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Miguel Vazquez and Michelle Hallack

European University Institute

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For further information
Loyola de Palacio Energy Policy Chair
Nicole Ahner (scientific coordinator)
Email contact: Nicole.Ahner@eui.eu
Robert Schuman Centre for Advanced Studies
European University Institute
Via delle Fontanelle, 19
I-50016 San Domenico di Fiesole (FI)
Fax: +39055 4685755
http://www.loyola-de-palacio-chair.eu

Abstract

Gas-fired power plants are increasingly used in the production of electricity, which in turn makes them a relevant part of the gas demand. In this paper, we investigate whether the current designs of gas and power markets are robust to the relatively new link between industries. Specifically, we study the cross-industry efficiency losses associated with designs aimed at increasing liquidity by limiting the amount of network services allocated through markets. In the short run, reducing the set of transmission services priced in one market (say gas) affects the use of transmission in the other market (say power). This may result in inefficiencies that should be accounted for when deciding on the network services to be allocated through market arrangements in each industry. We also identify long-term effects of such design strategies: the allocation of gas pipeline storage and transmission services without preference representation may weaken localization signals for power plants investment. In addition, lack of harmonization of market designs may raise barriers to network investment.

Keywords

1. Introduction*

Power and gas industries are increasingly linked. Gas-fired power plants are increasingly used in the generation of electricity, and will be used even more in the future to back up intermittent generation. Hence, gas-fired power plants have become relevant users of the gas system, which motivates the strong link between industries. Nonetheless, despite of the increased interaction between gas and electricity markets, most of the literature has dealt with these two industries separately.

In the gas industry, works dealing with market design aspects can be organized under three broad headers[1]. The first group of works analyzes the role of long-term contracts, see for instance Mulherin (1986) or Masten and Crocker (1985). The second group analyzes short-term regulatory aspects associated with the existence of a central network operator, see for instance Lapuerta and Moselle (2002) or Lapuerta (2003). More recently, a third stream of literature began to discuss different institutional arrangements for gas transmission, Correlje et al. (2012), and their impact on the gas market, Ruff (2012), Makholm (2012) or Vazquez et al. (2012) —which aims to link the two former streams of literature.

In the electricity industry, we find similar lines of regulatory research[2]. The contracting literature is in this case related to the design of organized markets; see for instance Sioshansi (2008) for a review in on the literature dealing with the design of mechanisms for market arrangements. Along the lines of gas industry literature, the short-term regulatory issues related to network coordination have been extensively analyzed, see for instance Stoft (2002) for a general description. A third stream of the literature copes with the institutional setting of power markets, Joskow and Schmalensee (1983), Glachant and Finon (2000), Rious et al. (2008).

In that view, it seems sensible to investigate whether the designs of gas and power markets are robust to the relatively new link between industries. Gas and electricity market interacts, and their interaction depends on how markets are designed. In both industries, not only have market designs to address the coordination between the demand and offer of commodity products, but also the coordination of network operation. Hence, gas and power market designs defines how network constraints are coordinated with com-

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[1]We do not consider here the research line that focuses on market structure and pricing, including modeling of strategic behavior, assuming a certain market design; see for instance Holtz et al. (2008).

[2]As in gas market literature, one also finds literature coping with strategic behavior issues, see for instance Ventosa et al. (2005) for a review.

modity trading. In this regard, on the one hand, there is a wide agreement that power markets must be based on the existence of a Transmission System Operator[3] (TSO). But such agreement is not found in gas industries, as it is possible to find gas market designs that build on long-term pipeline contracting (as the US market, see Makholm (2012) for a detailed description). In this case, the coordination of gas networks with commodity trading is decided on by market players (instead of by the interaction among TSOs and market players), and thus the possibility to design markets with the aim of increasing liquidity by reducing the set of networks services offered in the market is limited. As both networks and network users are market players, the room for design is significantly reduced. Therefore, this paper will be considering only gas market arrangements built on the existence of a TSO[4].

One of the most used motivations for the implementation of TSOs has to do with the interaction between networks and commodities in the short run. Gas and power networks are characterized by complex technical characteristics, so ensuring the security of the system operation typically involves a tight coordination between commodity and network services. As the characteristics of the network services needed to operate gas and power systems are significantly complex, they are the source of severe transaction costs (see for instance Glachant (2002) for the analysis of asset specificity in several network industries). This in turn implies that market arrangements may be highly inefficient, and hence some of those services are not traded by market participants but managed by the TSO. Following the power markets literature, e.g. Stoft (2002), we will refer to these services as ancillary services.

Providing a general definition of ancillary services in gas and power markets is not an easy task, but such definition plays a central role in the design of those markets. One possible reasoning comes from the observation that gas and power industries are made up of considerably specific assets. This complicates the implementation of market arrangements. But as shown in Riordan and Williamson (1985) in a general context, asset specificity is ultimately a design variable, and it is possible to reduce specificity at the cost of reducing efficiency. When applied to gas and power sectors, the definition of ancillary services can be associated with this strategy of reducing specificity to allow market arrangements.

We will not aim at defining generally these ancillary services. Instead, the strategy we pursue in this paper is to define the list of services actually traded by market players. The rest of network services will be considered ancillary services (we implicitly assume that they are characterized by prohibitively large transaction costs). Put it differently, we will define the network constraints that are taken into account when clearing each market. The gap

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[3]A regulated agent in charge of the network operation.
[4]Examples of such gas market design are Australian and European gas industries.

between the representation of network constraints and the physical characteristics of the market will be made up of ancillary services[5]. To do so, we will assume that all short-term trading may be represented by a single auction for each market (i.e. a single auction for the gas market and an additional single auction for the power market). In this regard, we will not discuss benefits and drawbacks of implementing alternative designs (e.g. a sequence of simpler auctions). We will consider that, given the definition of ancillary services, all designs are equivalent in terms of efficiency to the single-auction representation, see Vazquez (2003) for a detailed discussion.

In that view, we use the auction representation to characterize the efficient outcome of short-term gas and power trading. Our definition of efficiency is an auction outcome that allocates services to the players that value them most, see Holmstrom and Myerson (1983) or Wilson (1993) for a general treatment of mechanism efficiency definitions. The single-auction representation in turn relies on assuming no transaction costs, no private information, no uncertainty and no strategic behavior. Consequently, we place the analysis of both gas and power industries close to the spirit of nodal pricing introduced by Schweppe et al. (1988).

We then use the auction outcomes to study the difficulties associated with several measures aimed at reducing the specificity of gas and power assets. The logic for this is that, as we will show, many of the drawbacks of such measures remain hidden when analyzing each industry separately, and they should be taken into account when deciding on the set of ancillary services. In that view, we do not analyze potential benefits associated with sacrificing efficiency to reduce specificity. Our study is aimed at identifying additional costs of those measures that are associated with the interaction of gas and power markets.

Two fundamental interactions will be studied. On the one hand, inefficient allocation of transmission services (i.e. not according to players' preferences) in one industry (say gas) affects the results of the other industry (say electricity). For instance, if gas transmission is cheaper due to some regulatory measure than power transmission, there will be more trades using gas transmission than in the optimal solution (optimality defined as the result of the auction). Or if pipeline line-pack storage[6] is allocated without costs, there will be cross-subsidies of the gas market to the power market. Put it differently, if line-pack services[7] are valuable in the optimal solution, but they are costless in a certain market design, the costs of trading gas are sub-optimal.

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[5]The design of mechanisms to allocate ancillary services is beyond the scope of this paper.

[6]The capability of a pipeline to store gas inside it

[7]Line-pack services are the different kinds of services (economic functions) that the use of line-pack storage may provide. For instance, line-pack services include balancing the flows injected and withdrawn at different points in time.

As gas is an input for power markets, power markets will not behave as in the optimal solution.

Finally, we analyze the dynamic implications of the previous results. Short-term mechanisms are effective long-term signals. When such signals are distorted, there are relevant long-term effects both in the commodity and in the network sides of the market. We identify three main long-term effects. First, free gas flexibility may weaken localization signals for power plants investment. Second, transmission services without representation of players' preferences may also weaken signals for power plants localization. And third, lack of harmonization of market designs may raise barriers to investment.

After the introduction, section 2 is devoted to describe the rules to deal with the trade-off between efficiency and liquidity. Section 3 provides an overview of the methodology used in this paper, which is based on a single-auction representation. Section 4 develops the analysis of the drawbacks of some current regulations, by comparing them to the results of the single-auction representation. Section 5 describes the dynamic implications of the previous results, and section 6 collects our conclusions. The Appendix defines the single-auction representation of both gas and power markets.

2. EFFICIENT CLEARING, LIQUIDITY AND PRICING OF NETWORK SERVICES

To organize the gas industry transactions on a market base, a gas commodity has to be defined prior to the trade. This is done through the definition of a set of characteristics of gas (calorific power, pressure...), the time horizon and location of injection/delivery. To do so, the transmission infrastructures play a critical role. But gas and power networks operation is characterized by tight technical constraints. Thus, the contracting architecture required to implement the commodity delivery at different points of the network, within different time scopes, must be complex. This is the source of significant transaction costs, Williamson (1975), Williamson (1983) and Williamson (1985).

In order to reduce network specificity, and hence transaction costs, it is possible to simplify the actual network to broaden the trading space (at the cost of reducing efficiency), Riordan and Williamson (1985). Thus, many gas and power markets are build on the idea of "commercial networks". Many systems have created a set of arrangements where some key transmission services are socialized among players. This allows increasing the homogeneity of trading places and dealing with complex technical characteristics. The commercial network can be defined as this reduced set of network services taken into account by market players in their commodity trade. The remaining differences between the commercial network and the physical network

are socialized through the ancillary services.

2.1. REGULATORY MEASURES AIMED TO SIMPLIFY THE GAS AND POWER NETWORKS

The network operator can choose to reduce the specificity of each feasible trade. If the network operator simplifies the individual spatial characteristics of each trade, the spatial difficulties to trade in the network zone are reduced, and the number of market players trading the same product increases. The same idea is pursued when the TSO simplifies the temporal characteristics of gas or power by defining longer periods in which injections and withdrawals are considered simultaneous. That simplification strategy implies that several services will be part of the ancillary services, and hence will be socialized. We will next describe this simplification of the network analyzing the implicit spatial and temporal flexibility that different regulations may associate with the commodity definition.

2.1.1. Spatial flexibility

A point-to-point gas transmission arrangement could be thought of as the less simplified option for wholesale gas trade, where most of the actual physical characteristics of each trade are to be expressed in that trade. It is consequently the arrangement with the most limited trading area. This is the typical scheme implemented in the US and Australian gas markets. Although the US market is characterized by the absence of a TSO, the Australian market is based on point-to-point transmission allocated through an auction. In the EU, on the other hand, one finds a different capacity definition: the entry/exit system. It consists in selling separately the right to enter and exit the system, and the rest of spatial characteristics of the network are allocated implicitly. Thus, gas market players only reveal preferences on the right to enter and exit the gas systems. Within the system, all injections and withdrawals are considered to have the same price. In that view, the design implies free spatial flexibility and thus considers a larger part of network services as ancillary services.

The power-system version of point-to point transmission is often called nodal pricing, which is also the preferred design in USA. It can be though of as a combinatorial auction that allows bids specifying additional conditions to just price-quantity pairs. The corresponding market clearing, thus, must be done by solving some (more or less) complex optimization problem. But one also finds measures to reduce specificity in power markets, especially in the EU. The predominant design in Europe is to define spot markets as a sequence simple auctions, where power producers send bids specifying the price

required for selling each possible quantity, and the market is cleared simply by intersecting the supply and demand curves. These simple auctions are complemented with congestion management mechanisms. In that view, as part of those congestion management services are often socialized among a certain group of network users, the complete scheme implies larger spatial flexibility than nodal pricing schemes. For instance, one often finds mechanisms where the supply side offers according to their preferences but the costs are socialized.

2.1.2. Temporal flexibility

The specificity of gas and power trade may also be reduced by adding to the definition of the commercial network a certain flexibility in the time of injection/withdrawal. In this type of trading arrangement, the definition of the commercial network allows injections and withdrawals between times T_1 and T_{max} without additional costs or difficulties for the traders. Put it differently, transmission services between T_1 and T_{max} have the same cost from the point of view of the traders as network users. Therefore, players may inject in and withdraw from the system at different periods without affecting the market characteristics and value of their trades. Consequently, the temporal specificity of gas and power flows is reduced.

Most of the gas market designs based on TSOs rely on a certain level of temporal flexibility, as the storage ability of gas systems is not as limited as in power networks. For instance, it is possible to find designs based on defining gas as a daily product: during the day, all injections and withdrawals have the same price. Put it differently, markets do not see any temporal characteristic of the gas within the day, and the balancing of injections and withdrawals are the responsibility of TSOs.

On the other hand, there are a variety of electricity spot market designs. But in every case, power networks are characterized by significantly limited storage capability. In that view, TSOs need to coordinate tightly production and consumption in order to secure the system operation. To do so, they need to anticipate to some extent the system requirements. The time frame defined by the temporal characteristics of the products managed by TSOs define the temporal flexibility given in the market. For instance, if TSOs buy all services they need one year in advance (so that, for instance, they can respond to any situation after the day-ahead market), all temporal characteristics of electricity after the day-ahead market are socialized. On the other hand, if TSOs buy services only twenty minutes in advance, markets need to coordinate the operation up to that point. This coordination will be done according to market preferences (contrary to yearly reserves), at the cost of increased transaction costs.

2.2. SCOPE OF THE ANALYSIS

When a certain power or gas system offers both ample temporal and spatial flexibility for gas trade, the simplification increases the liquidity of gas trade by facilitating the access to transmission services. Under this design, the "commercial" transmission services (the ones that characterize the commercial network) may be viewed as rights to access an enlarged trading space, with possibly large temporal and spatial flexibility. This creates a regulated market liquidity.

In this paper, we show that the effects of that regulated liquidity are not limited to a single industry. Enlarging the trading space in one industry affects the efficiency of the other industry. Therefore, when analyzing the trade-off efficiency/liquidity, one needs to consider such cross-industry effects. To analyze these effects, this paper considers a hypothetical situation where minimal flexibility is given in the definition of the commodity. With that benchmark, we will analyze the effects of several regulatory rules found in power and gas markets.

To do so, we begin by considering a situation where gas and power markets are cleared according to a single, combinatorial auction (one auction for each market). We choose a representation based on combinatorial auctions to make explicit that market participants will be deciding on all services defined in such auction and that TSOs are deciding on any service not represented in it.

Our procedure is as follows:

- We define the efficient allocation as the result of the clearing process for the combinatorial auction

- We analyze the effects of several regulatory measures on the results of the hypothetical auctions. Such effects are interpreted as effects on allocation efficiency

- We analyze the long-term effects of the previous measures

The study developed in this paper is associated with short-term trading. Specifically, we will analyze trading from a day-ahead horizon until the point in time when the TSO takes over control of the network for security purposes. All trading in that interval will be modeled by the results of a combinatorial auction. We assume, in that context, that any alternative auction design for that (including the trades taking place within-day) will be equally efficient. In that view, our methodology does not allow studying the effects on network allocation of additional elements, e.g. private information or risk aversion. We define the day-ahead auctions as a representation of a certain set of mechanisms aimed at allocating network services through market arrangements.

Under such hypotheses, we analyze short-term gas-electricity interactions.

3. AUCTIONS FOR POWER AND GAS

The auctions considered in this paper are implicit auctions: players only bid for commodities and network services are allocated according to commodity bids. In the case of power markets, we consider combinatorial auctions along the lines of Hobbs et al. (2001). Loosely, they proposed more or less detailed unit-commitment models as candidates to clear short-term electricity markets[8], see for instance O'Neill et al. (2003) or Hogan and Ring (2003). The proposal of this paper is close to the one in Barquín and Vazquez (2008). In the case of gas markets, we will use the auction proposed in Vazquez and Hallack (2012).

The bids are only for trades in the commodities. That is, players bid for gas and power injections and withdrawals, and network services are allocated by the clearing algorithm. No uncertainty or strategic behavior is considered. Gas and power commodities (and hence the corresponding network services) are parameterized by t, the time unit that defines the duration of the product. All bids are send before the first period represented in the auction. For instance, if t represents an hour, gas and power commodities are hourly products (and so are network services) and the auction takes place one day before delivery, so that players send bids for the next twenty-four hours.

Under the assumptions of this paper, an implicit auction taking account of network constraints provides an efficient allocation. Any other auction design strategy (e.g. a design based on a sequence of auctions, or an iterative auction) is equivalent in terms of efficiency, as long as the definition of the network services represented in the auction is the same. The auctioneer receives the bids and clears the market. To do so, the auctioneer uses the bids as input to an optimization problem that represents the operation of the corresponding network. In that view, it is a uniform-price auction. For the sake of simplicity, we will consider that all gas storage facilities are managed by market players. Hence, they will be offered implicitly in the auction bids. In that view, all storage is allocated according to market preferences. When this is not the case, i.e. some storage capacity is managed by TSOs, there will be additional costs to the ones described below, but they will be similar to the costs associated with suboptimal pricing of line-pack storage described below. We will be using three general results (the detailed description of the algorithms and their properties are collected in the Appendix):

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[8]This design strategy is rather popular in the US, being the option chosen e.g. by PJM, NY...

Result 1: *The uniform price of both gas and power auctions is equal to the marginal bids.*

The uniform price of both auctions makes the marginal utility of production equal to the marginal utility of consumption. Such marginal utilities are defined by the offer and demand curves at each network node and point in time, which in turn are made up of the bids of market players. This result is obtained in the Appendix, and represented in equations (1)–(2) for the power auction and (9)–(10) for the gas auction.

Result 2: *The price of transmission resulting from both auctions is given by the price differences along the network.*

In the power clearing algorithm, these price differences are made up of two terms: a) the congestion costs, given by the Lagrange multiplier of the flow limit constraints, and b) and the power-flow costs, given by the multiplier of the power-flow equations. The latter is a typical characteristic of power flows: as electricity cannot be confined in a certain path, when any line of the network is congested, flow changes in any line affect transmission costs in all lines of the network. In the gas clearing algorithm, price differences have a different nature. Gas flow paths, contrary to electricity, can be controlled, so those price differences should be associated just with congestion rents. However, we take account of line-pack storage, so in fact such price differences measure the trade-off between line-pack and transmission. This result is obtained in the Appendix, and represented by equation (3) for the power auction, and equation (12) for the gas auction.

Result 3: *For the gas network, the auction price of line-pack storage at each network node is given by the price differences, between two consecutive periods, at each point of the network.*

This result is complementary to the gas part of the previous result. The gas clearing algorithm represents the trade-off between transmission and line-pack. The previous result described the pricing of transmission services, and this one represents the pricing of line-pack services. In the Appendix we also show that the gas auction is cleared so that the value of line-pack equals the value of transmission services, being both values implicit in players' bids, see equation (B.2). This result is obtained in the Appendix, and represented by equation (13).

4.   EFFECTS OF LIQUIDITY MEASURES

This section studies the effects of suboptimal pricing of transmission services. The optimal pricing is defined through the results described in the previous section. The motivation for suboptimal pricing was given in 2. Hence, the

aim of this section is showing the cross-industry costs of suboptimal pricing. Its possible benefits, e.g. those associated with reduced transaction costs, and the quantitative assessment are beyond the scope of this paper.

4.1. MEASURES AFFECTING THE PRICING OF TRANSMISSION SERVICES

We begin by illustrating the effects of suboptimal transmission pricing using a simple example. To do so, we consider the following particular applications of the previous results:

(R1G: Result 1–Gas market)

$C_t^{i,*}$ represents the last cleared bid of the aggregate bid curve for withdrawals in the gas auction, at point i and time t. The symbol $(*)$ denotes marginal point. $W_t^{i,*}$ represents the corresponding quantity specified in the bid. Thus, the marginal utility expressed in players' bids will be given by $\frac{\partial C_t^{i,*}}{\partial W_t^{i,*}}$. Consequently, using (*Result 1*), $\frac{\partial C_t^{i,*}}{\partial W_t^{i,*}} = \pi_t^{i,g}$, where $\pi_t^{i,g}$ is the gas auction price at point i and time t.

(R1P: Result 1–Power market)

$O_t^{j,*}$ represents the last cleared bid of the aggregate bid curve for production in the power auction, at point j and time t. The symbol $(*)$ denotes the marginal point. $P_t^{j,*}$ represents the corresponding quantity specified in the bid. Thus, the marginal utility expressed in players' bids will be given by $\frac{\partial O_t^{j,*}}{\partial P_t^{j,*}}$. Consequently, using (*Result 1*), $\frac{\partial O_t^{j,*}}{\partial P_t^{j,*}} = \pi_t^{j,p}$, where $\pi_t^{j,p}$ is the power auction price at point j and time t.

(R2G: Result 2–Gas market)

The price of transporting gas from point i to point j at time t will be denoted by $\mu_t^{i-j,F,g}$. Using (*Result 2*) and assuming no congestion in the pipeline, the transport price is given by the price difference, $\mu_t^{i-j,F,g} = \pi_t^{i,g} - \pi_t^{j,g}$.

(R2P: Result 2–Power market)

Analogously, the price of transporting power from point i to point j at time t will be denoted by $\mu_t^{i-j,F,p}$. Using (*Result 2*) and assuming no congestion in the power network, the transport price is given by the price difference, $\mu_t^{i-j,F,p} = \pi_t^{i,p} - \pi_t^{j,p}$.

4.1.1. An example

Assume that the set of nodes for the two networks are the same. Let us consider the following possibilities.

(Trade A): The first situation consists in:

- A power producer buys gas at node i at a price given by the marginal bid at the auction: $\frac{\partial C_t^{i,*}}{\partial W_t^{i,*}}$

- After that, the power producer transports the gas in the same period to the node j. The price for such trade is given by the value of transport determined by the gas auction (we assume that the pipeline is not congested): $\mu_t^{i-j,F,g}$

- Finally, the power producer sells electricity produced with the gas at node j: $\frac{\partial O_t^{j,*}}{\partial P_t^{j,*}}$

The unit revenue of the set of trades (assuming for the sake of simplicity that the heat rate of the plant is equal to one) is thus given by

$$unit\ revenue(A) = -\frac{\partial C_t^{i,*}}{\partial W_t^{i,*}} + \mu_t^{i-j,F,g} + \frac{\partial O_t^{j,*}}{\partial P_t^{j,*}}$$

Using the previous results R1G, R2G and R1P in the expression for the unit revenue, we have that

$$unit\ revenue(A) = \pi_t^{j,p} - \pi_t^{j,g}$$

That is, the unit revenue for the trade is equal to the difference between the power price at node j and the gas price at node j.

(Trade B): The second situation consists in:

- A power producer buys gas at node i at a price given by the marginal bid at the auction: $\frac{\partial C_t^{i,*}}{\partial W_t^{i,*}}$

- Then, the power producer transports electricity from node i to node j (assuming that the power line is not congested): $\mu_t^{i-j,F,p}$

- After that, the power producer sells electricity at node j: $\frac{\partial O_t^{j,*}}{\partial P_t^{j,*}}$

The unit revenue of the set of trades (assuming again that the heat rate of the plant is equal to one) is given by

$$unit\ revenue(B) = -\frac{\partial C_t^{i,*}}{\partial W_t^{i,*}} + \mu_t^{i-j,F,p} + \frac{\partial O_t^{j,*}}{\partial P_t^{j,*}}$$

Using the previous results R1G, R2P and R1P in the expression for the unit revenue, we have that

$$unit\ revenue(B) = \pi_t^{i,p} - \pi_t^{i,g}$$

That is, the unit revenue for the trade is equal to the difference between the power price at node i and the gas price at node i.

Suboptimal transmission pricing. It is possible that network allocation follows different rules than the ones described by the auction. Consider the case of postage stamp pricing in the gas system[9]. This implies that no transmission constraint is considered when clearing the market. As the gas auction is not cleared according to players' preferences (because transmission is not represented), there are situations where transporting gas is cheaper than transporting electricity. For instance, assume the postage stamp mechanism implies that the gas price is the average of the hypothetical gas auction described so far. Thus, the postage stamp price would be

$$\pi_t^{PS,p} = \frac{1}{N} \sum_{k=1}^{N} \pi_t^{k,g}$$

A possible situation would be characterized by $\pi_t^{j,g} < \pi_t^{PS,p} < \pi_t^{i,g}$. Thus, under postage stamp pricing, the unit revenue associated with the trade A would be higher ($\pi_t^{j,g} < \pi_t^{PS,p}$) and the unit revenue of trade B would be lower ($\pi_t^{PS,p} < \pi_t^{i,g}$).

4.1.2.   General lessons from the example

In the example above, there are more trades using gas transmission (*Trade A*) than the in efficient solution. This in turn implies that part of the gas market (the part not using gas transmission) is subsidizing the part of the market actually transporting. Hence, it is implicitly providing subsidies to the power market, as trades that should be done by transporting electricity are done by transporting gas. One may also find situations with prices that make cheaper transporting electricity (*Trade B*), e.g. if $\pi_t^{j,g} > \pi_t^{PS,p} > \pi_t^{i,g}$. In these situations, there will be implicit subsidies to the gas market, as trades that should be done transporting gas are done transporting electricity.

Moreover, from the example above, it is possible to design the complementary case: power transmission is given without representation of players' locational preferences but gas transmission is optimally priced. In this case, considering the power-system equivalent to postage stamp pricing, we will find analogous effects.

In general, the particular combination of effects depends on the pricing systems of each market. Nonetheless, any solution different of the optimal one

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[9]Note that we are not considering transmission tariffs but only short-term pricing of transmission capacity.

will result in some level of subsidization of one market to the other. Therefore, when some transmission services are offered without preferences representation, the use of the network is not optimal. This in turn implies cross-subsidies from one market (the market using more network capacity than in the optimal solution) to the other.

4.2. MEASURES AFFECTING THE ALLOCATION OF LINE-PACK STORAGE

In the following example, together with results R1G and R1P, we will apply *Result 3*:

(R3G: Result 3–Gas market)

The price of storing gas in the pipelines connected to i at time t will be denoted by $\mu_t^{i,L,p}$. Using (*Result 3*) and assuming no congestion in the gas network, the line-pack price is given by the price difference at node i between two consecutive periods, $\mu_t^{i,L,p} = \pi_{t+1}^{i,p} - \pi_t^{i,p}$.

Let us consider again two situations.

(Trade C): The first situation consists in:

- A power producer buys gas at node i and time t at a price given by the marginal bid at the auction: $\frac{\partial C_t^{i,*}}{\partial W_t^{i,*}}$

- After that, the power producer store the gas in the pipelines connected to node i until the next period $t+1$. The price for such trade is given by the value of line-pack storage determined by the gas auction (we assume that the pipeline is not congested): $\mu_t^{i,L,g}$

- Finally, the power producer sells electricity produced with the gas at node i and time $t+1$: $\frac{\partial O_{t+1}^{i,*}}{\partial P_{t+1}^{i,*}}$

The unit revenue (assuming that the heat rate of the plant is equal to one) of the set of trades is thus given by

$$unit\ revenue(C) = -\frac{\partial C_t^{i,*}}{\partial W_t^{i,*}} - \mu_t^{i-j,L,g} + \frac{\partial O_{t+1}^{i,*}}{\partial P_{t+1}^{i,*}}$$

Using the previous results R1G, R3G and R1P in the expression for the unit revenue, we have that

$$unit\ revenue(C) = \pi_{t+1}^{i,p} - \pi_{t+1}^{i,g}$$

(Trade D): The second situation consists in:

- The same power producer buys gas at node i and time $t+1$: $\frac{\partial C_{t+1}^{i,*}}{\partial W_{t+1}^{i,*}}$

- The power producer then produce electricity at the same node i and time $t+1$: $\frac{\partial O_{t+1}^{i,*}}{\partial P_{t+1}^{i,*}}$

The unit revenue (assuming that the heat rate of the plant is equal to one) of the set of trades is thus given by

$$unit\ revenue(D) = -\frac{\partial C_t^{i,*}}{\partial W_t^{i,*}} + \frac{\partial O_{t+1}^{i,*}}{\partial P_{t+1}^{i,*}}$$

Using R1G, R3G and R1P,

$$unit\ revenue(D) = \pi_{t+1}^{i,p} - \pi_{t+1}^{i,g}$$

Therefore, if line-pack is priced according to players' bids for gas commodity, the two trades are equivalent.

Suboptimal line-pack pricing. Consider that no line-pack constraint is considered when clearing the market. A typical example of this is found in the EU gas markets. As shown in section2, European markets often provides network users temporal flexibility. For instance, the implementation of a daily balancing mechanisms implies that line-pack storage is used by TSOs to balance the system within the day. Consequently, line-pack storage is given for free. Thus, the *Trade C* will have a unit revenue given by

$$unit\ revenue(C,DB) = -\frac{\partial C_t^{i,*}}{\partial W_t^{i,*}} + \frac{\partial O_{t+1}^{i,*}}{\partial P_{t+1}^{i,*}} = \pi_{t+1}^{i,p} - \pi_t^{i,g}$$

and *Trade D* will have

$$unit\ revenue(D,DB) = \pi_{t+1}^{i,p} - \pi_{t+1}^{i,g}$$

because now storing gas inside the pipeline is free. If $\pi_t^{i,g} < \pi_{t+1}^{i,g}$, then the revenue associated with the *Trade C* is higher under a daily balancing mechanism than in the optimal pricing scheme.

4.2.1. General lessons from the example

In the example considered above, as *Trade C* is less costly under a daily balancing mechanism, there will be more trades using line-pack storage than in the optimal solution. On the other hand, it is possible that $\pi_t^{i,g} > \pi_{t+1}^{i,g}$, so the revenue of *Trade C* under a daily balancing would be lower than in the optimal pricing scheme. This in turn implies that players would be using less line-pack storage than in the optimal solution. But players' revenues

would not change with respect to the optimal outcome, because the revenue associated with *Trade D* remains the same.

Assuming perfect foresight (we are not considering players' behavior under uncertainty), shippers will store gas in the periods when the gas price is low, in order to use it in the periods when the gas price is high. The general effect of free line-pack storage is to increase players' revenues, as their gas trades are cheaper when it is profitable to store gas, and they cost the same when storing gas is not profitable.

Therefore, under free line-pack storage, there will be more trades using line-pack than in the solution of the efficient auction. This implies that the part of the gas market that is not using line-pack is subsidizing the power market, because there are cheaper gas trades paid for by all gas network users.

4.3. FREE LINE-PACK STORAGE AFFECTS THE USE OF TRANSMISSION

So far we have dealt with suboptimal pricing of transmission and line-pack storage separately. However, the effects of the two pricing schemes are not independent. When line-pack is free in one node but costly in other node, it has implications for the transmission results. A first effect can be derived from the optimality conditions of the auction (see equation (B.2) in the Appendix): more line-pack offer implies less transmission capacity. But we are interested in cross-industry effects. In this regard, free line-pack services affects whether market participants are using gas transmission or power transmission.

4.3.1. An example

Let us consider again the two previous situations in section 4.1, but adding the effects of line-pack. We had that, in the efficient solution,

$$unit\ revenue\ A\ (transport\ by\ gas) = \pi_{t+1}^{j,p} - \pi_{t+1}^{j,g}$$

$$unit\ revenue\ B\ (transport\ by\ power) = \pi_{t+1}^{i,p} - \pi_{t+1}^{i,g}$$

Now consider that node j is offering free line-pack services and that $\pi_{t+1}^{j,g} > \pi_t^{j,g}$:

$$unit\ revenue\ A\ (transport\ by\ gas) = \pi_{t+1}^{j,p} - \pi_t^{j,g}$$

Gas transmission becomes cheaper, even if gas transmission is priced according to players' preferences.

4.3.2.   General lessons from the example

In the example above, more transport will be done using the gas network than in the optimal solution. And the effect is not related to the particular transmission pricing scheme, but to the line-pack pricing. Hence, network users will use more gas transmission when gas storage makes it profitable, increasing their revenues. When gas storage is not profitable, players' revenues will remain the same.

The general effect is that, regardless the transmission pricing scheme, giving free line-pack storage affects the use of transmission. Thus, besides the cross-subsidies described in section 4.2, free line-pack implies using, on average, more gas transmission than in the optimal auction.

5.   Long-term signals in the interaction between gas and power market designs

The previous section has shown that the operation of gas (power) markets is significantly affected by the operation of power (gas) markets. As such operation depends in turn on the design of the markets, the previous section described some interactions between gas and power market designs in the short run. In particular, we identified that

- Providing transmission rights without representation of market preferences implies affecting the choice of which commodity will be transported (section 4.1)

- Providing free line-pack storage services implies subsidizing the power market (section 4.2)

- Providing free line-pack storage affects the choice of the transported commodity (section 4.3)

The previous short-term effects also constitute relevant signals for the investment in power plants. To analyze these effects, we consider several interconnected systems with different degrees of spatial and temporal flexibility for both gas and power commodities. In doing so, we will be able to characterize the kinds of effects found in the interaction among different market designs. In that view, it is useful to consider a set of cross-system trades.

5.1.   Cross-border trading and infrastructure allocation

The basic scenario consists in two interconnected national (or sub-national) zones for each market (gas and power). Such zones are rarely under a single

regulatory frame, so trades must be coordinated according to each of the national set of rules. Hence, we describe a certain national system as a set of nodes in the single-auction representation. We will call this set of nodes a trading zone. The interconnection would be defined by (gas and power) transmission and line-pack services of a set of lines connecting the relevant set of nodes. We will consider two basic cases: lack of coordination in the allocation of transmission capacity between two zones, and different levels of free line-pack services in the two trading zones.

We identify the lack of tight coordination between zones with a case of more expensive transmission rights than the optimal value. This relies on a transaction cost argument. Lack of tight coordination often means the use of explicit network allocation. That is, players must purchase rights to transport gas or power through the network, besides trading gas or power commodity. Both gas and power markets, because of their complex technical characteristics, are faced by stringent time constraints. In that view, players would need to trade a large amount of services in a very short period. This is associated with significant transaction costs. We model such transaction costs by defining transmission services more expensive than in the single-auction representation. Hence, lack of tight coordination results in the effects described in section 4.1.

On the other hand, as a trading zone could be identified with a set of network nodes, it is possible to model different rules for line-pack allocation in different trading zones. In that view, the offer of free line-pack storage would be constrained to a certain set of nodes (possibly a single node), whereas line-pack storage in the rest of nodes is priced at the efficient value.

If a certain combination of designs is more beneficial in one trading zone than in another, it will constitute a localization signal for gas-fired power plants. In our discussion, we are only taking into account the relative conditions in two zones: the objective is to analyze the consequences of different incentives to invest in one of the two zones due to the conditions of use for gas-fired power plants. For instance, if the allocation of line-pack storage in the gas market design results in lower costs in a certain trading zone, gas-fired power plants will have an incentive to invest in that trading zone. Analogously, if the transmission services allocation results in lower costs in a certain zone, that will be an additional localization signal.

The previous heterogeneity results in long-term signals associated with the interaction of both market designs. Next sections are devoted to describe long-term effects of such interactions.

5.2. Free temporal flexibility may weaken localization signals for power plants investment

Consider two zones with different needs for power flexibility. The typical situation is a zone with significant presence of wind production and another zone with more constant generation patterns[10]. Under the auction representation, the zones will have signals for gas-fired power plants investment. In particular, high prices for short-term generation of the zone with high penetration of wind power should attract gas-fired power plants.

However, we have to consider also the temporal flexibility (free line-pack storage services) provided by the gas system. Gas-fired power plants will have lower costs in zones with less gas constraints. Let us assume that temporal flexibility is lower in the zone with the largest share of intermittent generation (zone A) and higher in the system with the smallest share of intermittent generation (zone B). The reduced costs associated with temporal flexibility may be associated with the effects described in section 4.2.

The artificially cheap gas prices for flexible use of the network will then attract investment in power plants to zone B, which has relatively low needs of them. The only solution for the zone with large needs of gas-fired power plants (zone A) is to buy short-term electricity from the zone with free storage services (zone B). This will create a clear signal for investment in the power network.

In this situation even if the power market design is providing the correct long-term signals, lack of harmonization in the designs of gas markets creates the need for power network investment. That need would not exist if the gas rules were harmonized. Moreover, large temporal flexibility is fading localization signals for gas-fired power plants.

5.3. Free spatial flexibility may weaken localization signals for power plants investment

Usually, in order to analyze the localization signals for power plants, one pays attention to the signals given by power prices. In that view, gas-fired power plants earn the efficient price when selling electricity, and hence they receive efficient localization signals. For instance, if there is one zone with higher price (the interconnection is congested), power plants see a short-term signal to invest in such zone, and thus to help removing the congestion. Such price differences are described by the clearing conditions of the auction.

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[10]The presence of wind production increases the need for back-up generation, which in turn increases the uncertainty and variability of gas-fired power plants consumption

But we observe that, regardless the design of power markets, the design of gas markets also gives signals to the localization of gas-fired power plants. We showed in sections 4.1 and 4.3 that affecting transmission prices in one market affected transmission prices in the other. As transmission prices are affected, long-term signals are affected as well.

Consider a case where two trading zones are not tightly coordinated (assuming tight coordination defined by any mechanism equivalent to the auction representation, e.g. market coupling). If the zones are not tightly coordinated, there may be an inefficient price difference between two zones. This results in a situation where gas purchases for power generation are cheaper than the optimal solution in one of the zones, and this constitutes a long-term signal.

One possible case is that the gas price is lower than the optimal solution in the zone with low power prices. In this case, even when the power market design is giving the correct long-term signals, such signals may be hidden by an inefficient gas price. If the inefficiency in the gas pricing is significant, one will observe gas-fired power plants investing in zones with low power price. In this situation, the signals from the gas market design are contributing to increase congestion in the power interconnection.

5.4. Lack of harmonization may raise barriers to network investment

Rious et al. (2011) described the investment in power networks as an anticipation problem. They described the investment in power networks related to the planner's expectations regarding the future needs of network. Such needs were related to the investment in generation plants. It is possible to use a similar reasoning for the analysis of the interaction between investment in gas and power networks. In that view, the expected localization of gas-fired power plants will affect the investment in both power and gas networks. And as showed above, such localization is affected by the combination of gas and power market designs. Therefore, the definition of the costs of gas-fired power plants implicit in the market design creates a link between investment in power and gas networks.

However, it is not clear whether power investments should anticipate gas investments or the other way around. A typical situation for investment needs created by the link between two markets is that both networks see advantages in a "wait and see" strategy, so that there is an incentive to delay network investment. Such incentive is less relevant when one of the two investment signals (gas or power networks) are strong enough or independent from the other market. But when needs for investments are created artificially in one

market, they may delay investments in the other market.

Consider the situations described in sections 4.1 and 4.3. For instance, let us assume that gas storage is cheaper in one zone (zone A) than in the other (zone B), everything else being the same. Let us also consider that electricity prices are lower in zone A. On the one hand, one could invest in the power network, building interconnection from zone A to zone B. One should then expect more investment in gas-fired power plants in the cheap-gas zone and observe exports of power from zone A to zone B. On the other hand, the gas network could be developed to provide cheap gas from zone A to power plants in zone B. The two situations show incentives for investment in gas networks from A to B and for investment in power networks from A to B.

The question thus is what to build. Consider that the power network is built first, so that energy is transported from A to B through the power network. There is a strong signal for power plant investment in the zone A (where the gas is more flexible). The gas price would increase enough, potentially enough to eliminate the interest of gas network investment. Consider otherwise: investment in the gas network takes place first, so that energy is transported from A to B through the gas network. In this case, there is a strong signal to invest in the zone with high power price (zone B), as gas prices are now more similar in the two zones. This eventually reduces power prices in zone B so that, after the investment in the gas network, it is possible that the power network investment is not profitable anymore.

The two previous cases show an incentive for the network planner to wait-and-see in order to observe the decisions of the other network. The situation was in turn created by artificial gas price differences, which were locational signals. As the initial network needs does not reflect the real network capacity (zone A has artificial cheap gas network prices), one observes an artificial need for gas network investment, which effectively competes with power network investments. Such artificial needs may delay investments in power networks, and hence result in barriers to network investment.

6. Conclusion

In this paper, we have studied the short-term interaction of market arrangements in power and gas systems. We have shown that several regulatory measures that affect the efficiency of one market also affect the other. The methodology used to study such interactions was based on the statement of an auction representation. By defining efficient operation as the results of such auctions, we have shown that the rules of each market constrain the possible efficiency of the other market. This paper showed that providing transmission or line-pack rights without representation of market pref-

erences implies affecting the choice of the commodity actually transported. In addition, this paper showed that providing free line-pack services implies subsidizing the power market.

Moreover, we have shown that the design of short-term operation has a significant impact on the resulting long-term signals. In particular, we showed that free gas flexibility and free transmission services may weaken localization signals for power plants investment. Finally, we showed that lack of harmonization between market designs may raise barriers to network investment. Therefore, when analyzing the costs and benefits of different designs, the cross-industry effects must be taken into account.

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Appendix

A. Allocation of network services through day-ahead auctions

A.1. A clearing algorithm for power markets

The algorithm for an implicit power auction is based on using nodal pricing models to clear the auction. The logic for the approach is to represent, by means of a simplified model of the operation of the power network, the optimal allocation of power flows implicit in players' bids for power commodity.

Consider a system made up of $i = 1, ..., N$ nodes and $j = 1, ..., M$ power lines. Let us denote (the transpose of a certain matrix $\mathcal{A}$ is denoted by $\mathcal{A}^T$):

- $P_t = \begin{pmatrix} P_t^1 & \dots & P_t^N \end{pmatrix}^T$ is the (column) vector of power productions at each network node at time t. $O_t(P_t)$ is the vector of production offers at each node i and time t.

- $D_t = \begin{pmatrix} D_t^1 & \dots & D_t^N \end{pmatrix}^T$ is the vector of power demands at each network node at time t. $U_t(D_t)$ is the vector of demand utilities at each network node at time t

- $f_t^{power} = \begin{pmatrix} f_t^{p,1} & \dots & f_t^{p,M} \end{pmatrix}^T$ is the vector of power flows through each power line of the system at time t

- $\mathcal{M}^p$ is the incidence matrix: the element $\mathcal{M}_{i,j}^p$ is 1 if the line j is leaving the node i, -1 if the line is arriving at the point, and zero otherwise

- $\mathcal{F}^p$ is the matrix relating flows through the power line and its phase differential. We use a DC representation

23

- $\theta_t = \begin{pmatrix} \theta_t^1 & \dots & \theta_t^N \end{pmatrix}^T$ is the vector of voltage phases at each network node at time t. We will choose the first node as the slack bus, so that $\theta_t^1 = 0$

In order to clear the auction, the auctioneer must take into account the system constraints. Power networks, however, are characterized by considerably non-linear equations. We will thus consider a DC linearization of the problem. Thus, the constraints are:

- The energy balance at each node

$$P_t = D_t + \mathcal{M}^p f_t^p$$

- The DC flow model

$$f_t^p = \mathcal{F}^p \theta_t$$

- The flow limits of power lines

$$f_t^{m,p} \le f_t^p \le f_t^{M,p}$$

With the previous notation, the total social surplus can be written as

$$\sum_t \left(O_t(P_t) - U_t(D_t) \right)$$

Therefore, the clearing algorithm can be represented by

$$
\begin{aligned}
\max_{P_t, D_t, f_t^p, \theta_t} \quad & \sum_t \left(O_t(P_t) - U_t(D_t) \right) \\
\text{s.t.} \quad & P_t = D_t + \mathcal{M}^p f_t^p && : \mu_t^{price,p} \\
& f_t^p = \mathcal{F}^p \theta_t && : \mu_t^{F,p} \\
& f_t^{m,p} \le f_t^p \le f_t^{M,p} && : \mu_t^{m,p}, \mu_t^{M,p}
\end{aligned}
$$

A.2. A CLEARING ALGORITHM FOR GAS MARKETS

The algorithm for an implicit gas auction that takes into account the line-pack is close to the reasoning of combinatorial auctions for electricity markets, see Vazquez and Hallack (2012). The logic for the application to short-term gas markets is to represent, by means of a simplified model of the operation of the gas network, the optimal allocation of gas flows and line-pack storage implicit in the players' bids for gas commodity.

In that view, the objective function of the optimization of the network services will be to maximize the social benefit. Consider a certain system made

up of $i = 1, \ldots, N$ entry/exit points (we assume, for the sake of simplicity, that entry/exit points are the same as the power network nodes) and $j = 1, \ldots, M$ pipelines. Let us denote (the transpose of a certain matrix $\mathcal{A}$ is denoted by $\mathcal{A}^T$):

- $I_t = \begin{pmatrix} I_t^1 & \ldots & I_t^N \end{pmatrix}^T$ is the (column) vector of injections at each entry/exit point at time t. $B_t(I_t)$ is the vector of injection offers at each entry/exit point i and time t.

- $W_t = \begin{pmatrix} W_t^1 & \ldots & W_t^N \end{pmatrix}^T$ is the vector of withdrawals at each entry/exit point at time t. $C_t(W_t)$ is the vector of withdrawal offers at each entry/exit point at time t

- $f_t^g = \begin{pmatrix} f_t^{g,1} & \ldots & f_t^{g,M} \end{pmatrix}^T$ is the vector of gas flows through the pipelines of the system at time t

- $l_t = \begin{pmatrix} l_t^1 & \ldots & l_t^N \end{pmatrix}^T$ is the vector of line-pack storage at each network point at time t

- $\mathcal{M}^g$ is the incidence matrix: element $\mathcal{M}_{i,j}^g$ is equal to 1 if the pipeline j is leaving the point i, -1 if the line is arriving at the point, and zero otherwise

- $\mathcal{F}_f^g$ is the matrix relating flows through pipelines to their pressure differential

- $\mathcal{F}_l^g$ is the matrix relating line-pack storage in pipelines to their pressure differential

- $\mathcal{L}^g = \mathcal{M}^g \mathcal{F}_l^g$ is the matrix relating line-pack storage at each node to pressure differentials in all pipelines connected to the point

- $p_t = \begin{pmatrix} p_t^1 & \ldots & p_t^N \end{pmatrix}^T$ is the vector of pressures at each entry/exit point at time t.

In order to clear the auction, the auctioneer must take into account the system constraints. Gas networks are also characterized by non-linear equations. If such physical characteristics are fully represented, there will be no linear price that clears the auction. We thus consider a linearization of the problem, so that both transmission capacity and line-pack storage are related to pressures through linear functions. In that view, the constraints that we are considering are:

- The energy balance at each entry/exit point

$$l_t = I_t - W_t + \mathcal{M}^g f_t^g + l_{t-1}$$

- The flow and line-pack definition in terms of nodes' pressure

$$f_t^g = \mathcal{F}_f^g p_t$$

$$l_t = \mathcal{L}^g p_t$$

- The pressure limits of pipelines

$$p_t^m \le p_t \le p_t^M$$

With the previous notation, the total social surplus can be written as

$$\sum_t \left(B_t(I_t) - C_t(W_t) \right)$$

Therefore, the clearing algorithm can be represented by

$$\max_{I_t, W_t, f_t^g, l_t, p_t} \quad \sum_t \left(B_t(I_t) - C_t(W_t) \right)$$

$$\text{s.t.} \quad l_t = I_t - W_t + \mathcal{M}^g f_t^g + l_{t-1} \quad : \mu_t^{price,g}$$

$$f_t^g = \mathcal{F}_f^g p_t \qquad\qquad\qquad : \mu_t^{F,g}$$

$$l_t = \mathcal{L}^g p_t \qquad\qquad\qquad : \mu_t^{L,g}$$

$$p_t^m \le p_t \le p_t^M \qquad\qquad : \mu_t^{m,g}, \mu_t^{M,g}$$

This auction mechanism is not intended to represent in full detail physical flows, but to separate the network services required to adjust shippers' portfolios from the complex technical characteristics that will be managed by the TSO.

B.   Optimality conditions and transmission pricing

B.1.   Allocation of power network services

In order to understand the functioning of the auction, it is useful to analyze its clearing conditions. They are given by the optimality conditions of the clearing algorithm. The optimality conditions for the previous program yields:

$$(Optimality \ of \ P_t): \qquad \frac{\partial O_t(P_t)}{\partial P_t} = \mu_t^{price,p} \tag{1}$$

$$(Optimality \ of \ D_t): \qquad \frac{\partial U_t(D_t)}{\partial D_t} = \mu_t^{price,p} \tag{2}$$

These two equations simply say that the marginal utility of production is equal to the marginal utility of consumption, and both are defined by $\mu_t^{price,p}$. Hence, the uniform of this auction π_t^p would be equal to the multiplier $\mu_t^{price,p}$. In that view, the price makes the marginal utility of production equal to the marginal utility of consumption.

$$(Optimality\ of\ f_t^p):\quad \mathcal{M}^{T,p}\mu_t^{price,p} - \mu_t^{F,p} + (\mu_t^{M,p} - \mu_t^{m,p}) = 0 \tag{3}$$

This equation gives the value of transmission along the whole network. It is expressed by means of the price differences among network nodes at a certain point in time.

$$(Optimality\ of\ \theta_t):\quad \mathcal{F}^p\mu_t^{F,p} = 0 \tag{4}$$

In addition, in order to solve the mathematical program, we need the constraints and the complementarity conditions:

$$(Power\ balance):\quad P_t = D_t + \mathcal{M}^p f_t^p \tag{5}$$
$$(DC\ power\ flow):\quad f_t^p = \mathcal{F}^p\theta_t \tag{6}$$
$$(Minimum\ flow):\quad (-f_t^{M,p} - f_t^p) \perp \mu_t^{m,p} \tag{7}$$
$$(Maximum\ flow):\quad (f_t^p - f_t^{M,p}) \perp \mu_t^{M,p} \tag{8}$$

B.2. ALLOCATION OF GAS NETWORK SERVICES

Again, auction clearing conditions are given by the optimality conditions of the clearing algorithm. The optimality conditions for the previous program yields:

$$(Optimality\ of\ I_t):\quad \frac{\partial B_t(I_t)}{\partial I_t} = \mu_t^{price,g} \tag{9}$$

$$(Optimality\ of\ W_t):\quad \frac{\partial C_t(W_t)}{\partial W_t} = \mu_t^{price,g} \tag{10}$$

Along the same lines as in the power-market auction, these two equations say that the marginal utility of production is equal to the marginal utility of consumption, and both are defined by $\mu_t^{price,g}$. Hence, the uniform price of this auction π_t^g would be equal to the multiplier $\mu_t^{price,g}$. As in the case of power auctions, the price makes the marginal utility of production equal to the marginal utility of consumption.

In addition,

$$(Optimality\ of\ f_t^g):\quad \mathcal{M}^{T,g}\mu_t^{price,g} - \mu_t^{F,g} = 0 \tag{11}$$

$$\tag{12}$$

27

$$(Optimality\ of\ l_t):\qquad \mu_{t+1}^{price,g} - \mu_t^{price,g} - \mu_t^{L,g} = 0 \qquad (13)$$

These two equations give the value of transmission and line-pack storage along the whole gas network. The former is expressed by means of the price differences among network nodes at a certain point in time, and the latter is expressed by the price difference, between two consecutive periods, at each network node.

In that view, the clearing algorithm is intended to decide how to determine the matching among bids at different network nodes and points in time. These two equations describe the procedure to define the values for line-pack and transmission in order to compare such bids.

$$(Optimality\ of\ p_t):\quad \mathcal{F}_f^{T,g}\mu_t^{F,g} + \mathcal{L}^{T,g}\mu_t^{L,g} + (\mu_t^{M,g} - \mu_t^{m,g}) = 0 \qquad (14)$$

In order to solve the mathematical program, we need the constraints and the complementarity conditions:

$$(Gas\ balance):\qquad\qquad l_t = I_t - W_t + \mathcal{M}^g f_t^g + l_{t-1} \qquad (15)$$
$$(Flow-pressure):\qquad\qquad f_t^g = \mathcal{F}_f^g p_t \qquad (16)$$
$$(Line\ pack-pressure):\qquad l_t = \mathcal{L}^g p_t \qquad (17)$$
$$(Minimum\ flow):\qquad\qquad (p_t^m - p_t) \perp \mu_t^{m,g} \qquad (18)$$
$$(Maximum\ flow):\qquad\qquad (p_t - p_t^M) \perp \mu_t^{M,g} \qquad (19)$$

The trade-off between line-pack storage and transmission services is relevant in our analysis. To analyze how line-pack storage is priced, consider that we do not have congestion, so

$$\mathcal{F}_f^{T,g}\mu_t^{F,g} = -\mathcal{L}^{T,g}\mu_t^{L,g}$$

On the one hand, using equation (13), we have that

$$-\mathcal{L}^{T,g}\mu_t^{L,g} = \mathcal{L}^{T,g}(\mu_{t+1}^{price,g} - \mu_t^{price,g})$$

and

$$\mu_t^{F,g} = \mathcal{M}^{T,g}\mu_t^{price,g}$$

On the other, the uniform price of the auction is defined by $\pi_t^g = \mu_t^{price,g}$. Hence, the previous clearing condition can be written as

$$\mathcal{F}_f^{T,g}\pi_t^g = \mathcal{L}^{T,g}(\pi_{t+1}^g - \pi_t^g)$$

The left-hand side of the equation represents the value of transmission along the network. The right-hand side of the equation gives the value of the

line-pack. Therefore, the algorithm clears the auction in order to make the marginal utility of transmission equal to the marginal utility of line-pack. Such marginal utilities are represented by offers of gas injections and withdrawals. From the viewpoint of players' bids, the choice between line-pack and transmission is done implicitly in their offers for gas commodity injections and withdrawals in the different hours of a day.

Authors contacts:

Miguel Vazquez

Federal University of Rio de Janeiro

Energy Economics Group (GEE), Economics Institute

Av. Pasteur, 250

Urca, Rio de Janeiro - 22290-240

Brazil

Email: Miguel.Vazquez.Martinez@gmail.com

Michelle Hallack

Fluminense Federal University, Economics Department

Rua Tiradentes, 17

Ingá, Niterói - 24210-510

Brazil

Email: MichelleHallack@gmail.com