

Market power and spatial arbitrage between interconnected gas hubs[☆]

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Abstract

This paper examines the efficiency of the arbitrages performed between two regional markets for wholesale natural gas linked by a capacity-constrained pipeline system. We develop a switching regime specification to (i) detect if the observed spatial arbitrages satisfy the integration notion that all arbitrage opportunities between the two markets are being exploited, and (ii) decompose the observed spatial price differences into factors such as transportation costs, transportation bottlenecks, and the oligopolistic behavior of the arbitrageurs. Our framework incorporates a test for the presence of market power and it is thus able to distinguish between the physical and behavioral constraints to marginal cost pricing. We use the case of the “Interconnector” pipeline linking Belgium and the UK as an application. Our empirical findings show that all the arbitrage opportunities between the two zones are being exploited but confirm the presence of market power.

Keywords: Law of one price, market integration, spatial equilibrium, interconnectors, natural gas.

JEL Classification: D43; F14; F15; L95; Q37.

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1. Introduction

Over the last two decades, a series of structural and regulatory reforms have been carried out to promote a competitive organization for the European natural gas industry. A major development in this restructuring was the emergence of a collection of wholesale markets for natural gas, the “gas hubs”, interconnected throughout the pipeline network. Though these hubs were initially developed to cope with local network balancing needs, they turned out to become a source of gas procurement as the previously monopolized industry structure gradually became more fragmented (Miriello and Polo, 2015). Crucially, EU-led reforms also allowed gas arbitrageurs to purchase intermarket transportation rights and compete to exploit spatial price differences between these interconnected markets.

The efficiency of these spatial arbitrages is key to ensure an efficient supply of natural gas, especially in the EU. The policy debates related to the organization of the EU’s internal market for natural gas repeatedly underline the importance of spatial arbitrages as a means to prevent balkanization (Vazquez et al., 2012). Indeed, security of natural gas supply is a recurrent source of concern in Europe as it is predominantly served by a small oligopoly of foreign producers (Abada and Massol, 2011). Geographically, each of these producers can be viewed as a dominant player in the adjacent national markets it serves (e.g., Russia in Eastern European countries, Algeria in Southern Europe). As the producers’ operations are located outside the EU jurisdiction, they can exert market power in supplying these markets, a situation that may be hard to moderate using the usual EU competition arsenal. To overcome that problem, the EU policy strongly promotes the “creation of a single gas market” – i.e., the spatial integration of the national wholesale markets – aimed at diluting the concentration observed in some countries within a wider economic market.

Defining and measuring integration, though, is not straightforward. In Stigler and Sherwin (1985), two geographical markets for a tradable good are set to be integrated if the spatial price difference between these two markets equals the unit transportation cost. However, empirically, assessing the geographic expanse of wholesale gas markets remains a challenging task because price spreads could also reflect other factors, including transportation bottlenecks and, more importantly, oligopolistic pricing by the arbitrageurs. To overcome this problem, we define integration using the equilibrium notion that all spatial arbitrage opportunities between the two markets are being exploited, i.e: that price spreads are consistent with the traders’ profit maximization behavior. This notion is derived from the theoretical literature on spatial price determination that was pioneered by Enke (1951), Samuelson (1952), Takayama and Judge (1971) and Harker (1986).

The aim of this paper is to develop an empirical methodology to assess the arbitrages performed between two regional markets for wholesale natural gas linked by a capacity-constrained pipeline. This methodology is designed to (i) detect if these markets are “integrated,” i.e., if all the spatial arbitrage opportunities are being exploited, and (ii) decompose the observed spatial price differences into factors such as transportation costs, transportation bottlenecks, and the oligopolistic behavior of

the arbitrageurs. Our framework incorporates a test for the presence of market power and is thus able to distinguish between physical and behavioral constraints to marginal cost pricing. As an application, we use the spatial arbitrages in the “Interconnector” pipeline which connects Europe’s two oldest spot markets for natural gas: the UK’s National Balancing Point and the Zeebrugge market in Belgium.

A large amount of empirical research has examined the degree of spatial integration between markets for wholesale natural gas with the help of time-series techniques.¹ These studies typically rely on local price data and assess the co-movements of prices at each market location. In these analyses, it is typically argued that high degrees of correlation and/or co-integration between the price series are evidence that the law of one price is being enforced through spatial arbitrages. These price-based empirical models provide useful insights into how local price shocks are transmitted to adjacent markets. However, the methodology used in these studies is of little help in assessing the competitive nature of the observed spatial arbitrages, as they fail to detect the presence of imperfect competition. Moreover, as suggested by the related agricultural economics literature (Barrett, 1996, 2001; Baulch, 1997; McNew and Fackler, 1997), these empirical models are unable to account for the pivotal role played by both intermarket transfer costs and trade flow considerations.²

In this paper, we consider an alternative approach based on the parity bounds model (PBM) first introduced in Spiller and Huang (1986).³ In a PBM, arbitrageurs are assumed to be profit-maximizing agents. Using that assumption, intermarket price spreads are examined using a “switching regime” specification, which estimates the probability of observing each of a series of trade regimes. Sexton et al. (1991), for example, consider three distinct trade regimes: an “arbitrage” regime where the spatial price difference equals the unit intermarket transportation cost, an “autarkic” one where the local prices differ by less than that transportation cost, and a “barriers to trade” regime where the observed spatial price difference is larger than that transportation cost. Barrett and Li (2002), our point of departure, make use of trade flow data to further distinguish whether trade occurs or not in each of the

¹ A tentative and non-exhaustive methodological clustering of these contributions includes: (i) the early correlation-based analyses (Doane and Spulber, 1994); (ii) the use of Granger causality tests to examine how natural gas price shocks are transmitted across interconnected wholesale markets (Doane and Spulber, 1994); (iii) the cointegration-based studies that test for the existence of a long-run equilibrium condition governing the local price series (e.g., De Vany and Walls, 1993; Serletis, 1997; Asche et al., 2002; Siliverstovs et al., 2005; Asche et al., 2013); (iv) the analyses examining a time-varying degree of price convergence among natural gas spot markets with the help of the Kalman Filter approach (King and Cuc, 1996; Neumann et al., 2006; Renou-Maissant, 2012); (v) the use of an autoregressive model of pairwise price differentials between geographically diverse locations to estimate the speeds of adjustment toward equilibrium (Cuddington and Wang, 2006); (vi) the joint assessments of the degree of market integration and price transmission across natural gas markets using tests of cointegration and the corresponding error-correction models (Park et al., 2008; Brown and Yücel, 2008; Olsen et al., 2015).

² These criticisms emphasize a lack of acquaintance with existing economic models of spatial price determination. Two lines of arguments motivate that shortcoming. First, intermarket transfer costs are typically omitted in these early empirical studies whereas, in theory, price equalizing arbitrage activities are triggered only when localized shocks result in spatial price differences which exceed these intermarket transfer costs (Barrett, 1996, 2001; Baulch, 1997; McNew and Fackler, 1997). Second, trade flows information play no role in these early empirical studies whereas theory suggests that either discontinuities in the trade flows or variations in the directions of these flows can have an impact on the degree of co-movements among prices at each market location (Barrett and Li, 2002).

³ This model has been further extended in Spiller and Wood (1988), Sexton et al. (1991), Baulch (1997), Kleit (1998, 2001), Bailey (1998), Barrett and Li (2002) and Negassa and Myers (2007).

three regimes. This direction-specific approach allows them to detect any violation of the theoretical equilibrium conditions that all arbitrage opportunities between the two markets are being exploited.

We propose two modifications of existing PBMs to apply them to the case of natural gas markets. Existing models assume the presence of perfect competition in the spatial arbitrages between two markets. So, we first propose an enriched specification to account for the role of market power and show that it can be used to test for the assumption of perfectly competitive arbitrages. Second, the role of transportation bottlenecks has so far been neglected whereas binding pipeline capacity constraints are likely to occur in the gas industry. So, we propose isolating the specific contribution of pipeline capacity constraints in the observed spatial price spreads.

We believe that this framework can provide useful guidance to a large audience interested in the functioning of the restructured natural gas industries (e.g., competition authorities, regulators, market analysts), and to researchers engaged in the detailed modeling of these industries.⁴ As an application, we examine the spatial arbitrages performed between the two oldest European markets for wholesale natural gas in Belgium and the UK. This allows us to present a series of original empirical findings that: (i) show that all the arbitrage opportunities between the two zones are being exploited, but (ii) confirm the presence of market power in the spatial arbitrages. As the detailed institutional arrangements created for these two markets have largely shaped the designs of the other Continental markets, we believe that these findings provide a valuable contribution to the policy debate related to the restructuring of the European market for natural gas.

Despite the importance of market power concerns in the energy policy debates, the market power potentially exerted by natural gas arbitragers has hitherto been little studied. A notable exception is the theoretical analysis in Ritz (2014) who highlights the potential role of the LNG exporters' market power in the observed price differentials between Asia and Northwest Europe. In an empirical analysis, Rupérez Micola and Bunn (2007) apply standard regression techniques to examine the relationship between the pipeline capacity utilization (i.e., the ratio of utilized to maximum capacity) and the absolute price difference between Belgium and the UK. Their results document the presence of market splitting at moderate levels of capacity utilization which, according to the authors, suggests the presence of market power inefficiencies. However, neither the direction of the trade flows nor the intermarket transfer costs play any role in their analysis. By taking these features into account, our paper confirms the presence of market power, even if all the arbitrage opportunities are being exploited, and connects the empirical results to the theoretical literature on spatial price determination.

The remaining sections of this paper are organized as follows. Section 2 details the theoretical conditions for spatial equilibrium between two markets linked by a capacity-constrained transportation

⁴ *In recent years, there has been an upsurge of interest in the application of operations research techniques to simulate the functioning of a restructured natural gas industry with the help of large scale equilibrium models (cf., Huntington, 2009). However, the selection of the behavioral assumptions used to represent spatial arbitrages in these numerical models remains controversial as some models posit the existence of competitive spatial arbitrages (e.g., Golombek et al., 1995), whereas imperfect competition assumptions are used in others (e.g., Abada et al., 2013).*

infrastructure. Section 3 presents an adapted empirical methodology to investigate whether these conditions hold or not. Then, Section 4 details an application of this methodology to the case of the Interconnector UK, a natural gas pipeline connecting the UK to Continental Europe. Finally, the last section offers a summary and some concluding remarks.

2. Theoretical background

This section presents the theoretical conditions for short-run spatial equilibrium between two markets connected by a capacity-constrained transportation infrastructure. We make two alternative assumptions regarding the *gas traders'* behavior: perfect competition and oligopolistic behavior à la Cournot. For simplicity, in both cases, the *local* supply in both markets is assumed to be competitive.

We consider two markets i and j located in different regions that trade a homogeneous commodity. At time t , the two markets are connected by a single transportation infrastructure that has direction-specific, non-negative finite capacities that can change over time, K_{ji} from market from j to i and K_{ij} in the opposite direction. During any trading period t , the infrastructure solely allows to move the commodity in a given direction, and therefore the directional capacities *de facto* verify $K_{ji} \times K_{ij} = 0$. The direction of the infrastructure is known at the beginning of each trading period. It can vary from one such period to the next but not within a given trading period. This framework is consistent with the physical constraints observed in the natural gas industry.⁵

Let us, from now on, concentrate on the direction-specific arbitrages that can be performed from market j to market i at time t . For each region i at time t , we assume that there is a linear inverse demand function: $p_i^D(q) = a_i - b_i q$ with $a_i > 0$ and $b_i > 0$.⁶ We assume that the local industries' aggregate supply functions are linear and upward sloping.⁷ In each region i at time t , we let

⁵ For example, the interconnector pipeline connecting Belgium and the UK analyzed in Section 4 has a bidirectional nature but, during the normal trading hours of a given day, it can only be operated in a given predetermined direction. This rigidity is imposed by the gas-pipeline technology: to physically move the gas from one inlet point to the outlet one, the pipeline operator has to start a compressor at the inlet point to increase the operating pressure there. Because of substantial system inertia, the flow direction cannot be changed within the trading hours. Therefore, the direction of the infrastructure is typically communicated to traders at the beginning of the trading hours who, in turn, know that their arbitrage decisions cannot modify the direction of the infrastructure within the day. Moreover, one should note that even if the direction of the infrastructure is kept unchanged between two consecutive days (for example from j to i), the pipeline capacity can fluctuate from one day to the next depending on a series of exogenous factors including: the operating pressures of the adjacent national pipeline systems, the flow temperature, the chemical composition of the natural gas (See Yépez (2008) or Massol (2011) for an engineering-based introduction to gas pipeline economics). Therefore, at two different dates \hat{t} and \mathcal{T} , we can have both $K_{ji} \times K_{j\hat{t}} > 0$ and $K_{ji} \neq K_{j\mathcal{T}}$.

⁶ We can remark that these slope coefficients are not subscripted with the time index and are thus assumed to be constant. In contrast, the intercepts of these inverse demand functions are assumed to be time-varying parameters (because of the seasonal variations observed in natural gas demand). These assumptions are frequently used in the context of restructured electricity markets (e.g., Day and Bunn, 2001).

⁷ The use of a linear functional form for the supply curves simplifies computations and is commonly adopted in the energy economics literature (e.g., Green, 1996; Boffa et al., 2010). Regarding the case of the natural gas industry, this assumption is usually justified on the following grounds. We assume that the gas supply industry consists of several firms, each of which, in turn, controls several fields with varying efficiency levels. In the short run, we assume that these fields produce their entire capacity whenever the price is above marginal extraction cost. As the local spot market price increases, more suppliers find

$p_{ii}^s(S_{ii}) = c_{ii} + d_i S_{ii}$, with $c_{ii} > 0$ and $d_i > 0$ and where S_{ii} is the local supply, denote the inverse supply function.⁸

The trading firms' unique activity is to perform spatial arbitrages. We assume that there are no transport lags so that spatial arbitrage can take place within each observation period. The non-negative aggregate trade flow from j to i measured at time t is denoted Q_{jit} .

When performing a spatial arbitrage from market j to market i at time t , a trader incurs the unit transfer costs T_{jit} . In addition, that trader must also purchase an appropriate amount of transportation rights. A transportation right provides its owner with the right to transfer up to one unit of good from market j to market i at a given time period t . We let ξ_{jit} denote the market clearing price of a transportation right from market j to market i at time t . The total number of rights offered at that time is K_{jit} .

a – Case A: Perfectly competitive spatial arbitrages

In this case, we assume that traders adopt a price-taking behavior at each location and in the market for transportation rights. Following the logic of the Enke-Samuelson-Takayama-Judge spatial equilibrium model, the traders' aggregate behavior at time t can be described using two complementarity conditions that together characterize the equilibrium conditions for competitive spatial arbitrages:

Proposition 1: *For the equilibrium conditions for perfectly spatial arbitrages to hold at time t , we need that the following aggregate complementarity conditions are verified:*

$$0 \leq Q_{jit}, \quad P_{ii} - P_{jt} - T_{jit} - \xi_{jit} \leq 0 \quad \text{and} \quad (P_{ii} - P_{jt} - T_{jit} - \xi_{jit}) Q_{jit} = 0, \quad (1)$$

$$0 \leq \xi_{jit}, \quad Q_{jit} \leq K_{jit} \quad \text{and} \quad (Q_{jit} - K_{jit}) \xi_{jit} = 0, \quad (2)$$

where P_{ii} and P_{jt} are the market clearing prices in each location, and ξ_{jit} is the price of a transportation right that is the price of capacity (in excess of T_{jit}) that ensures that demand for transportation services does not exceed supply K_{jit} .

it profitable to employ more fields for extracting natural gas. Notwithstanding the limitations associated with this representation (e.g., it neglects the intertemporal issues related to the exhaustible nature of natural gas), we proceed assuming that this linear supply curve is a sensible assumption in the context of a model focusing on short-term issues.

⁸ To avoid corner solutions, we also assume that: (i) in the destination market i , the price demanded when the import infrastructure is operated at full capacity is larger than the marginal cost of the least-costly local supplier (i.e., $a_{ii} - b_i K_{jit} > c_{ii}$), and (ii) in the origin market j , the marginal cost to solely supply a flow equal to the infrastructure capacity is lower than the local consumers' highest willingness to pay for that commodity (i.e., $a_{jt} > c_{jt} + d_j K_{jit}$).

The proof of that proposition is detailed in Appendix A. The complementarity condition (1) clarifies the value of the traders' marginal profit to spatial arbitrages. This marginal profit is defined as the difference between the market-clearing price at location i and the marginal cost which is the sum of three elements: the price at location j , the marginal transfer cost T_{ji} and ξ_{ji} the price of a transportation right. The complementarity condition (2) ensures that the price ξ_{ji} is equal to zero whenever the aggregate demand for transportation right Q_{ji} is lower than the supply (i.e., whenever the transportation capacity constraint $Q_{ji} \leq K_{ji}$ is slack), and that ξ_{ji} is positive when the constraint $Q_{ji} \leq K_{ji}$ is binding. In case of a zero price for transportation right (i.e., $\xi_{ji} = 0$), the complementarity condition (1) ensures: (i) that there is no trade from market j to market i (i.e., $Q_{ji} = 0$) when the marginal profit to spatial arbitrage is negative, and (ii) that the spatial price spread is equal to the marginal transfer cost T_{ji} when trade occurs and it is not constrained by the infrastructure's capacity (i.e., $0 < Q_{ji} < K_{ji}$). In case of a binding capacity constraint (i.e., $Q_{ji} = K_{ji}$), the complementary condition (1) ensures that the spatial price difference is larger than the marginal transfer cost T_{ji} . In this case, there exists a scarcity rent $\xi_{ji} K_{ji} = (P_i - P_j - T_{ji}) K_{ji}$.

b – Case B: Oligopolistic spatial arbitrages

We now assume that there are a total of G gas traders that behave à la Cournot in the local markets. As in Harker (1986), each trader thus knows how the prices in each region react to the quantities supplied and demanded thorough the intermarket infrastructure but rather takes the price of transportation right as given. The following proposition indicates that the traders' aggregate behavior at time t can also be described using two complementarity conditions.

Proposition 2: *For the equilibrium conditions for oligopolistic spatial arbitrages to hold at time t , we need that the following aggregate complementarity conditions are verified:*

$$\left\{ \begin{array}{l} 0 \leq Q_{ji}, \quad P_i - P_j - T_{ji} - \left(\frac{d_i b_i}{b_i + d_i} + \frac{d_j b_j}{b_j + d_j} \right) \frac{Q_{ji}}{G} - \xi_{ji} \leq 0 \quad \text{and} \\ \left(P_i - P_j - T_{ji} - \left(\frac{d_i b_i}{b_i + d_i} + \frac{d_j b_j}{b_j + d_j} \right) \frac{Q_{ji}}{G} - \xi_{ji} \right) Q_{ji} = 0, \end{array} \right. \quad (3)$$

$$0 \leq \xi_{ji}, \quad Q_{ji} \leq K_{ji} \quad \text{and} \quad (Q_{ji} - K_{ji}) \xi_{ji} = 0, \quad (4)$$

where P_i and P_j are the local market clearing prices.

The proof of that proposition is detailed in Appendix B. The economic interpretation of these conditions is similar to those detailed for the case of competitive arbitrages except that the traders' aggregate behavior at time t now accounts for the players' ability to exert market power in both

markets. At equilibrium, the marginal revenue obtained by a trader in the destination market is $P_{it} - \frac{d_i b_i}{b_i + d_i} \cdot \frac{Q_{jit}}{G}$ where $-\frac{d_i b_i}{b_i + d_i} \cdot \frac{Q_{jit}}{G}$ represents the marginal loss of revenue from getting a lower price for each of the units the player is selling there. The trader's marginal cost includes three distinct components: (i) the marginal purchase cost in the origin market $P_{jt} + \frac{d_j b_j}{b_j + d_j} \cdot \frac{Q_{jit}}{G}$ where $\frac{d_j b_j}{b_j + d_j} \cdot \frac{Q_{jit}}{G}$ represents the marginal cost increase from getting a higher price for each of the units the player is purchasing (i.e., the effect of the players' oligopsonistic behavior in market j); (ii) the marginal transfer cost T_{jit} , and (iii) the price of a transportation right ξ_{jit} .

It is instructive to compare these aggregate conditions with the ones obtained in case of competitive arbitrage. One may remark that, in the event of oligopolistic arbitrages, the spatial price differential in (3) is always larger than the marginal transfer cost T_{jit} when trade is observed. Moreover, from an empirical perspective, it is interesting to note that the spread between the spatial price differential and the marginal transfer cost is proportional to the aggregate trade flow when trade is observed and the congestion constraint is slack. We shall come back to this point in the sequel. For the moment, we simply highlight that this reflects the traders' ability to exert market power by restricting intermarket trade to generate some oligopolistic rents.

3. Methodology

This section presents the methodology used in this manuscript. We first adapt the existing PBM framework to take into account the role of both pipeline capacity constraints and market power. Subsequently, we detail the empirical specification.

3.1 An adapted parity bounds model

We now define seven mutually exclusive trade regimes and relate them to the theoretical conditions for spatial equilibrium detailed in the previous section. In addition to the six trade regimes considered in the PBM proposed in Barrett and Li (2002), we introduce a new one that takes into account the case of pipeline congestion. Moreover, for each of these trade regimes, we distinguish between the cases of perfectly competitive and oligopolistic spatial arbitrages.

From an empirical perspective, it is important to highlight that the price of a transportation right ξ_{jit} is seldom publicly available as its formation chiefly results from over the counter transactions. In the sequel, we thus follow the convention in Barrett and Li (2002) and define the marginal rents to spatial arbitrage in case of competitive arbitrages as the difference between the spatial price spread and the marginal transfer cost T_{jit} . For ease of exposition, we also define the marginal rents to spatial arbitrage in case of oligopolistic arbitrages as the difference between the marginal revenue obtained in market i (i.e., including the term representing the traders' ability to exert oligopolistic market power

there) and the sum of the marginal purchase cost in market j (i.e., including the term representing the traders' ability to exert oligopsonistic market power there) and the marginal transfer cost T_{jit} .⁹

As shown in Table 1, marginal rents to spatial arbitrage and trade flow considerations can be combined to define a taxonomy of trade regimes governing the arbitrages from market j to market i . Regarding marginal rents to spatial arbitrage, three basic states can be defined depending on their value: zero, strictly positive, or strictly negative. Regarding trade flows, two basic states can be identified depending on whether a positive trade flow is observed or not. Following Barrett and Li (2002), each of these six regimes is labeled I to VI, where odd numbers are used for regimes with strictly positive trade flows and even numbers for those without trade.

Table 1. The trade regimes in each direction

	Trade is observed: $0 < Q_{jit} \leq K_{jit}$	No trade is observed: $Q_{jit} = 0$
zero marginal rents to spatial arbitrage	Regime I λ_I	Regime II λ_{II}
positive marginal rents to spatial arbitrage	Regime III _a iff $Q_{jit} < K_{jit}$ λ_{III_a} Regime III _b iff $Q_{jit} = K_{jit}$ λ_{III_b}	Regime IV λ_{IV}
negative marginal rents to spatial arbitrage	Regime V λ_V	Regime VI λ_{VI}

In regimes I and II, the marginal rents to spatial arbitrage are equal to 0. As shown in the previous section, depending on the assumption posited for the behavior of the trading sector, one of the following conditions is binding:

<p><u>Case A: Competitive arbitrages</u></p> $P_{it} - P_{jt} - T_{jit} = 0 \quad (5)$		<p><u>Case B: Oligopolistic arbitrages</u></p> $P_{it} - P_{jt} - T_{jit} - \left(\frac{d_i b_i}{b_i + d_i} + \frac{d_j b_j}{b_j + d_j} \right) \frac{Q_{jit}}{G} = 0 \quad (6)$
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In case of price-taking behavior (Case A), the spatial price differential is equal to the marginal transfer cost. In case of oligopolistic arbitrages (Case B), the possibility to exert market power results in a spatial price differential that exceeds the marginal transfer cost and the difference between the two is proportional to the observed trade flow. In Case A (respectively B), each of the two regimes verifies

⁹ Hence, both definitions do not include the price of a transportation right and thus differs from the marginal profit to spatial arbitrages defined above.

the complementarity slackness condition (1) (respectively (3)) when there is no congestion cost (i.e., $\xi_{ji} = 0$). Therefore, both regimes are consistent with the conditions for a spatial equilibrium.

In regimes III and IV, the marginal rents to spatial arbitrage from j to i are strictly positive:

<p><u>Case A: Competitive arbitrages</u></p> $P_{it} - P_{jt} - T_{jit} > 0 \quad (7)$		<p><u>Case B: Oligopolistic arbitrages</u></p> $P_{it} - P_{jt} - T_{jit} - \left(\frac{d_i b_i}{b_i + d_i} + \frac{d_j b_j}{b_j + d_j} \right) \frac{Q_{jit}}{G} > 0 \quad (8)$
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In both of these regimes, markets are separated and there are unseized opportunities for profitable spatial arbitrage. Still, in case of positive trade (regime III), the observed insufficient arbitrages might result from the capacity-constrained nature of the transportation infrastructure. Indeed, the complementarity conditions detailed in the preceding section indicate that, in case of a binding capacity constraint (i.e., $Q_{jit} = K_{jit}$), observing a strictly positive value for the marginal rents to arbitrage is consistent with the conditions for a short-run spatial equilibrium. In contrast, the joint observation of strictly positive marginal rents to arbitrages and a slackening in the infrastructure's capacity constraint violates the conditions for a spatial equilibrium. Thus, we propose a modification to the original model and further decompose regime III into two mutually exclusive regimes labeled III_a and III_b. In regime III_a, the observed trade flows verify $0 < Q_{jit} < K_{jit}$ whereas a binding capacity constraint (i.e., $Q_{jit} = K_{jit}$) is observed in regime III_b. Therefore, the latter regime, but not the former, is consistent with the conditions for a spatial equilibrium.

In regimes V and VI, the marginal rents to arbitrage from j to i are strictly negative:

<p><u>Case A: Competitive arbitrages</u></p> $P_{it} - P_{jt} - T_{jit} < 0 \quad (9)$		<p><u>Case B: Oligopolistic arbitrages</u></p> $P_{it} - P_{jt} - T_{jit} - \left(\frac{d_i b_i}{b_i + d_i} + \frac{d_j b_j}{b_j + d_j} \right) \frac{Q_{jit}}{G} < 0 \quad (10)$
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In both regimes, there are no profitable arbitrage opportunities. In regime VI, trade is not occurring and the observed local prices correspond to autarky prices. This regime is consistent with the conditions for a spatial equilibrium. In contrast, regime V indicates that trade is occurring despite negative marginal profits which is not consistent with equilibrium conditions.

In sum, having introduced a further distinction between regimes III_a and III_b, a total of seven regimes are thus considered in our analysis. The estimated probability to observe regime r is denoted λ_r . Spatial equilibrium conditions hold with probability $(\lambda_I + \lambda_{II} + \lambda_{III_a} + \lambda_{VI})$ and the estimated probability to observe disequilibrium is $(\lambda_{III_b} + \lambda_V)$.

3.2 Empirical specification

We now detail the empirical specification aimed at estimating the probabilities of being in each regime using a data set of N observations for the local market-clearing prices, the marginal transfer cost, the trade flow, and the available transportation capacity.

In case of oligopolistic arbitrages, the slope coefficients for the local inverse demand and supply functions are unlikely to be readily available to the modeler. So, we introduce γ an unknown parameter to be estimated that will be interpreted as $\frac{1}{G} \left(\frac{d_i b_i}{b_i + d_i} + \frac{d_j b_j}{b_j + d_j} \right)$ the sum of the two local coefficients determined by the slopes of the inverse supply and inverse demand functions. So, we expect the estimated value for γ to be non-negative.

Denoting $R_{jit} \equiv P_{it} - P_{jt} - T_{jit}$ the series that represents the difference between the spatial price spread and the unit transfer cost, the marginal rents to arbitrage in each of the three distinct cases (zero, positive and negative) are modeled using the following switching regression model (Sexton et al., 1991; Baulch, 1997; Barrett and Li, 2002):

<u>Case A: Competitive arbitrages</u>	<u>Case B: Oligopolistic arbitrages</u>
Regimes I & II: $R_{jit} = \varepsilon_{jit} \quad (11)$	Regimes I & II: $R_{jit} = Q_{jit} \gamma + \varepsilon_{jit} \quad (14)$
Regimes III _a , III _b & IV: $R_{jit} = \varepsilon_{jit} + \mu_{jit} \quad (12)$	Regimes III _a , III _b & IV: $R_{jit} = Q_{jit} \gamma + \varepsilon_{jit} + \mu_{jit} \quad (15)$
Regimes V & VI: $R_{jit} = \varepsilon_{jit} - v_{jit} \quad (13)$	Regimes V & VI: $R_{jit} = Q_{jit} \gamma + \varepsilon_{jit} - v_{jit} \quad (16)$

where: γ is an unbounded parameter to be estimated; ε_{jit} is a random error that is assumed to be i.i.d. normally distributed with a zero mean and variance σ_ε^2 ; and μ_{jit} and v_{jit} are i.i.d. random samples from zero-centered normal distributions truncated above at 0 with respective variance parameters σ_μ^2 and σ_v^2 .

In applications, measurement and sampling error are likely to occur with any data to which this model might be applied. An extended specification may be justified to control for these issues. In the sequel, a regime-invariant mean parameter α_{ji} is systematically implemented in the equations to capture the time invariant component of possible measurement errors.

The specifications used to model the cases of competitive and oligopolistic spatial arbitrages differ only in the markup term $Q_{jit}\gamma$. Thus, a statistical test of the null hypothesis $\gamma=0$ (e.g., a likelihood ratio test) can be conducted to test the null hypothesis of perfectly competitive spatial arbitrages. For the sake of brevity, only the unrestricted model based on equations (14), (15), and (16) is detailed hereafter.

Denoting λ the vector of the probabilities to observe the seven regimes, $\theta \equiv (\alpha_{ji}, \gamma, \sigma_\varepsilon, \sigma_\mu, \sigma_v)$ the parameter vector to be estimated and $\pi_{jit} \equiv R_{jit} - \alpha_{ji} - Q_{jit}\gamma$ the random variable that gives the marginal profit from spatial arbitrage at time t , the joint density function for the observation at time t is the mixture distribution:

$$f_{jit}(\pi_{jit} | (\lambda, \theta)) \equiv A_{jit} \left[\lambda_I f_{jit}^I(\pi_{jit} | \theta) + ((1 - B_{jit})\lambda_{III_a} + B_{jit}\lambda_{III_b}) f_{jit}^{III}(\pi_{jit} | \theta) + \lambda_V f_{jit}^V(\pi_{jit} | \theta) \right] \\ + (1 - A_{jit}) \left[\lambda_{II} f_{jit}^{II}(\pi_{jit} | \theta) + \lambda_{IV} f_{jit}^{IV}(\pi_{jit} | \theta) + \lambda_{VI} f_{jit}^{VI}(\pi_{jit} | \theta) \right] \quad (17)$$

where: A_{jit} is an indicator variable that takes a value of 1 if trade is observed and zero otherwise; B_{jit} is an indicator variable that takes a value of 1 if the transportation infrastructure is congested and zero otherwise; $f_{jit}^I(\pi_{jit} | \theta)$ and $f_{jit}^{II}(\pi_{jit} | \theta)$ are normal density functions; $f_{jit}^{III}(\pi_{jit} | \theta)$ and $f_{jit}^{IV}(\pi_{jit} | \theta)$ (respectively $f_{jit}^V(\pi_{jit} | \theta)$ and $f_{jit}^{VI}(\pi_{jit} | \theta)$) are the density functions derived in Weinstein (1964) for the sum of a normal random variable and a centered-normal random variable truncated above (respectively below) at 0.

The likelihood function for a sample of observations $\{R_{jit}, Q_{jit}, K_{jit}\}$ is:

$$L(\lambda, \theta) \equiv \prod_{t=1}^N f_{jit}(\pi_{jit} | (\lambda, \theta)) \quad (18)$$

The model can be estimated by maximizing the logarithm of the likelihood function with respect to regime probabilities and model parameters subject to the constraints that the regime probabilities sum to one and that each of these probabilities lies in the unit interval.

As most existing PBM models, the specification described so far is based on a static formulation whereby shocks are posited to be serially independent and the variance parameters are held constant throughout the entire observation period. As these assumptions can be too restrictive in applications based on daily data, we use an enriched dynamic specification including a correction for serial correlation and GARCH-type time-varying variance, as detailed in Appendix C.

This specification differs from that of Barrett and Li (2002) in four ways. First, we show how a parity bound model can be used to test the null hypothesis of competitive spatial arbitrages. Second, contrary to Barrett and Li, the two markets under scrutiny are connected by a capacity-constrained transportation infrastructure. So, a seventh regime labeled III_b is introduced to account for the

explanatory role played by infrastructure congestion issues in the observation of positive marginal profits to spatial arbitrage. Third, we follow Baulch (1997) and Negassa and Myers (2007) and relax the restriction to use a unique variance parameter for the half-normal distributions of the two non-negative error terms μ_{ijt} and ν_{ijt} in the likelihood functions.¹⁰ Lastly, the specification is extended to a dynamic formulation.

4. Application

4.1 Background

This application focuses on the so-called Interconnector (hereafter abbreviated to IUK), a bi-directional natural gas pipeline system connecting the UK National Transportation System (using the Bacton Terminal) to Zeebrugge (Belgium). This infrastructure allows spatial arbitrages between Europe's two oldest spot markets for natural gas: (i) the UK's NBP, which allows counterparties to trade a standardized lot of natural gas piped via the UK National Transmission System with a delivery point at the so-called National Balancing Point (NBP); and (ii) the Zeebrugge local market in Belgium, which is labeled ZEE.

We consider the period covering October 1, 2003, to October 5, 2006.¹¹ During that period, the IUK pipeline was the unique infrastructure linking the UK and Continental natural gas markets. In addition, that period corresponds to a steady institutional environment with unchanged access rules for both the IUK and the adjacent national pipeline systems. These features make the IUK case an attractive experiment to investigate the efficiency of the spatial price arbitrages that can be performed in a deregulated natural gas industry.

4.2 Data

We use daily transaction price data for day-ahead wholesale natural gas traded during working days as published by Platt's, a price-reporting service. For each working day (i.e., Monday to Friday), they reflect the price range of a standardized quantity of natural gas to be delivered at a constant flow rate throughout the next working day after assessment (Platt's, 2012). All prices are denominated in €/MWh. Given the extremely limited liquidity of within-day markets, we follow the usual convention and refer to these day-ahead prices as "spot" since they provide traders with a final opportunity to trade gas out of a forward position before physical delivery.

¹⁰ One might argue that, in certain applications, sample size considerations could motivate the use of the restriction $\sigma_\mu = \sigma_\nu$ to reduce the number of parameters to be estimated. Yet, this restriction can hardly be justified a priori in the application discussed in this paper.

¹¹ This starting date has been chosen to omit the number of partial closures that happened during the summer of 2003 (Futyan, 2006). This terminal date corresponds to the opening of the Langeled infrastructure, a pipeline system that together with already existing offshore pipelines, allowed Norwegian gas producers to perform spatial arbitrages between the UK and the Continent, thereby offering an alternative to the IUK.

The unit transfer costs T_{ju} are direction-specific and are derived from the fuel used by the IUK operator to power its compressor equipment since this cost is billed to the traders. According to the pipeline operator, fuel gas consumption amounts to 0.8% of the quantity of gas transported when natural gas is piped from the UK to Belgium, and to 0.26% of the quantity of gas transported in the other direction. This fuel cost is evaluated using the price of natural gas in the exporting market.

Regarding trade flow data, the wish may be to use an aggregate variable gathering all the transportation nominations communicated at the end of any working day for delivery during the next working day. Unfortunately, these data are confidential. So, this study uses a proxy: a historical flow series representing the physical daily flow of natural gas, measured in GWh/day, that transited through the IUK as reported on the pipeline operator's website. Thus, we proceed under the assumption that the physical gas flow measured during a given working day represents an unbiased estimator of the aggregate transportation nominations decided during the previous working day (at the time when trade occurs in the corresponding day-ahead market).¹²

According to the Interconnector operator, the nominal transportation capacity from the UK to Belgium remained unchanged during the entire sample period. In the other direction, the installation of some compressor equipment in Zeebrugge on November 8, 2005, increased the transportation capacity. Unfortunately, information related to the available daily transportation capacities remains unavailable. So, we follow Rupérez Micola and Bunn (2007) and consider the historical maximum values of the trade flows. The historical maxima were: 624.63 GWh/day from the UK to Belgium, and 310.24 GWh/d prior to November 8, 2005, (respectively 511.80 GWh/d after that date) in the other direction. Nevertheless, it should be noted that the daily flow capacity of a point-to-point natural gas pipeline is a time-varying parameter that depends on a series of exogenous factors (e.g., the operating pressures of the adjacent national pipeline systems, the flow temperature, the chemical composition of the natural gas). Hence, the historical maximum daily flow cannot necessarily be attained. We proceed by assuming that congestion is likely to be a source of concern when the observed capacity utilization ratio (measured against the historically maximum) exceeds 80%. Hereafter, this threshold is used to distinguish regimes III_a and III_b .

The data set has been modified in two ways. First, both the Belgium and UK markets are closed on national bank holidays. To account for differences in the national calendars, all the observations related to a bank holiday in either Belgium or the UK have been disregarded in the subsequent analyses. Second, we excluded observations made on dates during which the Interconnector service was unavailable due to planned maintenance (these dates are documented on the IUK's website). As a

¹² On a given working day, pipeline users are offered the possibility to revise the transportation service requested at the end of the previous working day. This is the so-called within-day re-nominations. Yet, for the pipeline operator, these within-day re-nominations generate a significant extra operation costs. As a result, the detailed pricing rules adopted by the pipeline operator have been explicitly designed to render these within-day re-nominations extremely costly. So, users have a strong incentive to contract their real transportation needs for day $d+1$ at the end of day d (i.e., before the close of the day ahead market). Therefore, we proceed assuming that these within-day re-nominations can be neglected.

result, we assembled time series data containing 723 daily observations on prices, compressor fuel costs, and trade flows in each direction.

Lastly, the constant mean parameter α_{ji} is supplemented by a vector of observable exogenous variables in order to control for the possible impact of a time-varying measurement bias in the price and transfer cost data. The list of control variables includes a time trend (the associated parameter to be estimated is denoted β_{time}) and two dummy variables: $D_{2004-2005}$ that takes the value 1 during the period covering October 1, 2004, to September 30, 2005 (the parameter to be estimated is denoted $\beta_{D_{2004-2005}}$), and $D_{2005-2006}$ that takes the value 1 after October 1, 2005 (the parameter to be estimated is denoted $\beta_{D_{2005-2006}}$). Each of these period corresponds to a “standard gas year” during which the regulated Entry-Exit tariff system used by the UK National Transportation System is kept unchanged.

4.3 Descriptive statistics

An examination of trade data indicates that out of these 723 observations, 369 correspond to net positive exports to Belgium (of which 26 correspond to a congested infrastructure), 341 to net imports to the UK (of which 46 correspond to a congested infrastructure) and 13 to zero trade.

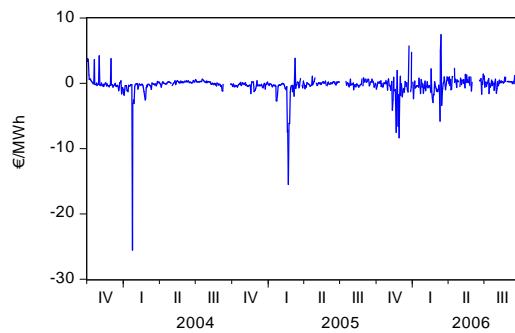
Table 2 summarizes the descriptive statistics for the two series R_{ji} (i.e., the difference between the spatial price spread and the unit transfer cost). The distributional properties of these series show some signs of non-normality as a very large leptokurtosis is observed in both cases. Figure 1 provides plots of these two series and the measured pipeline flow from Bacton (UK) to Zeebrugge (Belgium). A visual inspection of these plots suggests the presence of volatility clustering which motivates the use of our specification incorporating GARCH features. The estimated first-order autocorrelation coefficients reveal evidence of serial correlation (0.311*** for the series $R_{NBP \rightarrow ZEE,t}$ and 0.301*** for the series $R_{ZEE \rightarrow NBP,t}$). This finding is in favor of a dynamic specification able to correct for serial correlation.

Table 2. Descriptive statistics for the marginal rent to spatial arbitrage

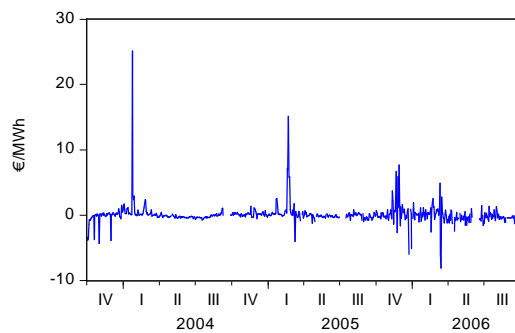
	Entire sample	
	$R_{NBP \rightarrow ZEE}$	$R_{ZEE \rightarrow NBP}$
Mean	-0.232	0.044
Median	-0.100	-0.051
Maximum	7.484	25.189
Minimum	-25.543	-8.096
Std. Dev.	1.581	1.557
Skewness	-7.394	7.396
Kurtosis	108.946	112.664
Jarque-Bera (<i>p-value</i>)	344730.200 (0.000)	368877.600 (0.000)
Observations	723	723

Figure 1. Data plots

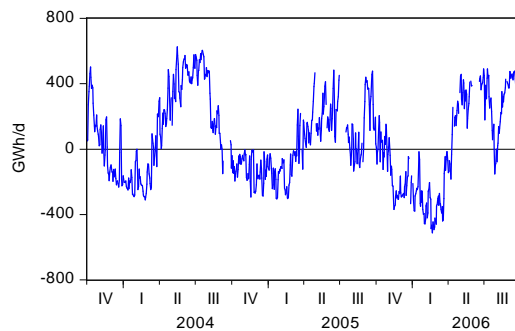
Price (Zeebrugge) - Price (NBP) - Shipping cost (UK->Belgium)



Price (NBP) - Price (Zeebrugge) - Shipping cost (Belgium->UK)



Flow (UK->Belgium)



4.4 Estimation and empirical results

a – Estimation procedure

The estimation procedure involves the constrained maximization of a non-trivial log-likelihood function. This is a non-linear, non-convex, constrained optimization problem that has to be solved numerically using hill-climbing procedures.¹³

To obtain a feasible starting point, we first consider the simplest possible static specification (i.e., omitting the time trend, the two dummy variables, the autocorrelation and the GARCH parameters). The converged solution for this restricted specification is then used as a feasible starting point for the unrestricted model. The optimization problem at hand has the potential for local maxima, which is a

¹³ All the estimates reported in this paper have been obtained using an iterative procedure that performs 20 iterations using the Davidon-Fletcher-Powell (DFP) algorithm followed by 20 iterations using the Broyden-Fletcher-Goldfarb-Shanno (BFGS) one, and then a switch back to DFP for 20 iterations, and so forth.

source of concern because the outcome of a non-linear programming solver may depend on the location of the starting point. To address this problem, the first solution is systematically compared to the ones obtained with a sample of 1,000 starting points uniformly drawn over a range of possible starting values. The converged solution that provides the highest likelihood value is systematically stored.

b – Empirical results

Estimation results are reported in Table 3. That table details the estimates obtained for: the market power coefficient (γ), the regime probabilities (λ 's), the measurement bias parameters (α , β_{time} , $\beta_{D_{2004-2005}}$, $\beta_{D_{2005-2006}}$), the autocorrelation parameter (ρ), the GARCH parameters used to model the heteroscedasticity related to regimes I and II (ϖ , δ , φ), the standard deviation parameters for the truncated normal distributions (σ_{μ} , σ_{ν}), and a series of likelihood ratio tests.

From these estimation results, several facts stand out. First, the high estimates obtained for λ_I and λ_{II} in both directions reveal that the observed spatial price difference is predominantly explained by the sum of the unobserved marginal transaction costs and the markup term. These very high values result in a very high probability of observing an imperfectly competitive spatial market equilibrium. Following Barrett and Li (2002) the probability of spatial market equilibrium conditions holding is in the range defined by the minimum and the maximum values of the direction-specific sums ($\lambda_I + \lambda_{II} + \lambda_{III_b} + \lambda_{VI}$), that is (0.9468, 0.9477).

Second, the estimated values for the coefficient γ are positive, as expected. These estimates are highly significant in both directions, which reveals the presence of imperfectly competitive arbitrages across the Channel. A further confirmation is provided by the likelihood ratio tests: the null hypothesis of competitive arbitrages is firmly rejected in both directions. So, we cannot reject the assumption of imperfectly competitive arbitrages during that period. This finding is consistent with the results in Rupérez-Micola and Bunn (2007).

Lastly, the probabilities λ_{III_b} to jointly observe infrastructure congestion and strictly positive marginal profits to spatial arbitrage regime are either zero or extremely low. These estimated values are consistent with the analysts' consensus summarized in Futyan (2006) on: (i) the oversized nature of the IUK's transportation capacity when natural gas is flowing to the Continent and (ii) the likely capacity-constrained nature of the IUK in the opposite direction (before the November 2005 capacity increase). In contrast, the estimated probabilities λ_{III_a} are larger and highly significant. Infrastructure congestion issues that are directly related to the Interconnector pipeline cannot be invoked to explain the presence of these strictly positive marginal profits to spatial arbitrage. These observed trade barriers could, for example, be due to pipeline congestion in the adjacent systems. Still, in relative terms, the probability of observing this regime is small.

Table 3. Estimation results for natural gas trade across the Channel

	From UK to Belgium	From Belgium to UK
Mean parameters		
α	-0.3164***	-0.0990***
β_{time}	0.2019	-0.7017***
$\beta_{D_{2004-2005}}$	-0.0401	0.2442***
$\beta_{D_{2005-2006}}$	-0.2391**	0.5304***
γ	0.0012***	0.0026***
ρ	0.3396***	0.4860***
GARCH parameters		
$\bar{\omega}$	0.0151***	0.0315***
δ	0.9413***	0.8691***
φ	0.0254	0.0257
Standard deviations		
σ_{μ}	2.2147***	8.4446***
σ_{ν}	6.3419***	2.0899***
Probabilities (in %)		
λ_I	48.5613***	41.5957***
λ_{II}	41.1580***	50.4989***
λ_{III_a}	2.4462***	1.6899***
λ_{III_b}	0.0000	0.9188**
λ_{IV}	2.8750***	0.4921
λ_V	0.0028	3.0477***
λ_{VI}	4.9568***	1.7569
Log likelihood	-982.6623	-991.7400
LR tests		
$H_0: \gamma = 0$	128.868 (0.000)	115.345 (0.000)
$H_0: \sigma_{\mu} = \sigma_{\nu}$	44.278 (0.000)	41.018 (0.000)
$H_0: \rho = \delta = \varphi = 0$	206.992 (0.000)	228.932 (0.000)
Observations	723	723

Note: Asterisks indicate significance at 0.10*, 0.05** and 0.01*** levels, respectively. Numbers in parentheses are the p -values of the χ^2 statistics.

In addition, we can note that the use of a unique variance parameter for the half-normal distributions of the two non-negative error terms μ_{ijt} related to regimes III_a, III_b, and IV and ν_{ijt} related to regimes V and VI is firmly rejected by the data.¹⁴

¹⁴ As a side remark, we can note that the use of a dynamic specification is justified for this specific data set as the estimated autocorrelation coefficients ρ and the estimated ARCH coefficients δ are significant in both directions.

5. Concluding remarks

In Europe, the question of how to detect market power in the spatial arbitrages observed in a restructured natural gas industry is one of the key challenges that regulators and competition authorities have to address. The objective of this paper is to offer an empirical methodology which is able to test for the presence of perfect competition in these spatial arbitrages. Our approach explicitly builds upon the literature dedicated to natural gas markets integration and extends it by focusing on the relationship between the observed spatial price difference and the intermarket trade flows.

A case study focusing on the IUK pipeline during the period 2003–2006 provided us with an opportunity to obtain a series of original findings. The estimated probability of spatial market equilibrium conditions holding is very high, suggesting high degrees of wholesale natural gas market integration, consistent with previous research on IUK price co-movements (Neumann et al., 2006). But, the empirical evidence also suggests the presence of imperfect competition in the observed spatial arbitrages, consistent with the price-data results in Rupérez-Micola and Bunn (2007). Although our discussion is centered on this specific infrastructure, it should be clear these results imply that some care is needed when interpreting the high degree of co-movements which is typically documented in the empirical studies conducted on European spatial market price data. Though these co-movements can be interpreted as objective signs of market integration, they do not necessarily reveal the existence of a perfectly competitive internal market.

Experience indicates that the institutional arrangements implemented in the UK have played a large part in shaping the EU's restructuring process. Future research will thus examine whether or not market equilibrium conditions hold in less mature continental markets. Such research could be useful for informing the current EU regulatory debates related to the functioning of the internal market for natural gas.

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Appendix A – Perfectly competitive spatial arbitrages

This Appendix details the formal proof of Proposition 1. We let: D_{it} and D_{jt} denote the quantities demanded at time t in each region, $B_i(D_{it}) = \int_0^{D_{it}} p_{it}^D(q) dq$ and $B_j(D_{jt}) = \int_0^{D_{jt}} p_{jt}^D(q) dq$ denote the gross consumer surplus in each region at that time, and $C_i(S_{it}) = \int_0^{S_{it}} p_{it}^S(q) dq$ and $C_j(S_{jt}) = \int_0^{S_{jt}} p_{jt}^S(q) dq$ denote the total cost incurred by the producers in each region. By construction, we have: $B_i'(D_{it}) = p_{it}^D(D_{it})$; $B_j'(D_{jt}) = p_{jt}^D(D_{jt})$; $C_i'(S_{it}) = p_{it}^S(S_{it})$ and $C_j'(S_{jt}) = p_{jt}^S(S_{jt})$.

Proof of Proposition 1: Following Takayama and Judge (1971), we define the net quasi-welfare function for the two regions as:

$$W(D, S, Q_{jit}) = B_i(D_{it}) + B_j(D_{jt}) - C_i(S_{it}) - C_j(S_{jt}) - T_{jit} Q_{jit}, \quad (A.1)$$

this form is also known as the net social payoff which maximizes the sum of producers' and consumers' surplus after deducting for transfer costs (Samuelson, 1952). The competitive market equilibrium is the solution of the following optimization problem (Takayama and Judge, 1971):

$$\text{Max}_{D, S, Q_{jit}} W(D, S, Q_{jit}) \quad (A.2)$$

$$\text{s.t. } D_{it} - S_{it} - Q_{jit} \leq 0 \quad (A.3)$$

$$D_{jt} + Q_{jit} - S_{jt} \leq 0 \quad (A.4)$$

$$Q_{jit} \leq K_{jit} \quad (A.5)$$

$$D_{it} \geq 0, D_{jt} \geq 0, S_{it} \geq 0, S_{jt} \geq 0, Q_{jit} \geq 0. \quad (A.6)$$

where the objective is to maximize the net social payoff subject to a set of linear constraints. Here, the constraint (A.3) states that the quantity consumed in market i is less than or equal to the sum of the local supply and the quantity shipped into that region; the constraint (A.4) states that the sum of the

quantity consumed in market j and the quantity shipped from that region is less than or equal to the local supply; and (A.5) is the capacity constraint related to the transportation infrastructure. We let: ϕ_{it} , ϕ_{jt} and ξ_{jit} denote the dual variables associated with the constraints (A.3), (A.4) and (A.5) respectively. The dual variables ϕ_{it} and ϕ_{jt} can be interpreted as the market clearing prices in the two markets and the dual variable ξ_{jit} can be interpreted as the market clearing price in the market for transportation rights. Hereafter, we let L denote the Lagrangian for this optimization problem.

As the objective function is quadratic and strictly concave with respect to both D and S , this problem has a unique solution $(D_{it}^*, D_{jt}^*, S_{it}^*, S_{jt}^*, Q_{jit}^*, \phi_{it}^*, \phi_{jt}^*, \xi_{jit}^*)$ that verifies the Karush-Kuhn-Tucker optimality conditions listed in Table A.1.

Table A.1. The Karush-Kuhn-Tucker optimality conditions for the optimization problem

$\frac{\partial L}{\partial D_{it}} :$	$p_{it}^D(D_{it}) - \phi_{it} \leq 0, \quad D_{it} \geq 0 \quad \text{and} \quad [p_{it}^D(D_{it}) - \phi_{it}]D_{it} = 0,$	(A.7)
$\frac{\partial L}{\partial D_{jt}} :$	$p_{jt}^D(D_{jt}) - \phi_{jt} \leq 0, \quad D_{jt} \geq 0 \quad \text{and} \quad [p_{jt}^D(D_{jt}) - \phi_{jt}]D_{jt} = 0,$	(A.8)
$\frac{\partial L}{\partial S_{it}} :$	$-p_{it}^S(S_{it}) + \phi_{it} \leq 0, \quad S_{it} \geq 0 \quad \text{and} \quad [-p_{it}^S(S_{it}) + \phi_{it}]S_{it} = 0,$	(A.9)
$\frac{\partial L}{\partial S_{jt}} :$	$-p_{jt}^S(S_{jt}) + \phi_{jt} \leq 0, \quad S_{jt} \geq 0 \quad \text{and} \quad [-p_{jt}^S(S_{jt}) + \phi_{jt}]S_{jt} = 0,$	(A.10)
$\frac{\partial L}{\partial Q_{jit}} :$	$-T_{jit} + \phi_{it} - \phi_{jt} - \xi_{jit} \leq 0, \quad Q_{jit} \geq 0 \quad \text{and} \quad [-T_{jit} + \phi_{it} - \phi_{jt} - \xi_{jit}]Q_{jit} = 0,$	(A.11)
$\frac{\partial L}{\partial \phi_{it}} :$	$D_{it} - S_{it} - Q_{jit} \leq 0, \quad \phi_{it} \geq 0 \quad \text{and} \quad [D_{it} - S_{it} - Q_{jit}]\phi_{it} = 0,$	(A.12)
$\frac{\partial L}{\partial \phi_{jt}} :$	$D_{jt} + Q_{jit} - S_{jt} \leq 0, \quad \phi_{jt} \geq 0 \quad \text{and} \quad [D_{jt} + Q_{jit} - S_{jt}]\phi_{jt} = 0,$	(A.13)
$\frac{\partial L}{\partial \xi_{jit}} :$	$Q_{jit} \leq K_{jit}, \quad \xi_{jit} \geq 0 \quad \text{and} \quad [Q_{jit} - K_{jit}]\xi_{jit} = 0.$	(A.14)

First, we examine the equilibrium at market i . We reason by contradiction and assume that, at market equilibrium, the quantity supplied by the local producers is zero: i.e., $S_{it}^* = 0$. Condition (A.9) imposes $\phi_{it}^* \leq p_{it}^S(0)$ i.e., $\phi_{it}^* \leq c_{it}$. Condition (A.7) indicates that $p_{it}^D(D_{it}^*) \leq \phi_{it}^*$ and thus $a_{it} - b_i D_{it}^* \leq c_{it}$ must hold. As $S_{it}^* = 0$, condition (A.12) indicates that $D_{it}^* \leq Q_{jit}^*$ and condition (A.14) indicates that $Q_{jit}^* \leq K_{jit}$. As $b_i > 0$, we must have $a_{it} - b_i K_{jit} \leq c_{it}$ which contradicts the assumption retained in Footnote 8 and thus invalidates the assumption $S_{it}^* = 0$. Hence, the equilibrium is such that the local supply is positive $S_{it}^* > 0$ which proves (cf. condition (A.9)) that the market price ϕ_{it}^* at the destination market is equal to the regional supply price, i.e. $\phi_{it}^* = p_{it}^S(S_{it}^*)$. As $\phi_{it}^* > 0$, the condition (A.12) is such

that $D_{it}^* = S_{it}^* + Q_{jit}^*$. As $S_{it}^* > 0$ and $Q_{jit}^* \geq 0$ (cf., (A.11)), the quantity demanded at market i is positive: $D_{it}^* > 0$ and the condition (A.7) reveals that, at market i , the market price ϕ_{it}^* verifies $\phi_{it}^* = p_{it}^D(D_{it}^*)$. Hence, the market price ϕ_{it}^* is equal to both $p_{it}^D(D_{it}^*)$ the price demanded by the local consumers and $p_{it}^S(S_{it}^*)$ the regional supply price. We let P_{it} denote that market clearing price.

Second, we examine the equilibrium at market j . Again, we reason by contradiction and assume that, at market equilibrium, the quantity demanded by the local consumers is zero: i.e., $D_{jt}^* = 0$. Condition (A.8) imposes $p_{jt}^D(0) \leq \phi_{jt}^*$ that is: $\phi_{jt}^* \geq a_{jt}$. As $\phi_{jt}^* > 0$, condition (A.13) indicates that $S_{jt}^* = Q_{jit}^*$ and thus $p_{jt}^S(S_{jt}^*) = p_{jt}^S(Q_{jit}^*)$. As $Q_{jit}^* \leq K_{jit}$, we have $p_{jt}^S(S_{jt}^*) \leq p_{jt}^S(K_{jit})$. From condition (A.10), we thus have $\phi_{jt}^* \leq p_{jt}^S(K_{jit})$ which indicates that the condition $a_{jt} \leq c_{it} + d_i K_{jit}$ must hold which contradicts the assumption retained in Footnote 8. So, the equilibrium is such that the local demand must be positive $D_{jt}^* > 0$ which suggests that the market price ϕ_{jt}^* at the destination market is equal to $\phi_{jt}^* = p_{jt}^D(D_{jt}^*)$ the price demanded there (cf., condition (A.8)). As $D_{jt}^* > 0$ and $Q_{jit}^* \geq 0$, the condition (A.13) reveal that $D_{jt}^* + Q_{jit}^* \leq S_{jt}^*$ which indicates that $S_{jt}^* > 0$ and thus, using condition (A.10), we obtain $\phi_{jt}^* = p_{jt}^S(S_{jt}^*)$. So, at market j , the market price ϕ_{jt}^* is equal to both $p_{jt}^D(D_{jt}^*)$ the price demanded by the local consumers and $p_{jt}^S(S_{jt}^*)$ the regional supply price. We let P_{jt} denote that market clearing price.

Substituting P_{jt} and P_{it} for ϕ_{it}^* and ϕ_{jt}^* in condition (A.11), one can readily identify the complementarity conditions (1) and (2) in the conditions (A.11) and (A.14) that must hold at equilibrium. Q.E.D.

Appendix B – Oligopolistic spatial arbitrages

In this Appendix, we present the technical developments needed to prove Proposition 2. We examine the collective behavior of the G gas traders. We proceed as in Gabriel et al. (2013) and define a series of conditions that together characterize the spatial equilibrium at time t : first, the collection of G mathematical programming problems describing the traders' individual behavior, and second, a complementarity condition similar to (2) that ties the traders' individual optimization problems and describes the market clearing condition in the market for transportation rights.¹⁶

First, each trader $g \in \{1, \dots, G\}$ is a profit maximizing agent that solves the following optimization problem:

¹⁶ From a technical perspective, this problem is an instance of what is known in the operations research community as a Generalized Nash equilibrium problem (which is also named a social equilibrium problem in economics). We refer to the survey in Facchinei and Kanzow (2010) for a comprehensive presentation of that type of problems and to Ruiz et al. (2014) for an overview of applications in the context of energy markets.

$$\text{Max}_{q_{ji}^g} \left[P_{ii}^D \left(S_{ii} \left(q_{ji}^g + q_{ji}^{-g} \right) + q_{ji}^g + q_{ji}^{-g} \right) - P_{jj}^D \left(S_{jj} \left(q_{ji}^g + q_{ji}^{-g} \right) - q_{ji}^g - q_{ji}^{-g} \right) - T_{ji} - \xi_{ji} \right] q_{ji}^g \quad (\text{B.1})$$

$$\text{s.t. } q_{ji}^g \geq 0$$

where the non-negative decision variable q_{ji}^g is the flow traded by g from market j to market i at time t , q_{ji}^{-g} is a short notation for the sum of the flows decided by the other traders, $P_{ii}^D(\cdot)$ and $P_{jj}^D(\cdot)$ are the local inverse demand functions. The objective function (B.1) describes the total profit obtained by trader g . In that objective function, the unit revenue obtained in the destination market i is $P_{ii}^D \left(S_{ii} \left(q_{ji}^g + q_{ji}^{-g} \right) + q_{ji}^g + q_{ji}^{-g} \right)$. The total unit cost is the sum of: $P_{jj}^D \left(S_{jj} \left(q_{ji}^g + q_{ji}^{-g} \right) - q_{ji}^g - q_{ji}^{-g} \right)$ the purchasing price in j , T_{ji} the unit transfer cost, and ξ_{ji} the price of a transportation right. The following reasoning is useful to further define the relations $S_{ii}(\cdot)$ and $S_{jj}(\cdot)$ that characterize how, in each market, the local industries' aggregate supply varies as a function of the traders' decisions. Using $Q_{ji} = \sum_{g=1}^G q_{ji}^g$ as a short notation for the aggregate flow of gas transferred by all the traders, we can remark that: at market equilibrium at time t , the local demanded price at the destination market i (respectively the origin market j) is $P_{ii}^D \left(S_{ii} + Q_{ji} \right)$ (respectively $P_{jj}^D \left(S_{jj} - Q_{ji} \right)$) and that price must be equal to the price obtained with the local inverse supply function $P_{ii}^S \left(S_{ii} \right)$ (respectively $P_{jj}^S \left(S_{jj} \right)$). Therefore, the functions $S_{ii}(\cdot)$ and $S_{jj}(\cdot)$ are:¹⁷

$$S_{ii} \left(Q_{ji} \right) = \frac{a_{ii} - c_{ii}}{b_i + d_i} - \frac{b_i}{b_i + d_i} Q_{ji}, \quad \text{and} \quad S_{jj} \left(Q_{ji} \right) = \frac{a_{jj} - c_{jj}}{b_j + d_j} + \frac{b_j}{b_j + d_j} Q_{ji}. \quad (\text{B.2})$$

Second, the market clearing condition at the market for transportation rights is given by the following complementarity condition that ensures that the price of a transportation right ξ_{ji} is equal to zero whenever $\sum_{g=1}^G q_{ji}^g$ the aggregate demand for transportation rights is lower than the supply (i.e., whenever the transportation capacity constraint is slack) and that ξ_{ji} is positive when supply falls short of demand (i.e., when this constraint is binding):

$$0 \leq \xi_{ji}, \quad \sum_{g=1}^G q_{ji}^g \leq K_{ji} \quad \text{and} \quad \left(\sum_{g=1}^G q_{ji}^g - K_{ji} \right) \xi_{ji} = 0, \quad (\text{B.3})$$

Replacing the relations (B.2) in the objective functions (B.1), deriving the Karush-Kuhn-Tucker conditions of the traders' optimization problems and using P_{ii} and P_{jj} as a short notations for the local

¹⁷ Recall that we assume that the condition $a_{ii} - b_i K_{ji} > c_{ii}$ is verified (cf., Footnote 8). As $Q_{ji} \leq K_{ji}$, the local supply in the destination market i in equation (B.2) is positive. Similarly, we also assume that $a_{jj} > c_{jj} + d_j K_{ji}$. Hence, the local supply in the origin market j in equation (B.2) is such that the amount consumed in the origin market (i.e., the difference between local supplies and exports $S_{jj} \left(Q_{ji} \right) - Q_{ji}$) is positive.

prices (i.e.: $P_{it} = p_{it}^D (S_{it} (Q_{jit}) + Q_{jit})$ and $P_{jt} = p_{jt}^D (S_{jt} (Q_{jit}) - Q_{jit})$), we obtain the following set of complementarity conditions that together characterize the equilibrium conditions for oligopolistic spatial arbitrages at time t :

$$\left\{ \begin{array}{l} 0 \leq q_{jit}^g, \quad P_{it} - P_{jt} - T_{jit} - \left(\frac{d_i b_i}{b_i + d_i} + \frac{d_j b_j}{b_j + d_j} \right) q_{jit}^g - \xi_{jit} \leq 0 \quad \text{and} \\ \left(P_{it} - P_{jt} - T_{jit} - \left(\frac{d_i b_i}{b_i + d_i} + \frac{d_j b_j}{b_j + d_j} \right) q_{jit}^g - \xi_{jit} \right) q_{jit}^g = 0, \quad \forall g \in \{1, \dots, G\}, \end{array} \right. \quad (\text{B.4})$$

$$0 \leq \xi_{jit}, \quad \sum_{g=1}^G q_{jit}^g \leq K_{jit} \quad \text{and} \quad \left(\sum_{g=1}^G q_{jit}^g - K_{jit} \right) \xi_{jit} = 0, \quad (\text{B.5})$$

The economic interpretation of these conditions is similar to those detailed for the case of competitive arbitrages except that the traders' marginal profits to spatial arbitrage are now modified to account for the players' ability to exert market power in both markets. The marginal revenue obtained by trader g in the destination market is $P_{it} - \frac{d_i b_i}{b_i + d_i} q_{jit}^g$ where $-\frac{d_i b_i}{b_i + d_i} q_{jit}^g$ represents the marginal loss of revenue from getting a lower price for each of the units the player is selling there. The trader's marginal cost includes three distinct components: (i) the marginal purchase cost in the origin market $P_{jt} + \frac{d_j b_j}{b_j + d_j} q_{jit}^g$ where $\frac{d_j b_j}{b_j + d_j} q_{jit}^g$ represents the marginal cost increase from getting a higher price for each of the units the player is purchasing (i.e., the effect of the players' oligopsonistic behavior in market j); (ii) the marginal transfer cost T_{jit} , and (iii) the price of a transportation right ξ_{jit} .

Lemma: *There exists a unique vector of individual decisions q_{jit}^{g*} and a unique price ξ_{jit}^* that verifies the equilibrium conditions (B.4) and (B.5).*

Proof: *The conditions (B.4) and (B.5) together define the linear complementarity problem LCP*

$$(m, M): \quad z \geq 0, \quad Mz + m \geq 0 \quad \text{and} \quad z^T (Mz + m) = 0, \quad \text{where:} \quad z = \left[q_{jit}^1 \quad \dots \quad q_{jit}^G \quad \xi_{jit} \right]^T;$$

$$M = \begin{bmatrix} A & B^T \\ -B & 0 \end{bmatrix} \quad \text{is a real matrix where } B \text{ is the all-ones row matrix of size } 1 \times G \text{ and}$$

$$A = \left(\frac{d_i b_i}{b_i + d_i} + \frac{d_j b_j}{b_j + d_j} \right) (I_G + J_G) \quad \text{where } I_G \text{ the identity matrix of size } G \text{ and } J_G \text{ the all-ones square matrix of size } G; \quad \text{and}$$

$$m = \left[\left(a_{jt} - b_j \frac{a_{jt} - c_{jt}}{b_j + d_j} - a_{it} + b_i \frac{a_{it} - c_{it}}{b_i + d_i} \right) \quad \dots \quad \left(a_{jt} - b_j \frac{a_{jt} - c_{jt}}{b_j + d_j} - a_{it} + b_i \frac{a_{it} - c_{it}}{b_i + d_i} \right) \quad K_{jit} \right]^T. \quad \text{Let}$$

z be a non-zero column vector of $(G+1)$ real numbers, we have $z^T M z > 0$ because

$$z^T M z = \left(\frac{d_i b_i}{b_i + d_i} + \frac{d_j b_j}{b_j + d_j} \right) \left(2 \sum_{\substack{i=1 \\ j \geq i}}^{G+1} z_i z_j \right) \text{ and } 2 \sum_{i=1}^{G+1} (z_i)^2 + 2 \sum_{\substack{i,j \\ j>i}} z_i z_j = \sum_{i=1}^{G+1} (z_i)^2 + \left(\sum_{i=1}^{G+1} z_i \right)^2. \text{ Hence,}$$

M is positive definite. The Theorem 3.1.6 in Cottle et al., (2009, p. 141) indicates that, if M is positive definite, there exists a unique solution to the LCP (m, M) . Q.E.D.

From an empirical perspective, the experience gained with restructured natural gas markets indicates that the individual decisions q_{jit}^g are seldom publicly available whereas the aggregate trade flow Q_{jit} are. As in the case of competitive arbitrage, one may wonder whether there exists aggregate complementarity conditions that must hold in case of an equilibrium. This is precisely the aim of the following proposition which is presented in Section 2.b.

Proposition 2: *If the following aggregate complementarity conditions:*

$$\left\{ \begin{array}{l} 0 \leq Q_{jit}, \quad P_{it} - P_{jt} - T_{jit} - \left(\frac{d_i b_i}{b_i + d_i} + \frac{d_j b_j}{b_j + d_j} \right) \frac{Q_{jit}}{G} - \xi_{jit} \leq 0 \quad \text{and} \\ \left(P_{it} - P_{jt} - T_{jit} - \left(\frac{d_i b_i}{b_i + d_i} + \frac{d_j b_j}{b_j + d_j} \right) \frac{Q_{jit}}{G} - \xi_{jit} \right) Q_{jit} = 0, \end{array} \right. \quad (\text{B.6})$$

$$0 \leq \xi_{jit}, \quad Q_{jit} \leq K_{jit} \quad \text{and} \quad (Q_{jit} - K_{jit}) \xi_{jit} = 0. \quad (\text{B.7})$$

where P_{it} and P_{jt} are the local market clearing prices, do not hold at time t , the equilibrium conditions (B.4) and (B.5) for oligopolistic spatial arbitrages are not verified at that time.

Proof: We reason by contradiction and assume that the equilibrium conditions (B.4) and (B.5) are verified and, using the lemma above, we let $z^* = (q_{jit}^{1*}, \dots, q_{jit}^{G*}, \xi_{jit}^*)$ denote the unique vector of decision variables that verifies these conditions. To begin with, we are going to prove that z^* verifies: either $q_{jit}^{g*} = 0$ for any $g \in \{1, \dots, G\}$, or $q_{jit}^{g*} > 0$ for any $g \in \{1, \dots, G\}$. Let us assume that z^* is such that there jointly exists at least one trader g with $q_{jit}^{g*} > 0$ and at least one trader g' with $q_{jit}^{g'*} = 0$. According to the equilibrium conditions (B.4), the marginal profits of these players are:

$$\text{Trader } g: \quad P_{it}^* - P_{jt}^* - T_{jit} - \left(\frac{d_i b_i}{b_i + d_i} + \frac{d_j b_j}{b_j + d_j} \right) q_{jit}^{g*} - \xi_{jit}^* = 0, \quad (\text{B.8})$$

$$\text{Trader } g': \quad P_{it}^* - P_{jt}^* - T_{jit} - \xi_{jit}^* \leq 0, \quad (\text{B.9})$$

where $P_{it}^* = p_{it}^D(S_{it}(Q_{jit}^*) + Q_{jit}^*)$ and $P_{jt}^* = p_{jt}^D(S_{jt}(Q_{jit}^*) - Q_{jit}^*)$. Subtracting (B.8) from (B.9), we obtain

$\left(\frac{d_i b_i}{b_i + d_i} + \frac{d_j b_j}{b_j + d_j}\right) q_{jit}^{g*} \leq 0$ which is a contradiction because we have assumed that q_{jit}^{g*} , d_i , d_j , b_i , and

b_j are all positive numbers. Hence, z^* has to be such that: either $q_{jit}^{g*} = 0$ for any $g \in \{1, \dots, G\}$, or $q_{jit}^{g*} > 0$ for any $g \in \{1, \dots, G\}$.

Using a similar argument, we can also prove that, if the equilibrium is such that $q_{jit}^{g*} > 0$ for any $g \in \{1, \dots, G\}$, we must have $q_{jit}^{g*} = Q_{jit}^{g*}/G$ for every trader $g \in \{1, \dots, G\}$. Let us assume that z^* is such that there exists two traders g and g' with $q_{jit}^{g*} \geq q_{jit}^{g'*} > 0$, the conditions (B.4) for these two traders are such that:

$$\text{Trader } g: \quad P_{it}^* - P_{jt}^* - T_{jit} - \left(\frac{d_i b_i}{b_i + d_i} + \frac{d_j b_j}{b_j + d_j}\right) q_{jit}^{g*} - \xi_{jit}^* = 0, \quad (\text{B.10})$$

$$\text{Trader } g': \quad P_{it}^* - P_{jt}^* - T_{jit} - \left(\frac{d_i b_i}{b_i + d_i} + \frac{d_j b_j}{b_j + d_j}\right) q_{jit}^{g'*} - \xi_{jit}^* = 0. \quad (\text{B.11})$$

Subtracting (B.10) from (B.11), we obtain the equation $\left(\frac{d_i b_i}{b_i + d_i} + \frac{d_j b_j}{b_j + d_j}\right) (q_{jit}^{g'*} - q_{jit}^{g*}) = 0$ that can

only be verified if $q_{jit}^{g*} = q_{jit}^{g'*}$. As such a reasoning is valid for every pair of traders, we obtain

$q_{jit}^{g*} = Q_{jit}^{g*}/G$ for every trader $g \in \{1, \dots, G\}$. As the condition $q_{jit}^{g*} = Q_{jit}^{g*}/G$ for every trader

$g \in \{1, \dots, G\}$ also holds when the aggregate output is equal to 0, we can simply replace q_{jit}^{g*} by

Q_{jit}^{g*}/G in the equilibrium conditions (B.4) and (B.5) to prove that if these conditions hold so do the

aggregate complementarity conditions (B.6) and (B.7). Q.E.D.

Appendix C – A dynamic specification

The specification in Section 3.2 has a static nature. This technical Appendix outlines how it can be extended to model the dynamics of the inter-period linkages that may exist in commodity markets. Section C.1. recalls how the Bayesian approach in Kleit (2001) can be adapted to correct for serial correlation. Section C.2. explains how this approach can also be adapted to model a possibly time-varying variance for the residual in regimes I and II.

C.1 – Correcting for autocorrelation

Serial correlation due to both supply shocks and speculative storage activity is commonly observed in the empirical studies dedicated to commodity prices (Deaton and Laroque, 1996).¹⁸ As the presence of unmodeled autocorrelation can result in inefficient estimates, the presence of serial correlation has to be appropriately corrected for.¹⁹ Interestingly, Kleit (2001) details a relevant strategy to overcome this limitation and his Bayesian approach can be adapted to adjust for the possible presence of serial correlation in our error term ε_{jit} . One has to keep in mind that the exact value $\varepsilon_{ji(t-1)}$ cannot be directly observed. However, one can consider the expected value of $\varepsilon_{ji(t-1)}$, given the evidence provided by the previous observation, which results in the modified specification:

$$\text{Regimes I \& II:} \quad R_{jit} - \alpha_{ji} - Q_{jit}\gamma - \rho_{ji}E\left(\varepsilon_{ji(t-1)} \middle| \eta_{ji(t-1)}\right) = \varepsilon_{jit} \quad (\text{C.1})$$

$$\text{Regimes III}_a, \text{III}_b \text{ \& IV:} \quad R_{jit} - \alpha_{ji} - Q_{jit}\gamma - \rho_{ji}E\left(\varepsilon_{ji(t-1)} \middle| \eta_{ji(t-1)}\right) = \varepsilon_{jit} + \mu_{jit} \quad (\text{C.2})$$

$$\text{Regimes V \& VI:} \quad R_{jit} - \alpha_{ji} - Q_{jit}\gamma - \rho_{ji}E\left(\varepsilon_{ji(t-1)} \middle| \eta_{ji(t-1)}\right) = \varepsilon_{jit} - \nu_{jit} \quad (\text{C.3})$$

where: ρ_{ji} is an autocorrelation coefficient such that $-1 < \rho_{ji} < 1$; $\eta_{ji(t-1)}$ is the observed lagged residual, that is $\eta_{ji(t-1)} \equiv \pi_{ji(t-1)} - \rho_{ji}E\left(\varepsilon_{ji(t-2)} \middle| \eta_{ji(t-2)}\right)$; and $E\left(\varepsilon_{ji(t-1)} \middle| \eta_{ji(t-1)}\right)$ represents the expected value of $\varepsilon_{ji(t-1)}$ given evidence provided by the observed lagged residual.

The expected value $E\left(\varepsilon_{ji(t-1)} \middle| \eta_{ji(t-1)}\right)$ can be computed as follows. Given the observed value of the lagged residual $\eta_{ji(t-1)}$ and the parameter vector $\theta_1 \equiv (\theta, \rho_{ji})$, Bayes theorem can be invoked to evaluate $P_{t-1}^r \equiv P_{t-1}\left(r \middle| \eta_{ji(t-1)}, \theta_1\right)$ the posterior probability that the residual observed at time $t-1$ was generated by regime r (Kiefer, 1980; Spiller and Wood, 1988):

$$P_{t-1}^r = \frac{\lambda_r f_{ji(t-1)}^r\left(\eta_{ji(t-1)} \middle| \theta_1\right)}{\left(\lambda_{III_a} + \lambda_{III_b}\right) f_{ji(t-1)}^{III}\left(\eta_{ji(t-1)} \middle| \theta_1\right) + \sum_{\substack{k=I \\ k \neq III}}^{VI} \lambda_k f_{ji(t-1)}^k\left(\eta_{ji(t-1)} \middle| \theta_1\right)}. \quad (\text{C.4})$$

¹⁸ In the application discussed in the present paper (an analysis of market integration between two markets connected by a pipeline system), at least two engineering-based arguments can motivate the presence of autocorrelation. First, from a dynamic perspective, a pipeline system can be described as a slow-moving transportation infrastructure as a couple of hours are typically needed to move a given molecule of methane from one market to the other. Second, the operation of a natural gas pipeline system can create temporary energy storage (the so-called line-pack buffer). As a result, daily observations are likely to jointly represent the outcome of decisions taken both today and yesterday.

¹⁹ Barrett and Li (2002, footnote 3) discussed the serial correlation issue and claimed that the Cochrane-Orcutt method could be used to correct for serial correlation. However, the distribution of the observed residuals is dramatically modified from one observation to the next in case of a regime switch. Therefore, one may question the validity of a Cochrane-Orcutt approach.

The expected value $E(\varepsilon_{ji(t-1)} | \eta_{ji(t-1)})$ can be constructed from the observed residual $\eta_{ji(t-1)}$ by: (i) subtracting $E(\mu)$ the expected value of the one-sided random variable μ_{ji} weighted by the posterior probability to observe the regimes III_a, III_b or IV; and, (ii) adding $E(v)$ the expected value of the non-negative half-normal random variable v_{ji} weighted by the posterior probability to observe the regimes V or VI,²⁰ that is:

$$E(\varepsilon_{ji(t-1)} | \eta_{ji(t-1)}) = \eta_{ji(t-1)} - [P_{t-1}^{III_a} + P_{t-1}^{III_b} + P_{t-1}^{IV}] E(\mu) + [P_{t-1}^V + P_{t-1}^{VI}] E(v). \quad (C.5)$$

The construction of $E(\varepsilon_{ji(t-1)} | \eta_{ji(t-1)})$ can be nested within the likelihood specification above. So, the estimation proceeds again from a maximization of the log-likelihood function with respect to the regime probabilities λ and the parameters θ_i subject to the preceding constraints and to $-1 < \rho_{ji} < 1$.²¹

C.2 – An adapted GARCH specification

Regimes I and II model the cases of zero marginal profit to spatial arbitrage. In these regimes, the random variable representing the marginal profit to spatial arbitrage is assumed to be equal to the stochastic error term ε_{ji} which has the same finite variance σ_ε^2 for all observations. Yet, one may question the relevance of this homoscedastic assumption as a large empirical literature has documented the tendency of commodity prices to exhibit time-varying volatilities. Accordingly, the spatial price differential (and thus the marginal rents to spatial arbitrage) is likely to show signs of heteroscedasticity. Inspired by the strategy proposed in Kleit (2001) to correct for serial correlation, it is also possible to design a modified specification whereby the variance of the marginal rents to spatial arbitrage observed in regimes I and II is allowed to vary over time.

For the purpose of capturing the dynamics of uncertainty, a Generalized Autoregressive Conditional Heteroscedasticity (GARCH) model (Bollerslev, 1986) represents an attractive approach that has been widely applied to model commodity markets. Given the time series R_{ji} and Q_{ji} defined above, a GARCH(1,1) specification can be written as follows:

$$\text{Regimes I \& II:} \quad R_{ji} - \alpha_{ji} - Q_{ji} \gamma - \rho_{ji} E(\varepsilon_{ji(t-1)} | \eta_{ji(t-1)}) = \varepsilon_{ji} \quad (C.6)$$

$$\text{Regimes III}_a, \text{ III}_b \text{ \& IV:} \quad R_{ji} - \alpha_{ji} - Q_{ji} \gamma - \rho_{ji} E(\varepsilon_{ji(t-1)} | \eta_{ji(t-1)}) = \varepsilon_{ji} + \mu_{ji} \quad (C.7)$$

²⁰ Denoting ϕ the density function of the standard normal distribution and Φ its cumulative distribution function, these expected values are: $E(\mu) \equiv \sigma_\mu \phi(0) / (1 - \Phi(0))$ and $E(v) \equiv \sigma_v \phi(0) / (1 - \Phi(0))$.

²¹ Regarding the particular case of the first observation, an arbitrary value has to be taken for $E(\varepsilon_{ji0} | \eta_{ji0})$ because η_{ji0} cannot be observed. In this paper, the initial value $E(\varepsilon_{ji0} | \eta_{ji0})$ is taken as equal to zero (that is, the conditional mean of ε_{ji} given $\varepsilon_{ji(t-1)}$).

$$\text{Regimes V \& VI:} \quad R_{jit} - \alpha_{ji} - Q_{jit}\gamma - \rho_{ji}E(\varepsilon_{ji(t-1)}|\eta_{ji(t-1)}) = \varepsilon_{jit} - \nu_{jit} \quad (\text{C.8})$$

$$\varepsilon_{jit} = h_{jit}e_{jit} \quad (\text{C.9})$$

$$h_{jit}^2 = \omega_{ji} + \delta_{ji} \left[E(\varepsilon_{ji(t-1)}|\eta_{ji(t-1)}) \right]^2 + \varphi_{ji}h_{ji(t-1)}^2 \quad (\text{C.10})$$

where: (C.6), (C.7) and (C.8) are the mean equations; (C.10) is the conditional variance equation; (C.9) relates the random error ε_{jit} to the standardized residual e_{jit} which is assumed to be an i.i.d. standard normal random variable; and ω_{ji} , δ_{ji} and φ_{ji} are the usual, non-negative, GARCH(1,1) parameters.

Compared to the usual GARCH specification, equation (C.10) involves the use of the squared expected value $\left[E(\varepsilon_{ji(t-1)}|\eta_{ji(t-1)}) \right]^2$ in spite of the true value $\varepsilon_{ji(t-1)}^2$ which cannot be observed in this regime switching model. Again, the construction of the expected value $E(\varepsilon_{ji(t-1)}|\eta_{ji(t-1)})$ is based on a Bayesian approach. Given the observed value $\eta_{ji(t-1)}$, the values of the parameters $\theta_2 \equiv (\theta_1, \omega_{ji}, \delta_{ji}, \varphi_{ji})$ and $h_{ji(t-2)}^2$, it is possible to evaluate the posterior probabilities P_{t-1}^r and thus $E(\varepsilon_{ji(t-1)}|\eta_{ji(t-1)})$ using (C.5).