be cost neutral and have the correct incentives to ensure that the costs incurred of taking residua) balancing actions are efficiently incurred." Para 1.26.
- "TSOs shall provide sufficient, well-timed and reliable on-line based information on the balancing status of network users." Para 3.41.
- "lt shall be the primary responsibility of network users to balance their own inputs and offtakes over the relevant period according to the rules and incentives of the respective balancing regime" Para 4.11.

ERGEG states, in reference to the role and responsibility of the TSOs, that:

- "Each TSO retains the overall responsibility for the economic and efficient operation of its system and therefore should retain a residua) role to maintain physical balance to ensure the safe, efficient and reliable operation of its system, subject to the incentives, information and flexibility and tools provided to shippers to balance their individual portfolio." Para 3.2.
- "The primary objective [of gas balancing] is to transfer the financial responsibility for ex-post balancing services to unbalanced shippers by means of balancing charges. These charges should, in principle, reflect the actual balancing costs for the system operator. The second objective consists in incentivising shippers to balance ex-ante, often by means of a non-cost- reflective penalty for unbalanced positions." Section 2 of 2 forum shopping for ex-post gas-balancing services, Nico Keyaerts and William D'haeseleer.

Ex-post balancing' means that end-of-balancing-period imbalances are financially settled through cash out.

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