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EUROPEAN GAS MARKETS, TRADING HUBS, AND PRICE FORMATION: A NETWORK PERSPECTIVE

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JEL Classification C32, F18, Q43, Q47, Q48

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1. Introduction

The creation of a single European energy market has been a long-standing European objective, initially proposed through the Treaties of Rome in 1957. Through the Treaties of Rome, the European Union (EU) established a customs union, agreeing to the progressive reduction of customs duties, and the establishment of a single market for goods, labour and services. Following this, the European Commission (EC) has issued a number of liberalisation directives for natural gas markets, notably the First Energy Package (1998), Second Energy Package (2003) and Third Energy Package (2009), which aim to increase market competition and consumer protection throughout Europe.

The Third Energy Package, enacted on 3rd September 2009 (Directive, 2009), was intended to further develop the internal European natural gas market. The directive aimed to address issues surrounding market access, transparency and consumer protection through the development of a competitive, integrated market. However, obstacles to a harmonised[1], single European market for natural gas remain. These are not only structural, with the relative level of transmission liberalisation holding price impact, but also contractual, with producers, who hold a high degree of market power, constraining market liberalisation through long-term 'take-or-pay' contracts.

The European Commission has taken the above measures to enforce competition and increase cross-border trade, offering all consumers a choice of supply, through development of short-term trade in gas markets. As such, it is possible that, although the European gas network is imperfectly connected, with substantial pipeline bottlenecks and regions of spare capacity, and considering the geographic disparity of market pairs, price signals may still propagate throughout the short-term gas markets, tacitly inferring that markets may be competitive.

The issue of whether European gas markets are integrated has been explored by numerous authors (Asche *et al.*, 2000; Asche *et al.*, 2002; Renou-Maissant, 2012; Neumann *et al.*, 2006), using a multitude of methodological approaches, such as cointegration, causality and state

[1] Throughout this paper, the terms 'Market Integration' and 'Market Harmonisation' are used interchangeably, inferring the development of a unified, competitive natural gas market within Europe, characterised by convergence of price returns toward a singular value, in the absence of transportation costs.

space modelling, achieving contrasting results. Whilst some authors accept the hypothesis of a harmonised European market (Asche *et al.*, 2000; Asche *et al.*, 2002), others find evidence to reject this (Renou-Maissant, 2012; Neumann *et al*., 2006). Previous academic studies have provided evidence of long-run convergence (Renou-Maissant, 2012; Growitsch *et al*., 2015; Neumann & Cullmann, 2012) through the measurement of long-run cointegration or equilibrium relationships, with the Agency for the Cooperation of Energy Regulators (ACER) regularly publishing Gas Market Monitoring Reports (2018) confirming a long-run convergence in European gas market integration. This paper provides a different perspective on the European gas market integration issue through analysis of short-run interactions, improving the resolution of the analysis.

We aim to investigate the time-varying interactions amongst European gas prices by measuring the Granger-Geweke (Geweke, 1982) causality between price return dynamics during the period 2016-2018. This enables dynamic observation of which hubs[2] act as 'price leaders' and 'price followers', which can be extracted to draw inferences relating to the development of the single European market for gas. Secondly, we seek to examine whether abnormal price behaviour within European gas markets can be explained by historical phenomena. Further to this, the origin and propagation of events that disrupt normal market functioning is elucidated.

In addition, we analyse the efficacy of the Third European Gas Directive through the generation of a European network density time series. In the case of an informationally efficient market, short-term price returns should not be related to the lagged values of other variables, hence a Granger-Geweke test should not detect a high degree of causality. However, given the stated European objective of a unified, competitive natural gas market, price returns, in the absence of transportation limitations, are expected to converge toward a singular value across all European hubs, quantified through the network density term.

As European gas injection occurs predominantly by pipeline, with gas transited between hubs by an interconnected pipeline network, application of network theory, which can measure the degree of interdependence and direction of causality between hubs, represents an appropriate methodology for assessment of the European gas market. We use a novel approach based on

[2] Hubs can be either physical or virtual points on the gas transmission system where ownership rights of gas can be transferred, logistically supported through the provision of market services by an impartial entity.

graph theory to model the dynamic interactions amongst European gas prices. The interactions between daily day-ahead gas prices are modelled as a connectivity network. Nodes represent different European trading hubs and edges between them denote the strength and direction of statistically significant influences between relative price variations. The dynamic propagation patterns between the different hubs' return series provides valuable information on the degree of market integration.

Although the application of complex network theory is in its infancy, literature has previously exploited symmetric (correlation-based) measures to formulate undirected networks, with Minimum Spanning Trees (MST) introduced to identify hierarchical market power within crude oil markets (Ji & Fan, 2016) and gas markets (Geng *et al*., 2014). Whilst this methodology permits dynamic assessment of interconnectivity within a network, it reduces the network to its most primitive structure, containing only the most intuitive information exhibited by the network. Through use of nonlinear extensions of Granger causality (Geweke, 1982), Granger causal networks can be developed, that can elucidate which hubs act as 'price leaders' and 'price followers', permitting observation of the interactive evolution of market dynamics. As such, this study holds novelty through the use of a network approach that specifies multivariate, directed networks in order to understand the multivariate interactions between European gas prices, rather than static investigation into univariate profiles.

We show that the harmonisation of the European natural gas markets remained at a low mean throughout the sample period. A number of spikes were observed throughout the sample period, however abnormally positive and negative changes in connectivity were similar in number and magnitude. We infer that the path toward attainment of a sustained, high degree of gas market integration, which characterises a Single European Market for natural gas, appears to be long.

This paper is organised as follows: Section 2 discusses the institutional framework and reviews the literature, whilst Section 3 outlines the methodologies employed throughout the paper. Section 4 specifies the dataset, with Section 5 reporting the empirical findings, which are subsequently discussed in Section 6. Section 7 concludes.

2. The European Natural Gas Market

The price of natural gas depends on a range of economic and non-economic supply and demand parameters, including weather conditions, proximity to production, transmission constraints, geopolitical factors and import diversification. This section provides a brief overview of the European spot gas markets, discussing market organisation and structure (Section 2.1), then providing a critical analysis of previous studies on European gas market integration (Section 2.2).

2.1 Institutional Framework

European gas companies were largely considered to be conventionally regulated national monopolies until the EU embarked upon its natural gas reformation programme, aiming to correct distortions and increase competitive pricing through legislating three Energy Directives (1998, 2002 and 2009). The market framework underwent substantial change due to new unbundling rules, capacity allocation rules and the removal of destination clauses. Critically, two barriers to a singular, internal European market for gas remain; non-physical barriers, characterised by contract inflexibility and a lack of market liberalisation, and physical barriers, namely trade constriction through a lack of available transmission capacity. Although the three Energy directives have increased competition within European gas markets, a dual-tier pricing system has developed, with long-term supply contracts and hub-based mechanisms emerging. Whilst hub-based pricing is short-term in nature, the inherent limitations in transmission capacity and contracted volume flexibility provide gas markets with relatively unique characteristics, causing the spot market to act as a one-day forward market.

European day ahead trading responds to the prevailing domestic supply and demand fundamentals, with Brown & Yücel (2008) finding that crude oil prices, weather, seasonality and storage play ancillary roles in price discovery. Meanwhile long-term contracts are typically negotiated for a period of 10-30 years, with natural gas pricing indexed to the pricing of oil products. Whilst long-term contracts still account for 70% of gas procurement in Europe (Heather, 2015), a transition from oil product indexation to short-term hub-based pricing is underway, with consumer dissatisfaction with inflexible, long-term contracts driving an increased volume of day ahead market trade. The relatively low “swing” volume and destination inflexibility inherent in long-term contracts, has encouraged volume growth of the day ahead gas trade in Europe. The increase in volume, and by extension, importance within supply portfolios, motivates our investigation into day ahead pricing.

Gas markets hold a number of stylised characteristics that reduce the incumbent's ability to exercise time or space arbitrage. Two important examples of this are pipeline transmission constraints and the national interests of each hub pertaining to wholesale gas markets. That said, due to the EU objective of a single, common pricing structure, capacity decisions and pricing strategies are becoming increasingly more simultaneous amongst European natural gas markets, based on increases in shared information and cooperation amongst regulatory bodies.

The European gas network is broadly considered to be imperfectly connected, with substantial pipeline bottlenecks and regions with spare capacity, with ENTSOG issuing biennial Ten-Year Network Development Plans (TYNDP) in order to correct these distortions. However, even in an imperfectly connected network of geographically disparate market pairs, price signals may still propagate throughout European gas markets, tacitly inferring that markets may be competitive.

2.2 Previous Literature

The liberalisation of natural gas markets has driven a growing academic interest in the process of market integration. A number of studies (DeVany & Walls, 1993; Walls, 1994; King & Cuc, 1996; Serletis, 1997; Cuddington & Wang, 2006) have focussed on North American natural gas market integration following the Federal Energy Regulatory Commission's (FERC) regulatory developments throughout the 1980's. European gas market literature is both narrower in scope and more current, owing to more recent regulatory developments. As such, there is a growing interest in ascertaining whether natural gas markets in Europe are converging toward the EU goal of a single, competitive internal market, often measuring the degree to which price coupling and harmonisation is being practically achieved. Since the early 2000's, a broad array of methodologies have provided a series of contradictory findings, with some studies displaying evidence of increasing integration amongst gas pricing, and others finding the opposite. Notably, none of these studies have assessed the dynamic relationships among all European hubs in order to assess the time-varying nature of European market integration.

For example, based on a cointegration analysis, Asche *et al.*, (2000) and Asche *et al.*, (2002) accept the market integration hypothesis for French and German import pricing, finding that the "Law of One Price" holds. More recently, Bourbonnais & Geoffron (2007), found an increasing degree of integration between Belgian, French, German, Italian, UK and Spanish natural gas prices from 1999-2005. Conversely, state-space model based studies such as (Neumann *et al*., 2006), suggest that convergence between Zeebrugge and the UK increased following the addition of an interconnector, whilst market integration amongst continental European hubs was not apparent. Taken in unison, the mixed results of these studies highlight the importance of the geographic proximity of the hubs studied, which increases the probability of market harmonisation. Furthermore, the assessed time period will impact the empirical findings of the study, emphasising the requirement of a dynamic model specification, that continually reassesses the degree of market integration. Robinson (2007) augments the Neumann *et al*. (2006) study through the application of the Nahar & Inder (2002) methodology to annual retail pricing of Finland, France, Ireland, Netherlands, Spain and the UK, documenting only Dutch pricing to converge throughout the observed period.

More recently, Renou-Maissant (2012) found strong integration amongst continental European gas markets, with the exception of the Belgian market. Furthermore, Growitsch *et al.* (2015) employed state-space modelling with the extension of an error correction model to demonstrate the increasing integration of hubs within North-West Europe. Whilst the measured hubs exhibited an increased degree of integration since the introduction of the 'entry-exit' system, information efficiency between the hubs also increased. Moreover, Neumann & Cullmann (2012), who extended Growitsch *et al.'s* (2015) dataset, found geographical proximity and available transmission capacity to play a role in price harmonisation. The study found that Danish consumers pay a premium due to network externality, and Austrian pricing diverges from other measured hubs. These findings are not surprising, as Austria serves as a thoroughfare for Russian gas into Southern and South-East Europe (Baumgarten), with hubs in these regions disregarded in the data specification.

The objective of a unified European natural gas market should, in the absence of transportation capacity limitations, should be to determine the convergence of gas prices toward a singular price at all European trading hubs. If this assertion holds, the integration of European natural gas markets, characterised by the network density term, can be expected to increase throughout the sample.

3.0 Methodology

We discuss the construction of multivariate directed networks, developed through a rolling-window computation of Granger causality (Geweke, 1982) between price return series of European natural gas hubs. The topology of the network is then quantified through the measurement of node weights and network density.

In order to investigate the evolution of the European gas pricing network, it is important to measure the degree of connectedness between European gas hubs as well as the directionality of each of these relationships. Consequently, we employ Granger-Geweke causality (Geweke, 1982), a statistical notion of causality based on the relative forecasting power of multiple time series. Through the use of a Vector Autoregressive (VAR) structure, we apply the Granger-Geweke network theory to the European gas network. The mathematical framework supplied by directed networks characterises interdependent systems well, enabling assessment of network evolution over time, which provides valuable information on how prices interact dynamically.

Nearly 70% of European natural gas is landed by pipelines, with gas transited between hubs by a large, interconnected pipeline network. As such, application of network theory, which can measure the degree of interdependence and direction of causality between hubs, is a logical step in the assessment of the short-term dynamics of the European gas market. If the European gas market is informationally efficient, short-term price returns should not be related to the lagged values of other variables, hence a Granger-Geweke test should not detect a high degree of causality. However, the objective of a unified, competitive gas market throughout Europe, price returns, in the absence of transportation limitations, should converge toward a singular value across all European hubs, quantified through the network density term.

3.1 Connectivity Networks

This section outlines the methodology of the multivariate, directed network used to assess the interdependencies of the European natural gas network, initially developed by Seth (2010). As we are employing a multivariate system (MVAR), Granger-Geweke causality (Geweke, 1982) is employed. The individual autoregressive representation of each return series is displayed in (1) and (2):

$$x(t) = \sum_{k=1}^{p} a_{1k}x(t-k) + \epsilon_1(t), \qquad var(\epsilon_1(t)) = \Sigma_1 \tag{1}$$

$$y(t) = \sum_{k=1}^{p} d_{1k}y(t-k) + \eta_1(t), \qquad var(\eta_1(t)) = \Gamma_1 \tag{2}$$

where a_{1k} and d_{1k} are autoregressive coefficients, $\epsilon_1(t)$ and $\eta_1(t)$ are noise terms and $k = 1, \dots, p$. The joint description of the bivariate series $[x(t), y(t)]^T$ is given by the p^{th}-order AR (3) and (4), where noise terms are not correlated over time and the covariance matrix is expressed as (5).

$$x(t) = \sum_{k=1}^{p} a_{2k}x(t-k) + \sum_{k=1}^{p} b_{2k}y(t-k) + \epsilon_2(t) \tag{3}$$

$$y(t) = \sum_{k=1}^{p} c_{2k}x(t-k) + \sum_{k=1}^{p} d_{2k}y(t-k) + \eta_2(t) \tag{4}$$

$$\Sigma = \begin{bmatrix} \Sigma_2 & \Upsilon_2 \\ \Upsilon_2 & \Gamma_2 \end{bmatrix} \tag{5}$$

where $\Sigma_2 = var(\epsilon_2(t))$, $\Gamma_2 = var(\eta_2(t))$ and $\Upsilon_2 = cov(\epsilon_2(t), \eta_2(t))$. Whereas $\Sigma_1$measures the ability of previous values of $x(t)$ to predict the present value of $x(t)$, Σ_2 represents the predictive capacity of $x(t)$ and $y(t)$'s previous values. If $x(t)$ and $y(t)$ are independent, then b_{2k} and c_{2k} are zero. Following Granger (1969), causality is defined as (6), with an MVAR approach applied to create the network (7), where each matrix, A_m , is determined by elements a_{ij} describing the linear relationship between $y_j(t-m)$ on $y_i(t)$, p is the number of lags, and $E(t)$ is the vector of error terms.

$$GC_{y\to x} = w_{yx} = \log\left(\frac{\Sigma_1}{\Sigma_2}\right). \qquad GC_{x\to y} = w_{xy} = \log\left(\frac{\Gamma_1}{\Gamma_2}\right). \tag{6}$$

$$Y(t) = \sum_{m=1}^{p} A_m Y(t-m) + E(t) \tag{7}$$

As the MVAR model described in (7) provides a time-invariant representation of the country Y's price as a function of the 11 other input values and their lags, a sliding window estimation is employed, facilitating time variation. A time-varying model, employing daily data allows a time-series of network connectivity strength to be generated, facilitating the study of gas market integration over time.

The MVAR model was estimated using the Burg algorithm (Burg, 1967), which recursively calculates the solution to an equation containing a Toeplitz matrix. Schlögl and Supp (2006) shows that when the Burg algorithm (Burg, 1967) is extended for multivariate Autoregressive models through the Nuttall-Strand method, the MVAR Burg algorithm provides the most accurate estimates.

The model order q can be selected according to the Akaike criterion:

$$AIC(p) = 2\log[\det(\Sigma)] + \frac{2pM^2}{n} \tag{8}$$

where Σ is the estimated noise covariance matrix of the bivariate Autoregressive model, n denotes the length of the data window, and M is the number of time series employed by the model. $2\,log[det(\Sigma)]$ holds an inverse relationship to p, whereas $2pM^2/n$ punishes models with a high order. The Akaike information criterion optimises q in order to minimise the cost function, which is defined by balancing the variance of the Autoregressive model against the volume of coefficients estimated.

3.2 Node Strength

The mathematical representation of a network is the adjacency matrix, from which the node strength can be determined. The node strength represents the sum of the weights of the total edges extending to other nodes within the system, which in turn, is divided between in-strength d_{In}, and out-strength d_{Out}, due to the directional nature of Granger causality, hence the relationships:

$$d_{In}(i) = \sum_{jEV} A_{i,j} \qquad d_{Out}(i) = \sum_{jEV} A_{j,i} \tag{9}$$

$$d_{Net}(i) = d_{Out}(i) - d_{In}(i) \tag{10}$$

d_{In} represents the total strength of incoming edges for vertex i, where V is the number of nodes, $A_{i,j}$ is the causal direction from node j to i, with causality weight between -1 and 1 determined through Equation (7). Any interactions which do not achieve statistical significance shall be set to 0. $d_{Out}(i) = \sum_{jEV} A_{j,i}$ represents the total strength of outgoing edges for vertex i, where V is the number of nodes.

The in-strength represents the cumulative causality directed towards a node, whilst the out-strength represents the cumulative causality directed from a node towards the rest of the network. $d_{Net}(i)$ represents the Net causality, with positive values indicating 'price leading' behaviour, and negative values indicating 'price following' behaviour. When applied to gas hubs, the in-strength represents the cumulative causality received from other hubs, with a high value indicating that pricing at the hub is strongly influenced by other hubs. Conversely, a large out-strength value indicates that the hub has a strong ability to influence pricing at other hubs within the network.

3.3 Network Connection Density

In order to assess overall market integration at a given time period, the global connection density, D, is computed:

$$D = \frac{1}{N(N-1)} \sum_{i,jEV} A_{i,j} \tag{11}$$

where V is the set of available nodes and N is the total number of nodes. As per Billio *et al.* (2012), this facilitates measurement of the total amount of causal activity throughout the sample period, with the value determining the coordination of markets measured.

4.0 Data

In order to analyse European gas market integration, a definition of a gas hub must first be derived. Neumann *et al*. (2006) provides a definition, stating that a hub can be either "physical (local) or virtual (notional) - on the gas transmission system where the transfer of gas can take place, logistically supported by a body offering the follow-up of the transfer of ownership, standardised contracts for trade at freely negotiated prices and other services".

Since Order 1775 was enacted in 2005, the European gas network has operated an entry-exit system, in which 'entry' gas is transported to either a physical or virtual trading hub within the network, from which it can be transported to an 'exit' point. Although entry and exit pricing is location specific by nature, volume-based price discrimination cannot be enacted amongst network users. As such, zones, based on proximity to entry-exit points, are defined within the transmission network, within which a singular price for gas is quoted, giving rise to 'virtual' trading hubs (VTP).

In order to accurately capture the dynamics of the European natural gas network, a hub, either physical or virtual, is specified within each 'trading zone'. As such, daily time series data of a sample of 12 wholesale gas day ahead prices, covering the period 2016 to 2018 are considered. This time series is of sufficient length to reveal the degree of integration, and possible structural distortions within the European gas market. In order to fully represent the dynamics of the European gas market, the sample period begins upon commencement of day ahead trading at VTP Gaz System (Poland), the most junior trading hub within the network. The markets considered are: CEGH (Austria), VTP Gaz System (Poland), VHP-Gaspool (Germany), VHP-NCG (Germany), PSV (Italy), PVB (Spain), PEG Nord (France), PEG TRS (France), Zeebrugge (Belgium), TTF (Netherlands), ETF (Denmark) and NBP (UK). Midpoint day ahead prices were obtained from Bloomberg with time sampling of one day.

To negate lag structure requirements arising from time-zone differences, daily periodicity was chosen, with midpoint pricing employed. All prices not quoted in €/MWh are converted by the daily spot midpoint price in the case of currency, and standard unit conversions (1 UK Therm = 0.02931 MWh) in the case of unit. Each market's time series is comprised of 498 observations, as only 'gas days' are employed, due to this providing the most accurate portrayal of European gas markets functioning under normal conditions, in which all market participants are actively engaged with the market. Inclusion of non 'gas day' data may result in misleading conclusions on the state of integration of the European gas network, as market participants in certain regions may not actively participate in price discovery. As 'gas day' misalignment due to national holiday schedules occurs throughout the sample, it is negated through synchronising the data through addition of the last available information pertaining to a missing observation. This has limited impact on the autocorrelation structure of the return series, with Granger & Ramanathan (1984) showing that the power of the augmented Dickey-Fuller test is increased through substituting missing observations with the previous observation.

4.1 Pricing at Trading Hubs

The twelve daily day ahead natural gas prices and hub characteristics are described in Table 1. The highest gas price present in the sample is at the VTP Gaz System, Poland (€88.63/MWh) on 01/03/2018. This coincides with the highest price observed at ten of twelve hubs measured, which can be attributed to a demand shock following an unseasonal pan-European 'cold snap'. The pan-European 'cold snap' was referred to as 'Storm Emma', and precipitated a UK Formal Deficit warning due to a lack of gas availability and low storage levels. The high price observed in Poland is likely due to a number of concomitant factors, such as Polish gas infrastructure acting as the first European landfall for a large proportion of Russian swing capacity, extremely low temperatures in Eastern Europe and Poland's physical network externality.

Hub	Mean	Std. Dev.	Skewness	Kurtosis	JB Test
PVB (Spain)	22.54	5.06	1.22	2.31	<0.001
PSV (Italy)	21.86	4.93	4.28	35.08	<0.001
PEG-TRS (France)	21.45	5.41	3.65	31.83	<0.001
VTP Gaz System (Poland)	21.18	4.84	6.07	76.65	<0.001
CEGH (Austria)	20.19	3.89	3.03	21.83	<0.001
NBP (UK)	20.00	5.03	5.46	68.89	<0.001
NCG (Germany)	19.93	4.85	5.82	68.38	<0.001
PEG-Nord (France)	19.78	4.43	3.65	31.83	<0.001
Gaspool (Germany)	19.68	4.14	2.75	20.27	<0.001
TTF (Netherlands)	19.68	4.51	4.62	49.90	<0.001
Zeebrugge (Belgium)	19.51	3.90	1.40	4.82	<0.001
ETF (Denmark)	18.86	3.89	1.91	9.24	<0.001

Table 1: Mean and standard deviation of wholesale day-ahead natural gas prices between 2016 and 2018. The normality distribution (Jarque-Bera) test, including skewness and kurtosis values, are also reported.

Physical network externality can be considered as a pertinent factor, as NBP (UK), which also exhibits physical network externality, registered the second highest price in the sample. Due to the characteristics of Granger-causality (Granger & Ramanathan, 1984), prices aren't normalised, as raw data should provide more insight into network topology at each point in time.

4.2 Traded Physical Volumes

Day ahead traded volume provides an important metric pertaining to market activity and development, as it provides a concise estimation of market liquidity and information critical to the development of market liquidity. Day ahead traded volume is an important component in the determination of churn rate, with large absolute volumes in the day ahead market typically associated with a high churn rate, indicative of a well-developed market with a large number of market participants. Table 2a displays the mean day ahead volumes at each hub measured and coefficient of variation of day ahead volumes, which depicts variance of traded volume at each hub.

4.3 Churn ratio

Heather & Petrovich (2017) proffer that churn ratio is amongst the most important measures of each gas hubs' commercial success, as it considers day ahead and total volume traded at each hub, whilst tacitly considering the number of market participants engaged in trading activities at each hub. The churn ratio, total traded volume divided by physical volume, provides an accurate indicator, based on the number of times each physical 'parcel' of gas is traded at the hub, of hub liquidity and commercial success. Gas markets are typically considered to be commercially successful, mature hubs when the churn ratio is larger than ten, with many market participants reluctant to engage in activity at hubs with churn ratios below this threshold. Table 2b reports the churn ratios of the European gas hubs measured. As shown in Table 2b, TTF (Netherlands) is by far the most liquid and commercially successful hub, with a continued development of 7.35% in 2017. CEGH (Austria) and Zeebrugge (Belgium) both experienced a substantial decline in churn ratio in 2017, with the decline at Zeebrugge (Belgium) linked to a reduced output of North Sea fields and decreasing usage of Norwegian gas in favour of cheaper supply from Russia.

4.4 Market Participants

The number of market participants engaged at each trading hub is indicative of the development and commercial success of a market, as it provides information pertaining to the barriers to market entry of new participants, whilst also providing information on ease of interaction for incumbent market participants. In an ideal scenario, the type of each active market participant would be recorded, however, due to data availability, the total number of market participants are recorded at each hub. As a general rule, a larger number of active market participants increases market competition, lowering the bid-offer spread, increasing market depth and ultimately reducing susceptibility to market manipulation.

TTF (Netherlands) and NBP (UK) were considered to be substantially more developed in terms of market participation in 2014, confirmed by the large churn ratios and mean traded volumes observed in Table 2b and Table 2a. Whilst TTF (Netherlands) and NBP (UK) have been usurped in the number of registered participants by NCG (Germany) and Gaspool (Germany), Neumann & Cullmann (2012) noted that the large number of market participants in Germany is a function of the vast number of subordinated network operators.

Hub	Mean Traded Volume	Coefficient of Variation	Connections	2016 Churn Ratio	2017 Churn Ratio	% Change	Market Participants (2014)	Market Participants (2017)
Zeebrugge (Belgium)	121.08	0.43	5	4.10	2.95	-28.17	82	115
Gaspool (Germany)	116.27	0.19	5	2.50	3.05	21.90	105	230
NCG (Germany)	111.45	0.26	8	4.00	4.50	12.44	90	502
PSV (Italy)	109.47	0.24	3	1.20	3.15	162.26	118	190
PEG-Nord (France)	104.35	0.24	4	1.70	2.19	29.11	55	120
TTF (Netherlands)	90.73	0.61	4	57.10	61.30	7.35	130	140
CEGH (Austria)	90.48	0.27	2	5.70	3.51	-38.44	53	30
VTP Gaz System (Poland)	75.60	0.17	1	0.80	1.09	36.23	58	80
PEG-TRS (France)	37.57	0.22	2	0.60	1.10	83.14	37	65
NBP (UK)	34.62	0.73	2	22.10	21.81	-1.31	200	190
PVB (Spain)	8.66	0.52	1	0.10	0.61	513.94	70	105
ETF (Denmark)	2.76	0.87	2	1.20	2.03	69.27	43	60

(a) Mean traded volume (b) Churn ratio (c) Market Participants

Table 2: *a*) The mean day ahead volume in MCM/d and coefficient of variation, depicting the relative standard deviation in day ahead trading volumes and the number of physical pipeline connections of each hub. *b*) The churn ratios of each hub for both 2016 (Heather & Petrovich, 2017) and 2017, with the percentage change. *c*) Number of registered market participants at each hub in 2014 (Heather & Petrovich, 2017) and 2017, including companies both registered to trade and registered as shippers, rounded to the nearest five participants. The data was collated from a range of sources, with no standardised calculation methodology.

5.0 Results

This section first discusses network representations, followed by in-strength, out-strength and net-strength estimations, and then by results relative to global connectivity.

5.1 Network Representation of European Gas Prices

The system of European natural gas price interactions, summarised throughout the global connection density series by computing the degree of Granger causality between gas price returns, produces a dynamic network. Two examples of the network estimation are displayed in Figure 1, with the adjacency matrices and network graphs shown at the points at which the largest and smallest network density terms were observed. From this visualisation, it is clear that a substantial difference in the intensity and number of Granger causal interactions were observed throughout the sample. This is implied by the number of arrows displayed within the network graphs, and the intensity displayed by the adjacency matrices.

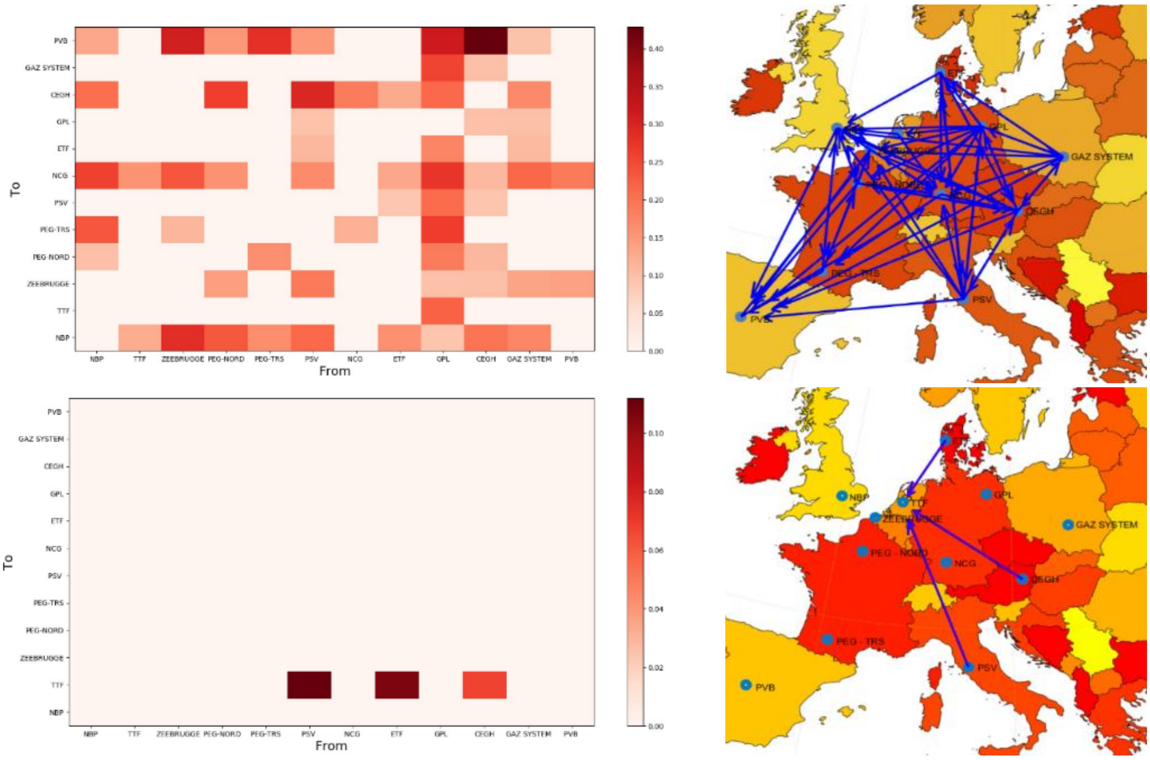


Figure 1: The adjacency matrices (*left panel*) and network graphs (*right panel*) relative to the highest and lowest observations of network density are presented. The highest network density term was observed on 29/01/2018 (upper images), with the lowest network density term observed on 10/10/2018 (lower images). The direction of the arrow corresponds to the direction of the Granger causality between the variations of European gas prices, whilst the adjacency matrices (left panel) depict the intensity of Granger causal interactions between markets. Each matrix entry displays the intensity of Granger-causality between the price variations observed in two sample countries, depicted by the adjacent colour scale.

5.2 In-strength estimations

As per the methodology, in-strength estimations detail the degree to which a given hub's price returns are impacted by price signals from other hubs within the network. Exhibition of a high mean in-strength indicates that hub pricing is highly impacted by other European gas prices. Conversely, a low mean in-strength indicates that hub pricing is marginally impacted by price formation in other markets, instead, it is determined by local factors.

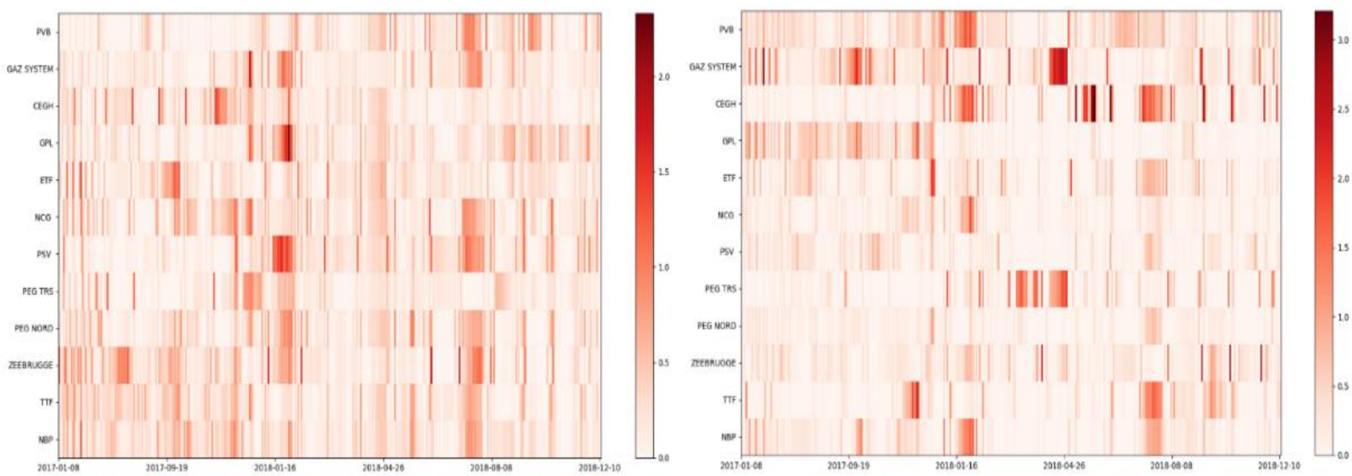
Upon estimation, the day-ahead market that was least impacted by other European natural gas prices, as characterised by the lowest mean in-strength causality (0.179) was PEG-TRS (France). PEG-TRS (France) displays the characteristics of an emerging hub, with a churn ratio of 1.10 (Table 2b) and a mean traded volume of 37.57MCM/d (Table 2a). The low levels of liquidity and physical interconnection of PEG-TRS are plausible explanations for susceptibility to local supply and demand imbalances.

The second lowest mean in-strength (0.190) was recorded at PVB (Spain), which is physically connected to PEG-TRS (France) at VIP-Pirineos. The low mean in-strength causality at PVB (Spain) can be attributed to a number of concomitant factors, including physical network externality, competitive pipeline import pricing from North Africa and substantial regasification capacity. This is further discussed in Section 6.1. The largest mean in-strength causality (0.284) is at Zeebrugge (Belgium), indicating that, on average, this market is most Granger caused by other gas prices. Further to this, the in-strength variance was lower than the sample average, indicating that day ahead pricing at Zeebrugge (Belgium) is consistently influenced by other European gas prices. This is intuitive, as Zeebrugge (Belgium) is physically connected to five other large, liquid trading hubs.

We observe a number of periods in which individual node in-strength values increase within the sample period (Figure 2a). However no clear patterns emerge with regard to average node in-strength throughout the sample period. This implies that European gas price fluctuations held a higher degree of dependence upon variations in other European prices at certain periods, characterised by the intense colours depicted in Figure 2a. Meanwhile, there is no trend indicating an increasing degree of price harmonisation across the period. This phenomenon is further investigated through the utilisation of a network density term in Section 5.5.

Hub	Mean In-Strength	Mean Price (€/MWh)	Physical Connections
Zeebrugge (Belgium)	0.284	19.51	5
PSV (Italy)	0.268	21.86	3
NBP (UK)	0.263	20.00	2
NCG (Germany)	0.262	19.93	8
TTF (Netherlands)	0.244	19.68	4
Gaspool (Germany)	0.239	19.68	5
PEG-Nord (France)	0.236	19.78	4
ETF (Denmark)	0.219	18.86	2
CEGH (Austria)	0.209	20.19	2
VTP Gaz System (Poland)	0.205	21.18	1
PVB (Spain)	0.190	22.54	1
PEG-TRS (France)	0.179	21.45	2

Table 3: The mean in-strength causality, mean price (€/MWh) and number of physical connections of each gas trading hub measured in the sample.



(a) In-strengths (b) Out-strengths

Figure 2: Behaviour of the 12 European price in-strength and out-strength values between 2016-2018. Darker colours indicate larger values, as indicated on the colour bar. Each unit on the y-axis represents one of the 12 markets.

5.3 Out-strength estimations

Out-strength estimations detail the degree to which a given market's pricing impacts price signals at other markets within the network. Exhibition of a high mean out-strength indicates that the market holds a high degree of importance in price formation of gas prices at other European hubs. Conversely, a low mean out-strength indicates that the market holds a limited capacity to impact price formation at other hubs.

The hub price with both the highest mean out-strength (0.412) and standard deviation (0.594) was VTP Gaz System (Poland). This indicates that Polish gas pricing showed a large potential to influence other European gas prices under certain market conditions, specifically in periods of high day ahead gas demand within continental Europe (Figure 2). Poland acts as a good proxy for Russian swing capacity in our sample, holding the Yamal-EuRoPoL pipeline, one of the main transit routes for baseload gas imported from Russia. Consequently, VTP Gaz System (Poland) exhibits a low coefficient of deviation (Table 2a). However, swing capacity is present in the Yamal-EuRoPoL pipeline, characterised by a standard deviation of 12.85MCM/d.

Hub	**Mean Out-Strength**	**Mean Price (€/MWh)**	**Physical Connections**
VTP Gaz System (Poland)	0.412	21.18	1
PVB (Spain)	0.347	22.54	1
CEGH (Austria)	0.343	20.19	2
Zeebrugge (Belgium)	0.227	19.51	5
Gaspool (Germany)	0.221	19.68	5
PEG-TRS (France)	0.215	21.45	2
NBP (UK)	0.213	20.00	2
TTF (Netherlands)	0.212	19.68	4
ETF (Denmark)	0.207	18.86	2
PSV (Italy)	0.156	21.86	3
NCG (Germany)	0.138	19.93	8
PEG-Nord (France)	0.112	19.78	4

Table 4: The mean out-strength causality, mean price (€/MWh) and number of physical connections of each gas trading hub measured in the sample.

PVB (Spain) also exhibits a high mean out-strength causality, indicating potential to influence other European gas prices under specific market conditions. That said, these conditions are considerably different (Figure 2b, Figure 3) to those exhibited by VTP Gaz System (Poland), with the relative out-strengths holding a correlation of -0.24. When considering the fundamental drivers of European gas pricing, pipeline gas from Russia or Norway and LNG, the global context in which these markets operate must be considered.

The ability of pipeline gas or LNG to influence European pricing, characterised by out-strength values, is largely dependent on Asian hub pricing. A substantial premium at Asian hub prices tends to draw spot LNG to Asian markets, leaving Russian or Norwegian swing capacity to dictate European day ahead pricing. Conversely, weak demand in Asia allows for increased spot LNG delivery to Europe, displacing Russian or Norwegian gas as European price leaders (Figure 3).

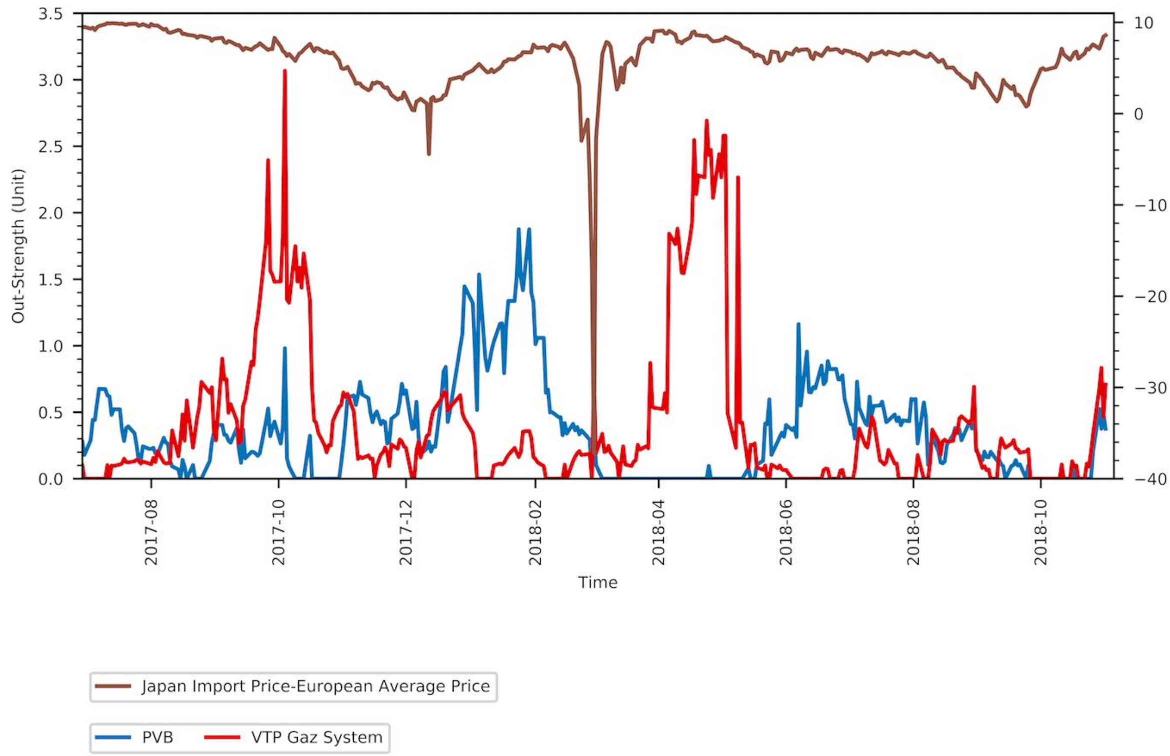


Figure 3: A visual representation of the systematic premium between Japanese Import Price and the average European gas price (€/MWh), PVB (Spain) out-strength causality and VTP Gaz System (Poland) out-strength. When the Japan-Europe premium is large, LNG cargoes are attracted to Asia, allowing VTP Gaz System (Poland) to act as a price leader in European gas, characterised by high out-strength values (Correlation = 0.141). Conversely, when the Japan-Europe premium is low, LNG cargoes are attracted to Spain's large regasification capacity, increasing PVB's out-strength causality, (Correlation = -0.058).

Conversely, the hub that recorded the lowest mean out-strength (0.112), therefore the lowest ability to impact European prices, was PEG-Nord (France). Further to this, PEG-Nord also displayed the lowest out-strength variance, indicating that PEG-Nord consistently had a marginal capacity to influence other European day ahead prices. This is in contrast to PEG-TRS (France), which held a considerably larger ability to influence European gas pricing throughout the sample, recording a mean out-strength of 0.215. The bifurcation of the French gas market is further discussed in Section 6.2.

5.4 Net-strength estimations

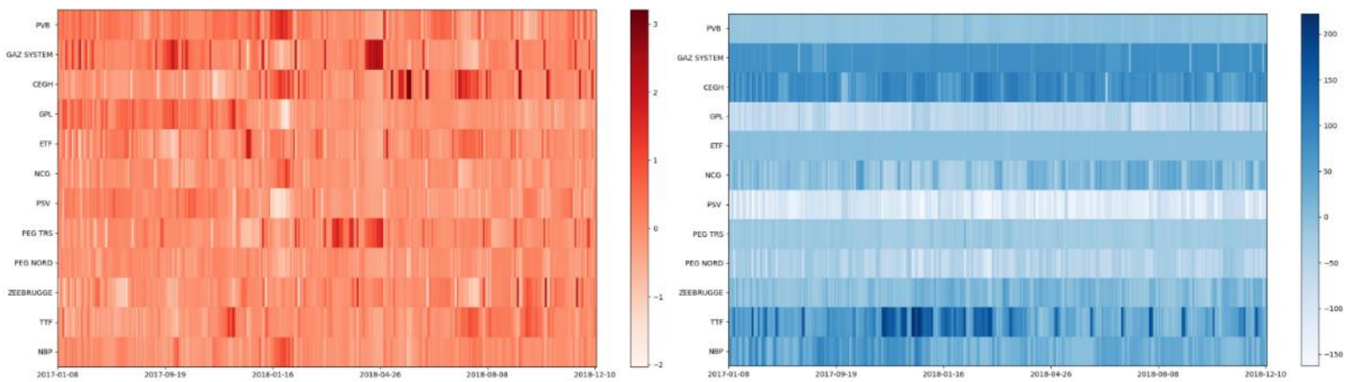
Following estimations of in-strengths and out-strengths, the net-strengths are estimated. A large, positive net-strength indicates that the trading hub shows a high potential for influencing prices at other hubs, acting as a 'price leader' within European day-ahead gas pricing. Conversely, hubs which exhibit negative net-strengths indicates that pricing at the hub is mostly Granger caused by pricing at other hubs, acting as a 'price follower'.

Hub	Mean Net-Strength	Variance	Mean Price (€/MWh)
VTP Gaz System (Poland)	0.206	0.663	21.18
PVB (Spain)	0.158	0.449	22.54
CEGH (Austria)	0.134	0.699	20.19
PEG-TRS (France)	0.036	0.510	21.45
ETF (Denmark)	-0.012	0.450	18.86
Gaspool (Germany)	-0.018	0.429	19.68
TTF (Netherlands)	-0.032	0.394	19.68
NBP (UK)	-0.050	0.286	20.00
Zeebrugge (Belgium)	-0.057	0.513	19.51
PSV (Italy)	-0.113	0.394	21.86
NCG (Germany)	-0.124	0.302	19.93
PEG-Nord (France)	-0.124	0.253	19.78

Table 5: The mean net-strength causality, variance of net-strength causality and mean price (€/MWh) of each hub measured in the sample.

The hub which recorded the largest mean net-strength (0.206) is VTP Gaz System (Poland), followed by 0.158 recorded at PVB (Spain) and 0.134 at CEGH (Austria). This indicates that these hubs exhibit the highest degree of ‘price leader’ behaviour within European gas markets. In isolation, each hub has a number of unique characteristics. The aforementioned hubs hold a commonality of physical proximity to gas injection into the European network. Whether it is LNG regasification capacity at PVB (Spain), or major pipeline (Yamal-EuRoPoL, Soyuz) terminals from production fields in Russia (VTP Gaz System, CEGH), the hubs which display positive net-strengths have acted as net exporters to other hubs, with the exception of PVB (Spain).

VTP Gaz System (Poland), which acts as the first European landfall of one-fifth of Russian exports transited by the Yamal-EuRoPoL pipeline, had a mean net export of 75.60MCM/d exclusively to Gaspool (Germany). As such, VTP Gaz System’s prominence as a ‘price leader’ within the study is unsurprising. This hypothesis is further investigated through the analysis of adjacency matrices in Section 6.2.



(a) Net-strengths (b) Net export volumes

Figure 4: *a*: The 12 European price net-strength values between 2016 and 2018. Darker colours indicate larger influential values, whereas lighter colours indicate more prominent values. The units of the y-axis represent the 12 markets. *b*: Net export volumes from each trading hub between 2016-2018, expressed in million cubic meters per day (MCM/d). Darker colours indicate large net export volumes, whilst lighter colours indicate large net import volumes, as per the colour bar.

Extended periods of disconnection from the European pricing system, further discussed in Section 6.4, were observed at PVB (Spain), culminating in a mean net-strength value of 0.158. Critically, PVB (Spain) also displa yed the largest mean price of the sample, indicating that an improved degree of integration into the European pricing system could be beneficial for domestic consumers.

A number of conclusions can be drawn; Firstly, hubs that have access to substantial physical injection into the European network hold influence over European natural gas pricing. When interpreting Figure 4a, it becomes apparent that a determining characteristic in the pricing of European gas is exogenous to the study, with Asian hub pricing most likely playing a role in determining whether LNG or Russian and Norwegian swing capacity acts as the 'price leader' in the European day ahead market. This is intuitive, as high prices at Asian hubs act to draw LNG away from European regasification plants, allowing Russian and Norwegian swing capacity to act as the European day ahead 'price leader', evidenced by the large net-strengths exhibited at VTP Gaz System (Poland) and CEGH (Austria).

5.5 Network Density of European Gas Prices

Network density, as defined in Section 3.3, remained around the relatively low mean value of 0.141 throughout the sample time frame, with a standard deviation of 0.074. The maximal value of network density, recorded on 29/01/2018, is displayed as the largest peak in Figure 5. Through observing the causal interactions between EU natural gas prices, the model provides a dynamic quantification of European gas market price harmonisation, the system's network density term, which exhibits stochastic behaviour, as depicted in Figure 5.

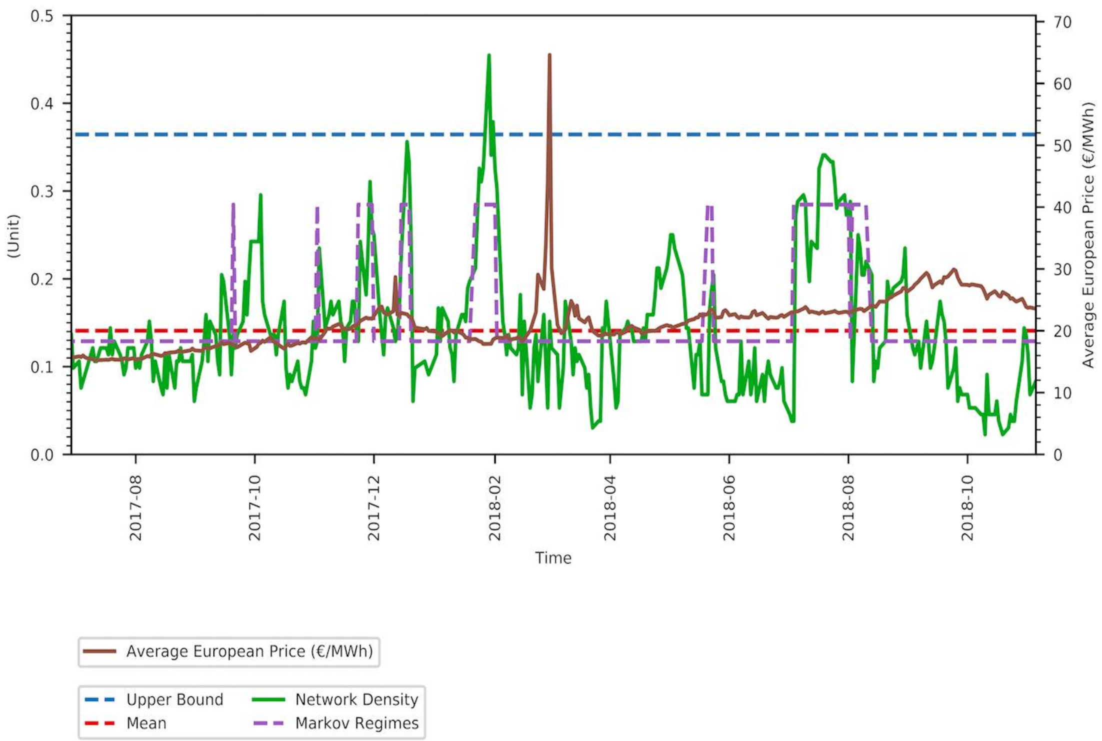


Figure 5: Network density of twelve European day ahead gas prices between 2016 and 2018. The dotted horizontal lines represent the mean and upper confidence bounds (Z>1.96). Time is on the x-axis, with the network density value displayed on the y-axis. The two Markov regimes are depicted by the purple dotted line, with coefficients of 0.129 and 0.285 respectively.

Subsequently, the distribution of the network density term was analysed, with the z-score calculated in order to understand at which observations of time the network density was three standard deviations above the mean (Z>$1.96, p<0.05). Values lying outside the confidence bounds imply abnormal market behaviour at the observation, characterised by an unusually large network density term.

The occurrence of abnormally large network density terms coincided with factors such as pipeline capacity reductions, seismic activity and uncharacteristically cold weather. Periods of lower than normal connectivity occurred as frequently as those of greater than normal connectivity, indicating that short-run gas market integration is not substantially pronounced. Results relative to global connection density display the occurrence of a large spike in January 2018, reaching a magnitude of 0.45 on 29/01/2018. This can be attributed to the pipeline disruption that occurred between Oude Statenzijl (Netherlands) and Bunde (Germany) between 27/01/2018 and 28/01/2018. Further to this, an initial interconnectivity peak of c.ca 0.30 can be observed within the first 69 model shifts (04/10/2017).

The following peaks reached 0.31 and 0.36 respectively, with the mean level of network density remaining c.ca 0.15 throughout the sample. The longest peak in global density was recorded during the period 05/07/2018 to 02/08/2018, with an over basal increase of 194%. When referring to Figure 5, there is a noticeable lack of correlation between peaks in the average European day ahead price and the network density term, indicating that abnormal price phenomena did not produce the network density peaks observed.

Subsequently, a Markov regime switching model was applied to the connection density time series, detecting the exact points at which connection density peaks occur. Observed jumps in global connectivity were considered as changes to another regime, which occurred seven times throughout the sample, as shown in Figure 5.

We applied an ARIMA (1,0,0) model to the network density term to investigate whether the network density, and by extension, market integration, represents a stochastic process. Results show that a random walk process could have produced the network density time series, therefore an AR(1) model is an appropriate representation of European network density. From this, it can be surmised that the most accurate representation of the network density term at time t is network density at time $t-1$.

6.0 Discussion

6.1 In-Strengths

The mean in-strength causality of 0.190 exhibited at PVB (Spain) (Table 3) can be attributed to a number of concomitant factors, including physical network externality, competitive pipeline import pricing from North Africa and substantial re-gasification capacity. The low physical interconnection to the European market (16.89MCM/d) makes Spain reliant on North African imports to meet its domestic demand, with Algeria supplying 56.8% of total import demand in 2016 (ENTSOG, 2017). Further to this, Spain holds 39% of total European regasification capacity, with LNG imports constituting a substantial proportion of domestic supply, through term contracts with Norway, Nigeria and Qatar. As such, PVB (Spain) exhibits a low mean in-strength, as pricing is determined by a combination of LNG and North African imports. As such, the Spanish gas market is largely driven by domestic supply and demand conditions, as opposed to pan-European supply and demand balances.

When considering Iberia's physical network externality, the systematic disparity of €1.08/MWh between the adjacent trading regions of PEG-TRS (France) and PVB (Spain) is comprehensible. The aforementioned trading regions are connected by 16.89MCM/d of pipeline capacity at VIP Pirineos, which is rarely utilised at maximal capacity (Figure 6). Consequently, the premia paid at PVB (Spain) arises from a low availability of transmission capacity for day ahead market participants that are not engaged in term contracts (Heather & Petrovich, 2017). This constraint has inhibited the Iberian peninsula's integration into the European natural gas network.

Both PEG-TRS (France) and PVB (Spain) display the characteristics typical of emerging hubs, detailed in Table 2a and Table 2b. As such, the low levels of liquidity may adversely impact cross-border trade volumes, characterised by the low pipeline utilisation rates displayed at VIP Pirineos (Figure 6). This has the impact of decreasing arbitrage flows, with arbitrage only occurring when the PVB premium becomes uncharacteristically large (Figure 6). This is confirmed through analysis of the adjacency matrices, as PEG-TRS (France) caused pricing at PVB (Spain) (above a 95% confidence) in 136 of 347 (39.19%) sampled days.

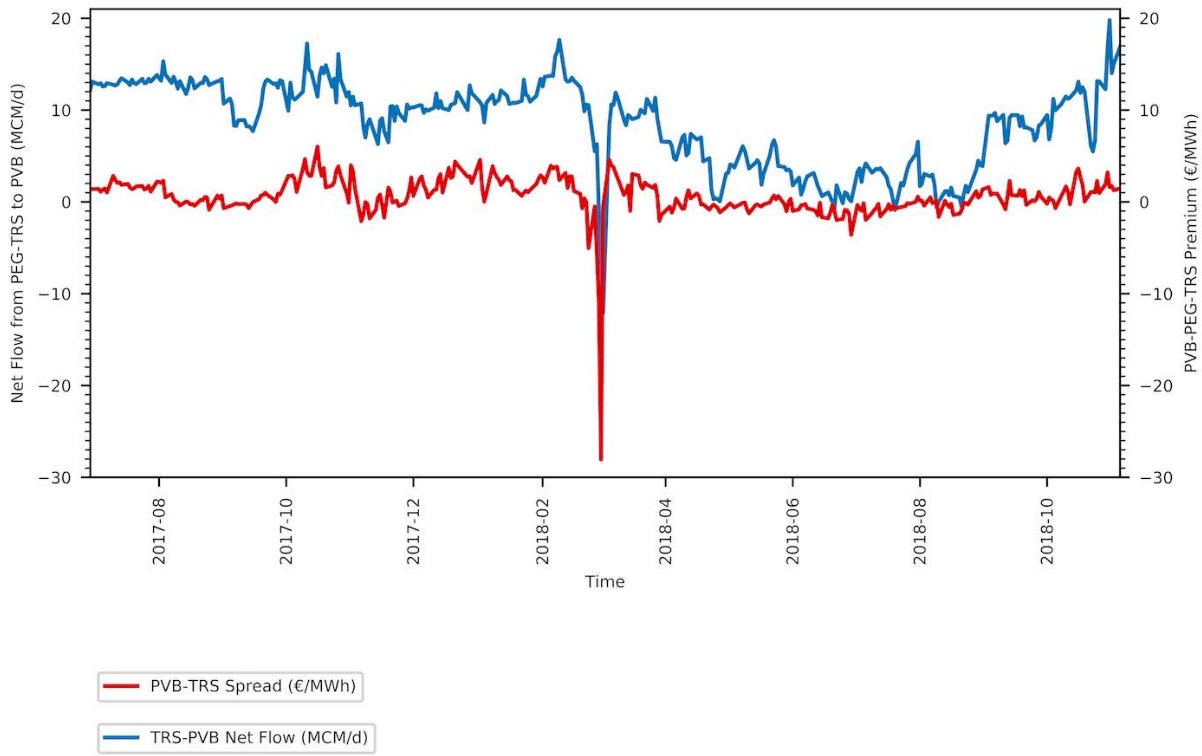


Figure 6: The systematic price difference between PVB (Spain) and PEG TRS (France), combined with the net flow in million cubic meters per day (MCM/d) through the VIP Pirineos link, connecting the trading regions.

Broadly, when geographical position of hubs is considered, those that exhibit physical network externality (Figure 1), such as PVB (Spain), PEG-TRS (France) and VTP Gaz System (Poland), display a larger mean price than those that exhibit network centrality (Table 3). These hubs are also characterised by a low mean in-strength causality, indicating that the day ahead pricing is marginally impacted by pricing at other European hubs.

Gaspool (Germany) is an exception, as it holds a central network position, connected to five other hubs, yet exhibits a low degree of prominence, combined with a high variance of in-strength. This can be explained by Gaspoool's (Germany) high concentration of Russian and Norwegian imports, with pricing at Gaspool (Germany) showing a low dependence on other European market pricing. It is plausible that the relationship with Russian and Norwegian day ahead pricing supersedes the relationship with European pricing. The high degree of in-strength variance confirms this, as under specific market conditions, pricing at Gaspool (Germany) can be highly dependent on other European day ahead prices, which coincides with a high network density term. However, under normal market functioning, pricing at Gaspool (Germany) appears to exhibit a stronger relationship with Russian and Norwegian gas prices.

The largest mean in-strength causality was recorded at Zeebrugge (Belgium), indicating that, on average, it is mostly Granger caused by other gas prices. Also, the in-strength variance was low, indicating that day ahead pricing at Zeebrugge (Belgium) is consistently influenced by other European natural gas prices. This is intuitive, as Zeebrugge (Belgium) holds a central network position, connected to five other hubs. Furthermore, Zeebrugge's status as the oldest trading hub within continental Europe, physical proximity to other large, liquid trading hubs (TTF, PEG-Nord, NBP) and status as a net-exporter throughout the sample compound the characteristic of network centrality, increasing the degree to which Zeebrugge acts as a ‘price follower’ within the day ahead market.

6.2 Out-Strengths

The largest mean out-strength of 0.412 was recorded at VTP Gaz System (Poland). This is intuitive, as Poland holds one of the main transit routes for European-bound gas from Russia, the Yamal-EuRoPoL pipeline. Therefore, Poland is one of the first points at which Russian ‘swing’ capacity is priced into our sample. In periods of high demand, VTP Gaz System (Poland), due to its physical proximity to the gas fields which serve European day ahead supply, exerts a high degree of influence on European pricing, characterised by a high mean out-strength.

VTP Gaz System (Poland) holds 112.39MCM/d of interconnection capacity to Gaspool (Germany). In spite of this, pricing within Poland holds a systematic premium to pricing at Gaspool (Germany), with 18.44% of adjacency matrices showing day ahead pricing at Gaspool (Germany) is Granger caused by VTP Gaz System (Poland) at the 5% confidence level. Meanwhile, pricing at Gaspool (Germany) influenced pricing at VTP Gaz System (Poland) for 24.78% of sampled days. Throughout the sample, despite the systematic €1.50/MWh premia at VTP Gaz System (Poland), negligible arbitrage flows occurred from Gaspool (Germany) to VTP Gaz System (Poland). Conversely, VTP Gaz System (Poland) acted as a net exporter to Gaspool (Germany), exporting an average of 75.60MCM/d (67.27% utilisation) throughout the sample. This finding supports Heather & Petrovich's (2017) assertion that capacity constraints are not the primary factor in Poland's systematic price premium in the day ahead market, elucidating that Polish gas pricing is determined by local supply and demand imbalances. From this, it can be inferred that the country's gas system is not fully liberalised or integrated into the European gas network.

PVB (Spain) also exhibits a high mean out-strength (0.347, Table 4), indicating that Spanish pricing can influence other European gas prices, albeit under specific conditions. These conditions are considerably different (Figure 2b) to those exhibited by VTP Gaz System (Poland), with the relative out-strengths holding a correlation of -0.24. When considering the fundamental drivers of European natural gas pricing, gas imported from Russia and Norway or LNG, the context in which these markets operate must also be considered. The ability of pipeline gas or LNG to influence European pricing, characterised by out-strength values, is largely dependent on Asian hub pricing, as a substantial premium at Asian hub prices tends to draw spot LNG cargoes to Asia, leaving Russian or Norwegian swing capacity to dictate European day ahead pricing. Conversely, weak demand in Asia allows for increased spot LNG delivery to Europe, displacing Russian or Norwegian gas as European price leaders (Figure 3).

Considering the above, the out-strengths displayed in (Figure 2b) are intuitive, as Russian day ahead flows, which are first priced into the sample at VTP Gaz System (Poland) or CEGH (Austria) hold negative correlations (-0.24 and -0.37 respectively) with countries with large LNG regasification facilities, such as PVB (Spain). As Spain accounts for 39% of European LNG regasification capacity, PVB (Spain) has considerable influence on European day ahead pricing when Asian LNG demand is weak.

Conversely, the hub that recorded the lowest mean out-strength (0.112, Table 4), therefore the least ability to impact European gas prices, was PEG-Nord (France). Further to this, PEG-Nord also displayed the lowest out-strength variance of the sample, indicating that PEG-Nord consistently had a limited capacity to influence other European day ahead gas prices. This can be attributed to France's 70% dependence on nuclear capacity for energy generation, lack of indigenous production following the closure of the Lacq field in 2013, and net importer status throughout the sample.

When considering the North-South (PEG-Nord, PEG-TRS) division of the French gas market, a disparity between the characteristics of the two hubs can be observed, as PEG-TRS (France) displays the sixth largest mean out-strength, whilst PEG-Nord (France) displays the lowest.

The bifurcation of the French gas market can be explained by three stylised facts, origin of gas mixture, degree of interconnection and network position. LNG is essential to meet demand within PEG-TRS (France), constituting 39% of volume (ENTSOG, 2017). As such, PEG-TRS

(France) is subject to similar global LNG dynamics to PVB (Spain). However, PEG-Nord (France), which holds marginal LNG volume (3%, ENTSOG, 2017) within the import portfolio, is subject to day ahead price dynamics from Russia, Norway and the Netherlands. Furthermore, PEG-Nord's interconnection to Zeebrugge (Belgium), NCG (Germany) and PEG-TRS (France) provides it with a larger degree of network centrality than PEG-TRS (France), which holds comparatively small interconnection capacity to PVB (Spain) and PEG-Nord (France). Finally, the high utilisation of the Liason Nord-Sud pipeline (96%) highlights the price disparity between the two hubs, as the premium at PEG-TRS increases as the Liason Nord-Sud pipeline utilisation rate increases beyond 95%.

On November 1st, 2018, the French gas market merged its two virtual trading points (VTPs), PEG-Nord and PEG-TRS, in order to form a single VTP called Point d'Èchange de Gaz (PEG). Consequently, the price difference (Table 1) between PEG-Nord (France) and PEG-TRS (France) is expected to be reduced, as a single national market is established. As such, an increase in market integration is anticipated.

Following the merger, a change in French gas market dynamics occurred, with a decrease in mean out-strength from 0.217 to 0.031 exhibited at PEG-TRS (France) (Figure 2b). This indicates that following the merger, price formation characteristics in France were similar to those exhibited at PEG-Nord (France) prior to the merger. It is anticipated that these dynamics shall evolve due to the pending completion of the Val de Saone and Gascogne-Midi pipeline projects, which aim to equalise gas pricing within the France.

6.3 Net-Strengths

The net-strengths, which account for a given hub's impact on the system, minus the system impact on the hub, provides valuable information pertaining to which hubs act as 'price leaders' or 'price followers'.

A combination of low mean in-strengths and high mean out-strengths culminate in high net-strengths recorded at VTP Gaz System (Poland) and CEGH (Austria). This indicates that a variable beyond the scope of the sample, Russia, would probably act as a strong 'price leader' for European gas hubs.

VTP Gaz System (Poland) exhibits the largest mean net-strength of 0.206 (Table 5). This is intuitive, given that Poland acts as the first European landfall of one-fifth of Russian export capacity. VTP Gaz System's (Poland) ability to act as a 'price leader' within central European gas pricing is confirmed through adjacency matrix analysis. Pricing at Gaspool (Germany), NCG (Germany) and ETF (Denmark) was influenced by VTP Gaz System (Poland) in 46, 64 and 40 instances respectively.

CEGH (Austria) recorded the third largest net-strength of 0.134 (Table 5), exhibiting dynamics which were similar to those observed at VTP Gaz System (Poland). Given that Baumgarten, within the CEGH (Austria) trading region, is one of the major European terminals of Russian export flows, it acts as a thoroughfare for capacity to South-Eastern Europe and the central European market, namely Germany (NCG and Gaspool) and Italy (PSV). CEGH (Austria) also recorded the largest mean net export value of 77.84MCM/d, with net exports of 81.36MCM/d to PSV (Italy). However, pricing at CEGH (Austria) only influenced pricing at PSV (Italy) 5.19% of the time.

As discussed in Section 5.4, PVB (Spain) exhibited the second largest Net-Strength of 0.158 (Table 5). This is precipitated by a multitude of reasons, addressed in Section 6.1 and Section 6.2. Critically, the premium paid for day-ahead gas at PVB (Spain) is not derived from infrastructure constraints, as average utilisation at VIP Pirineos remained at 50.3% throughout the sample (Figure 6), with LNG regasification infrastructure utilisation c.ca 40.0%. Of the concomitant factors restricting PVB's (Spain) integration into the European network, the most pertinent appears to be the low availability of transmission capacity for day ahead market participants who are not engaged in term contracts (Heather and Petrovich, 2017). As PVB (Spain) matures as a hub, and PEG-TRS (France) is integrated into a singular French market, it is anticipated that PVB (Spain) shall become more integrated into a singular European market.

6.4 Physical and Non-Physical Reasons for Market Decouplings

As indicated in Sections 6.1, 6.2 and 6.3, the dislocation of markets from the European network are typically caused by one of two core reasons; physical and non-physical.

When considering the physical reasons for a lack of market harmonisation, pipeline congestion is amongst the most pertinent factors. The €1.67/MWh mean differential displayed between

PEG-Nord (France) and PEG-TRS (France) (Table 5) may be the result of a lack of available capacity on the Liason Nord-Sud pipeline (Heather and Petrovich, 2017), as mean sample utilisation was 96%. Whilst other factors, such as the disparity in LNG composition of the gas mixture, relative consumption volumes and network centrality may have impacted the differential, Liason Nord-Sud pipeline constraints appear to be the most important determinant of the differential between the two trading zones. As noted in Section 6.2, the Val de Saone and Gascogne-Midi pipeline projects are anticipated to supress this differential, increasing the degree of price harmonisation within European gas pricing.

Given the absence of capacity constraints at PVB (Spain) and VTP Gaz System (Poland), non-physical factors appear to be the cause of low levels of integration into the European network. Both hubs hold common characteristics, such as a lack of indigenous production, the capacity to inject large volumes of gas into the central European market, and physical network externality.

Extended periods of disconnection from the European network were observed at PVB (Spain), leading Natural Gas World (2019) to declare the Iberian Peninsula a "gas island". Pipeline utilisation remained at 50.3% throughout the sample, yet PVB (Spain) was priced at a premium (Figure 6) to PEG-TRS (France), indicating that arbitrage forces are not fully operational between the two hubs. Heather and Petrovich (2017) propose that a low availability of transmission capacity for day ahead market participants who are not engaged in term contracts reduces capacity utilisation, and consequently arbitrage flows. Further to this, low levels of liquidity, displayed in Tables 2a and 2b, may discourage market participants from entering into geographic arbitrage.

Following the PEG-TRS (France) and PEG-Nord (France) merger and creation of a singular French market, liquidity is expected to increase, and increased arbitrage volumes shall reduce the PVB (Spain) premium. Further to this, the completion of the Val de Saone and Gascogne-Midi pipeline projects should alleviate capacity restrictions on the Liaison Nord-Sud pipeline and effectively eliminate the premium paid within the day ahead market in the region formerly identified as PEG-TRS (France).

VTP Gaz System's (Poland) premium to Gaspool (Germany) stipulates that arbitrage forces should be in effect, however VTP Gaz System (Poland) exported a mean of 75.60MCM/d to

Gaspool (Germany), indicative of a non-physical barrier to market integration. It is plausible that a low degree of internal market liberalisation is the primary reason for low integration into the European market. Notably, VTP Gaz System (Poland) is the only hub denominated in an emerging market currency. It is plausible that European market participants impound a higher degree of foreign exchange risk into pricing at VTP Gaz System (Poland).

6.5 Network Density and the Third Energy Package

To what degree has the Third Energy Package impacted gas markets? The network density term remained at a relatively low mean level of 0.141, indicating a low degree of harmonisation within the European market. Application of an ARIMA (1,0,0) model to the network density term revealed that network density follows a random walk process, indicating that the expected change in network density is appropriately characterised by white noise. As such, the best estimate of network density at time t is represented by the value produced at time $t-1$. Additionally, the number and magnitudes of both abnormally positive and negative network density behaviours implies a lack of increasing, sustained market integration amongst European gas prices. Taken in unison, these findings provide a clear indication that price harmonisation within the European day ahead gas market did not exhibit a substantial, sustained increase between 2016 and 2018.

The regime model identifies two distinct regimes within the European day ahead gas market, with the peaks in network density coinciding with pipeline disruptions, hub disruptions and seismic activity. On 12/12/2017, an explosion at Baumgarten, Austria forced the operator to close the facility and physical trading to cease at CEGH (Austria), leading Italy to declare a national gas shortage. It is likely that the market responded to this event through impounding the capacity loss into the market, characterised by a spike in network density, lasting until 19/12/2017. Additional evidence for this hypothesis is obtained through the analysis of out-strengths (Figure 2b) and net-strengths (Figure 4a), where CEGH (Austria) uncharacteristically (Table 5, 0.134) held no capacity to influence pricing at other hubs, acting as a strong 'price follower'. PSV (Italy), which has a substantial import reliance on CEGH (Austria) temporarily transitioned to 'price leader' behaviour following the outage, returning to 'price follower' behaviour on 20/12/2017.

A plausible cause of the January 2018 peak is the impact of extreme temperatures throughout Europe, combined with a pipeline disruption between Oude Statenzijl (Netherlands) and Bunde

(Germany) between 27/01/2018 and 28/01/2018. Through correlation analysis of European heating/cooling days and network density (Correlation = 0.102), the elevated network density values cannot be directly attributed to weather patterns. As such, the pipeline disruption between the Netherlands and Germany likely impacted trade (Figure 5), harmonising pricing and producing a spike in the network density term.

The mean in-strength exhibited stochastic behaviour throughout the period sampled, indicating that price returns at any given hub were not subject to a larger amount of influence from other European natural gas markets at the end of the sample as opposed to the beginning. When considered alongside the network density term, which also exhibited stochastic behaviour, it becomes clear that, although periods of high network integration occurred, no sustained increase in European market integration was observed.

7.0 Conclusions

We apply graph theory in order to model the interactions between 12 European day ahead gas markets during the period 2016-2018. The relationships between the markets is measured through the network density term (Section 3.3), which characterises the quantity of causal interactions within the system at a given point in time. The novelty of this work lies in the application of network theory and Granger-Geweke causality to gas markets, disentangling the dynamic relationships between markets and measuring market integration and relative market power.

The detection of historical exogeneous events verifies the modelling technique. The observation of in-strength, out-strength or net-strength dynamics relative to these occurrences provides valuable information on how the European gas system may react to future exogenous shocks.

Network density analysis resulted in the discovery of a two regime Markov model, with an abnormally large spike of c.ca 0.45 observed on 29/01/2018, which possibly reflects the impact of a pipeline capacity reduction between Oude Statenzijl (Netherlands) and Bunde (Germany).

Further to this, abnormal connectivity behaviours were evenly distributed, with abnormal connectivity distortions similar in number and magnitude. Application of an ARIMA (1,0,0) model to the network density term revealed network density to be a random walk process, indicating that the expected change in network density is best characterised by white noise. Taken in unison, these findings imply a lack of sustained increase in market integration amongst European day ahead gas prices, indicating that attainment of a 'Single European Gas Market' is not imminent.

Our results confirm that the short-term gas trade in Europe is developing, however each hub holds unique characteristics, providing different rates of development and integration. The low number of physical barriers to market integration detected implies that the Third Energy Package's focus on cross-border mechanisms has been broadly successful, alleviating many pipeline capacity constraints throughout the European network. Conversely, the persistence of non-physical barriers to trade suggests that the development of specific national gas markets (VTP Gaz System, PVB) is yet to be achieved, inferring that improvements in technical arrangements are required.

It is imperative that European system operators enable full integration of day ahead gas markets, considering market concentration, market design and regulation, all of which are crucial to the development of a single European market. The elimination of physical barriers to market integration, in conjunction with improved legislative integration, implies the future convergence of day ahead gas prices toward a single European price (in the absence of transmission costs). This holds tertiary benefits in the reduction of pipeline congestion, increased efficiency, and market power reduction of participants within national markets.

Critically, the methodology elucidates the importance of specifying a dynamic model, which is capable of monitoring the time-varying interactions within a network structure, as each market has a continually evolving ability to influence (out-strength) and be influenced by (in-strength) other markets. The model, which is able to observe the dynamic nature of interactions, is also able to detect underlying changes in market integration, which can be driven by either exogenous (Baumgarten) or endogenous events (Oude-Stanzijl-Bunde). As such, it can be considered a suitable tool for measurement of the both market dynamics and the degree of market integration.

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