



## Price and Volatility Spillovers between Crude Oil and Natural Gas markets in Europe and Japan-Korea

Theodosios Perifanis, Athanasios Dagoumas\*

Energy and Environmental Policy Laboratory, University of Piraeus, 150 Androutsou str, PC 18532, Piraeus, Greece.

\*Email: [dagoumas@unipi.gr](mailto:dagoumas@unipi.gr)

Received: 12 March 2020

Accepted: 10 June 2020

DOI: <https://doi.org/10.32479/ijeeep.9774>

### ABSTRACT

The shale gas developments over the last two decades have challenged the gas price linkage with crude oil. The decoupling of the US wholesale gas from oil markets is mainly attributed to the rapid development of unconventional production, which formed a regional natural gas market based on regional market fundamentals. Moreover, investments in exporting facilities in the US made more quantities available to the rest of the world making global integration more plausible. This paper provides empirical evidence on the price and volatility transmission among the main European (National Balancing Point and Title Transfer Facility) and the Japan-Korean Marker (JKM) gas markets with that of Brent crude oil market, a crude oil benchmark used in Europe and Asia. The paper provides evidence that there are no price spillovers among oil and gas in European gas hubs. The European markets, contrary to the JKM market, seem to be mature enough as in the case of the US gas market. Finally, the paper provides policy recommendations on key elements for establishing functional gas hubs.

**Keywords:** Natural Gas and Oil Markets, Price and Volatility Spillovers, Europe, Japan

**JEL Classifications:** Q40, Q41, C5

### 1. INTRODUCTION

Potential spillovers among crude oil and natural gas markets is a long-standing issue of research and business community due to its dynamic nature. Crude oil pricing is mainly driven by market fundamental factors like supply and demand (Perifanis and Dagoumas, 2019 and Perifanis, 2019). On the other hand, natural gas and other substitutes and byproducts had to somehow be priced using crude oil prices as a benchmark. An example was the natural gas pipeline contracts when many countries used long-term oil-indexed contracts because benchmarking offered the competitive advantage of substitution against oil, as well as transparency, avoiding price upsets from a non-liquid natural gas market.

The global gas market attempts to evolve away from the oil one. The gas market can be separated into the natural gas (produced and not liquefied), and LNG which is liquefied and then regasified. Both

require severe long-term investment and infrastructure (pipeline networks, LNG terminals, etc.). The grid bound dependence of the gas industry also adds to the regional character of the market according to some market experts. One way to surpass this kind of character, even if there is no physical trading, is to establish virtual trading points (VTP) where the participants just contract volumes. LNG terminals were constructed in an attempt to diversify suppliers. This led to contracting changes since countries could order quantities from suppliers even if there were no network connections. This drove the developments and now Russia and Qatar emerged as swing producers between Europe and Asia. Asian markets become even more important as China increases its imports from Russia, while Japan and Korea follow suit.

The transition from oil to gas is enhanced by regulatory and policy initiatives. The European Gas Target model by the European Union aims at the security of supply, a fully integrated wholesale market

with upstream competition and gas' flexible complementing role to renewable production.<sup>1</sup> This development leads to a deviation from oil benchmarking through the development of liquid gas hubs. Gas hubs as National Balancing Point (NBP), Title Transfer Facility (TTF) and CEGH (Central European Gas Hub or formerly known as Gas Hub Baumgartner) play a new role in the European gas supply and pricing, as European production will be replaced by imports due to the maturity of domestic fields.

Another example of a country that tried to distant itself from its already primary energy source is Japan. The Fukushima Daiichi nuclear power plant accident in 2011 changed its energy mix as Japan's natural gas consumption increased dramatically. Remarkably, the Japanese natural gas demand rose to 4.4 trillion cubic feet in 2015 i.e. an increase of 42% in a decade. Japan is the largest LNG importer and is accountable for 32% of global LNG purchases in 2016. Asian LNG prices have been linked to international crude oil prices for decades and the sharp increase of the Japanese market made the global market tighter. There was a 70% increase in import prices from 10\$/MMBtu to more than 17\$/MMBtu since the Fukushima accident to 2012. Most of the LNG was headed to power generation as Japan took the initiative in 2011 to close its nuclear power plants.

The paper provides empirical evidence on the price and volatility transmission among the main European (NBP and TTF) and the Japan-Korean Marker (JKM) gas markets with that of the Brent crude oil market. We study whether oil leads the information process i.e. whether the "law of one price" holds.

## 2. LITERATURE REVIEW

The creation of gas hubs and gas trading points aim at forming fully integrated and efficient markets. There is extended literature on whether this is achieved –or will ever be achieved- or on the contrary, the "law of one price" between oil and gas holds. Opolska (2017) suggests that liberalization tools bring results when it comes to competition. However, they should be implemented combinedly and not on a stand-alone basis. Interestingly, VTP, market-based balancing, market opening, and privatization are the most competition-improving tools. Barnes and Bosworth (2015) suggest that the global natural gas market becomes more integrated after studying 92 countries. Geng et al. (2014) suggest that the markets in North America, Europe, and Asian are not integrated and that improvement of market integration will advance trade globalization.

Jensen (2004) proposes that the natural gas market was separated into regional markets due to the high transportation costs and the required infrastructure. Bachmeier and Griffin (2006) and Li et al. (2014) add that the global gas market is separated into three distinguished peripheral markets (European, North American and Japanese/Korean), while they find that only the NBP and JKM markets are integrated, not by fundamental pricing, but rather than oil-indexed pricing.

Miriello and Polo (2015) study the gas hubs of the UK, Netherlands, Germany, and Italy. They highlight that the natural gas of the Netherlands and the UK are leading the process of development of efficient and fully functioning wholesale markets. However, the gas hubs of Germany and Italy follow as they have limited supply. Dahl et al. (2011) propose that the historical relationship between Brent and NBP does not hold since 2007, and they suggest that the "law of one price" is no longer valid. On the contrary, Asche et al. (2012) present evidence that vast differences can arise in the short-term, but in the long-term, an equilibrium mechanism exists which eliminates differences in the UK. The long-term equilibrium is justified by the substitution between oil and gas, and the "law of one price" is confirmed. Van Goor and Scholtens (2014) present evidence that the UK gas market has a seasonal effect between October 2001 and September 2005. However, since then there is no seasonal volatility because the gas market became more liquid and consequently decoupled from oil. Geng et al. (2016b) add that both West Texas Intermediate and Brent prices heavily influenced Henry hub and NBP prices respectively, but this kind of condition altered due to the shale gas revolution when European gas markets remain coupled to oil volatility. Misund and Oglend (2016) suggest that the UK gas system has mitigating mechanisms like flexible assets such as interconnection and storages which smooth effects from deviations in a single demand or supply variable. They also add that spot contracts influence volatility more than long-term ones, while the UK gas volatility's decrease can be attributed to the decreased gas demand.

Erdoş (2012) suggests that US oil and gas prices were correlated in the short-run and that they were cointegrated between 1997 and 2008. This kind of relationship does not hold since 2009 as the prices decoupled. He further suggests that since European gas prices were higher than those in the US, and Europe imported quantities from the US, then price adjustments should take place. The difference between the prices is justified by the difference in supply since the shale gas revolution took only place in the US. This kind of arbitrage between the US and Europe did not fully happen due to the lack of exporting infrastructure in the US. The shale gas revolution helped the US gas market to decouple from the oil-indexed European and Asian markets. Hulshof et al. (2016) find that in TTF, oil prices had little positive influence over gas prices and that the day-ahead prices are primarily fundamentally determined. Kim and Kim (2019) suggest that the European and Asian markets are cointegrated between 2000 and 2017 but there is a switching over the lead market. European markets became the leader since 2011 when Asian markets were the leader before that. Lin and Li (2015) suggest that the oil-indexed European and Japanese gas markets are cointegrated with Brent oil prices. The cointegrating relationship does not hold for the US gas market, which is more market-determined. But, even if oil and gas prices are decoupled, oil price spillovers could still be present. Geng et al. (2016), while they study the US gas market, they find that the seasonal effects are lost due to the shale revolution and the sudden supply increase. They suggest that crude oil patterns remain prevalent in the European gas markets. Last, they also suggest that this might alter if the European countries diversify their supply. Nick and Thoenes (2014) suggest that crude oil and coal prices can be accountable only for the long-run gas price formulation,

<sup>1</sup> <http://www.acer.europa.eu/events/presentation-of-acer-gas-target-model-documents/european%20gas%20target%20model%20review%20and%20update.pdf>.

while for the short-run development, abnormal temperatures and supply shocks are the only to be accountable. They further add that German gas prices were severely affected by supply shocks and exacerbated by simultaneous extraordinary demand. Ji et al. (2014) suggest that oil prices influence more gas prices than global economic activity. This kind of impact is variable by the studied market. They compare the US gas market to Europe's and they conclude that the US market experiences weak oil influence, while the European market with its mature gas hubs experiences the volatility shocks with a lag, at a lower level, and for shorter periods.

Stern (2014) proposes that oil benchmark contracts, especially in Asian markets, did not reflect fundamental pricing. Wakamatsu and Aruga (2013) suggest 2005 as the year since then the cointegration between the US and the Japanese market drifted apart holding the shale gas revolution as accountable. The US autonomous course since 2005 might be challenged if the US increase exports to Japan. They further add that gas is considered a necessary good and this is why gas consumption to income is inelastic. Shaikh et al. (2016) reveal that Japan and Korea have proceeded with source and route diversification to improve their supply security. Vivoda (2014) argues that even if Asian importers cooperated, their effort does not have sufficient results on regional pricing, while Japan's LNG strategy diverting from oil-indexation will bring results from 2020 and onwards. Zhang et al. (2018) suggest that although oil indexation is simple and common in some markets, hub pricing causes less extreme price changes. The explanation is that hub-based pricing is much more fundamentally driven, while otherwise, speculation can cause explosive bubbles. They also suggest that price bubbles are more prevalent in Japan and Europe. Shi (2016) provides an introduction to gas pricing and trading hubs in East Asia, while Shi et al. (2019) investigate whether the natural gas markets are integrated in East Asia providing evidence that country-specific heterogeneities dominate the dynamics of LNG prices. Shi and Variam (2016) suggest that the relaxation clauses will reduce costs for East Asian LNG importers. Further, they suggest that the NBP and TTF should work as an example for the East Asian market. A recent paper (Zhang et al. 2018) concludes that Asian premium in gas markets is more likely due to oil indexation pricing rather than market fundamentals and suggests the development of Asia's benchmark prices based on their market fundamentals.

Additionally, what is considered as a game-changer in the global gas market is that ample spare volumes, especially due to the shale revolution, are now available. However, it is questioned whether the US can export these volumes to the rest of the world and whether this is cost-effective. Bernstein et al. (2016) suggest that US gas exports are non-competitive in the near term, while they become significant if there are excess natural gas sources. The US gas exports become competitive under the scenario of supply (Russian disruptions) or demand (Asian demand increase) shocks. Nikhalat-Jahromi et al. (2016) propose a profit-maximizing model for LNG exporters taking into account the tanker type, routing, inventory management, contract obligations, arbitrage, and uncommitted LNG. They propose that Middle Eastern exporters should export their quantities to the highest spot price between the UK and Japan. del Valle et al. (2017) study how natural gas

hubs affect shippers' decision making. They suggest that virtual gas hubs equalize shippers' marginal cost to the transparent gas hub price. Second, shippers increase their profits as they gain more flexibility. However, a natural gas hub is not enough to foster competition or discourage anticompetitive behavior.

### 3. DATA AND MARKETS

The first market we examine is that of the United Kingdom. The United Kingdom's gas hub is named as NBP, or more commonly referred to as NBP, and it is a VTP. It is the second most liquid point in Europe and with a variety of delivery periods, as there are contracts for within-day, day-ahead, months, quarters, summers (April to September) and winters (October to March). It is Europe's longest-established gas market and it does not require trades to be balanced having as a consequence no fixed penalty for imbalances. When a participant is out of balance at the end of the day, then the "cash-out" procedure closes automatically the imbalance by making him buy or sell quantities at the marginal system price, which is very close to the spot price. We use the Intercontinental Exchange UK Natural Gas Continuous Futures price as the gas price. The price is posted in Sterling per 1000 therms of gas per day.

The second market of our study is that of the TTF. It is again a VTP in the Netherlands, and almost identical to NBP. What is most important is that it has become the leading gas market, not only for the whole Europe but globally. Many consider it as the most liquid market after the United States' Henry Hub. We use the Platts TTF Day-Ahead Futures closure price and it is stated in Euros per MWh.

Our third market is the Japan Korea Marker, or most commonly referred to as JKM. It is the LNG benchmark price for spot physical cargoes. It is the benchmark because Japan and Korea jointly account for the largest gas imports in the world. We use the Platts Spot Cargo prices posted in USD per MMBtu.

All gas prices are examined with the Intercontinental Exchange's (ICE) Brent Crude Continuous Futures contract. We consider this blend, as the most appropriate since it is the European blend, and two out of the three markets are European. Japan Korea Marker and the rest of LNG trade in Asia used Japanese Customs-Cleared Crude Oil (JCC) indexed contracts<sup>2</sup>. However, the whole LNG market required more transparency. We conducted our research for the third market again in relation to the Brent, as Kaufmann and Ullman (2009) recognize Brent futures as the gateway crude contracts Granger causing other blends. Further, Fattouh (2009) suggests that price differentials are stationary and that different crude oil blend prices are integrated in the long-run and that the law of "one great pool" holds since the opposite case would create opportunities for arbitrage.

Finally, we would like to inform that our data are daily and between 02 February 2009 and 28 June 2019. This period is selected since the shale revolution in the US started around 2008-2009. We

2 <https://www.oxfordenergy.org/wpcms/wp-content/uploads/2014/02/NG-81.pdf?v=f214a7d42e0d>.

transformed the prices into natural logarithms, and therefore their first differences are the respective returns. Our data are all stationary at first differences I(1). Further, there is no cointegration between the pairs of oil and gas prices (results available upon request).

## 4. METHODOLOGY

### 4.1. Time Domain Causality Tests

Our first applied methodology researches whether price information from one commodity passes to the other. We apply Granger (1969) causality tests or Wald tests in our Vector Autoregressive (VARs). We conduct this kind of tests having both variables as causal. If information is included in one commodity price and it is passed to the second's price, then the first one's price should Granger cause the second's price.

The Granger causality tests are conducted as in-sample F or as Wald tests in VAR models. Since there is no cointegration between the pairs of prices, we use VARs with first differences. We construct our "Unrestricted" models where we assume that there is price transmission if the second's commodity price has significant coefficients (Tables 1-3).

$$\Delta Oil_t = \alpha_0 + a_1 \Delta Oil_{t-1} + \dots + a_p \Delta Oil_{t-p} + \beta_1 \Delta Gas_{t-1} + \dots + \beta_p \Delta Gas_{t-p} + \varepsilon_{st} \tag{1}$$

$$\Delta Gas_t = a_0 + a_1 \Delta Oil_{t-1} + \dots + a_p \Delta Oil_{t-p} + b_1 \Delta Gas_{t-1} + \dots + b_p \Delta Gas_{t-p} + \varepsilon_{ot} \tag{2}$$

$\Delta Oil_t$  and  $\Delta Gas_t$  are the first differences of our data in natural logarithms at time t, and  $\Delta Oil_{t-p}$  and  $\Delta Gas_{t-p}$  are the lagged differences of the p class VARs. The p order of our VARs models is suggested by the Akaike criterion. We assume that our commodity prices are endogenous to avoid structural assumptions as Kilian (2009) does (SVAR) while studying crude oil price shocks. The hypothesis we test is the following:

$$H_0: \beta_1 = \beta_2 = \dots = \beta_p = 0 \tag{3}$$

For the second model the hypothesis is:

$$H_1: a_1 = a_2 = \dots = a_p = 0 \tag{4}$$

If the null hypotheses are rejected, and one commodity price has significant coefficients explaining other's evolution, then there is information transmission and as a result spillovers. The consequence is that the second commodity can forecast the price of the first one.

We conduct the tests for the full sample which is the aggregate result. Our effort to test even for transient information transmission drives us to use a rolling window of our observations. Our rolling window is of 250 observations – a full trading year-since commodity exchanges work for approximately 252 working days/year. The rolling periods advance every 100<sup>th</sup> observation.

### 4.2. In and Out of Sample Forecasting Ability Tests

We can compare the in and out of sample forecasting ability of different models in our effort to detect potential spillovers. If a commodity's price precedes the other's, then the unrestricted models (1) and (2) will present better forecasting ability than that of the restricted models. The respective restricted models are those of (7) and (8):

$$\Delta Oil_t = a_0 + a_1 \Delta Oil_{t-1} + \dots + a_p \Delta Oil_{t-p} + \varepsilon_{st} \tag{5}$$

$$\Delta Gas_t = a_0 + a_1 \Delta Gas_{t-1} + \dots + a_p \Delta Gas_{t-p} + \varepsilon_{ot} \tag{6}$$

We obtain the forecasts for both the restricted and unrestricted models for one-step-ahead and then we compare their forecasting ability with the Diebold and Mariano (1995) test. The null hypothesis of Diebold and Mariano (1995) is that each model separately gives forecasts of equal Mean Squared Forecast Errors (MSFE) i.e. they have equal forecasting ability. If the null is rejected and one model gives forecasts of lower MSFE, then its forecasting ability is better.

We conduct the Diebold and Mariano (1995) test in the sample i.e. for the whole period and out-of-sample i.e. for shorter iterations (a market year). The transient effects of information transmission might be revealed with the shorter iterations.

### 4.3. Long-term Impacts

Our effort is not only to detect, potential spillovers but also to quantify them. The time-domain causality tests calculate the probability of spillover and not its magnitude. We consider both

**Table 1: NBP bivariate VAR**

Variables	$\Delta Oil_t$	$\Delta Gas_t$	Std. error	t-value	Probability
C	0.0001		0.0004	0.3950	0.6931
$\Delta Oil_{t-1}$	-0.0538 <sup>a</sup>		0.0195	-2.750	0.0060
$\Delta Gas_{t-1}$	-0.0225		0.0151	-1.4900	0.1363
$\Delta Oil_{t-2}$	0.0013		0.0195	0.0660	0.9469
$\Delta Gas_{t-2}$	0.0186		0.0151	1.2280	0.2196
C		-0.0003	0.0004	-0.6160	0.5382
$\Delta Oil_{t-1}$		-0.0007	0.0252	-0.0300	0.9763
$\Delta Gas_{t-1}$		0.0252	0.0195	1.2910	0.1968
$\Delta Oil_{t-2}$		-0.0567 <sup>b</sup>	0.0251	-2.2550	0.0242
$\Delta Gas_{t-2}$		-0.0381 <sup>c</sup>	0.0195	-1.9510	0.0512
Breusch-Godfrey LM test					0.2297
ARCH (multivariate)					2.2e <sup>-16</sup>

<sup>a</sup>Indicates significance at all levels (1%, 5%, and 10%). <sup>b</sup>Indicates significance at 5% and 10%. <sup>c</sup>Indicates significance at 10%



Table 2: TTF bivariate VAR

Variables	$\Delta Oil_t$	$\Delta Gas_t$	Std. error	t-value	Probability
C	0.0001		0.0003	0.4350	0.6639
$\Delta Oil_{t-1}$	-0.520 <sup>a</sup>		0.0197	-2.6320	0.0085
$\Delta Gas_{t-1}$	0.0009		0.0096	0.0980	0.9215
$\Delta Oil_{t-2}$	-0.0033		0.0197	-0.1680	0.8667
$\Delta Gas_{t-2}$	0.0087		0.0096	0.9070	0.3646
$\Delta Oil_{t-3}$	0.0210		0.0197	1.0620	0.2884
$\Delta Gas_{t-3}$	0.0102		0.0096	1.0550	0.2913
$\Delta Oil_{t-4}$	0.0123		0.0197	0.6250	0.5321
$\Delta Gas_{t-4}$	-0.0105		0.0097	-1.0850	0.2778
$\Delta Oil_{t-5}$	0.0132		0.0197	0.6710	0.5024
$\Delta Gas_{t-5}$	-0.0035		0.0096	-0.3670	0.7139
$\Delta Oil_{t-6}$	0.0139		0.0198	0.7030	0.4822
$\Delta Gas_{t-6}$	0.0016		0.0096	0.1740	0.8615
$\Delta Oil_{t-7}$	-0.0218		0.0198	-1.104	0.2698
$\Delta Gas_{t-7}$	-0.0040		0.0097	-0.4130	0.6798
$\Delta Oil_{t-8}$	-0.0048		0.0197	-0.2470	0.8050
$\Delta Gas_{t-8}$	-0.0136		0.0096	-1.4100	0.1586
$\Delta Oil_{t-9}$	0.0028		0.0197	0.1410	0.8877
$\Delta Gas_{t-9}$	-0.0004		0.0096	-0.0480	0.9614
$\Delta Oil_{t-10}$	0.0316		0.0197	1.6101	0.1096
$\Delta Gas_{t-10}$	-0.0095		0.0096	-0.9930	0.3207
C		-0.0003	0.0007	-0.4530	0.6508
$\Delta Oil_{t-1}$		-0.0277	0.0403	-0.6880	0.4916
$\Delta Gas_{t-1}$		-0.0345 <sup>c</sup>	0.0197	-1.7480	0.0806
$\Delta Oil_{t-2}$		-0.0120	0.0403	-0.2980	0.7659
$\Delta Gas_{t-2}$		0.0996 <sup>a</sup>	0.0196	-5.0650	4.38e <sup>-7</sup>
$\Delta Oil_{t-3}$		0.0682 <sup>c</sup>	0.0403	1.6920	0.0908
$\Delta Gas_{t-3}$		-0.0963 <sup>a</sup>	0.0197	-4.8740	1.16e <sup>-6</sup>
$\Delta Oil_{t-4}$		0.0847 <sup>b</sup>	0.0403	2.0980	0.0359
$\Delta Gas_{t-4}$		-0.0511 <sup>a</sup>	0.0198	-2.5830	0.0098
$\Delta Oil_{t-5}$		0.0138	0.0403	0.3420	0.7324
$\Delta Gas_{t-5}$		-0.0683 <sup>a</sup>	0.0197	-3.4610	-0.0005
$\Delta Oil_{t-6}$		0.0469	0.0403	1.1610	0.2455
$\Delta Gas_{t-6}$		-0.1000 <sup>a</sup>	0.0197	-5.0670	4.32e <sup>-7</sup>
$\Delta Oil_{t-7}$		0.0043	0.0404	0.1070	0.9144
$\Delta Gas_{t-7}$		0.0262	0.0198	1.3240	0.1856
$\Delta Oil_{t-8}$		0.0509	0.0403	1.2620	0.2069
$\Delta Gas_{t-8}$		-0.0265	0.0197	-1.3480	0.1778
$\Delta Oil_{t-9}$		0.0654	0.0403	1.6220	0.1050
$\Delta Gas_{t-9}$		-0.0128	0.0196	-0.6540	0.5129
$\Delta Oil_{t-10}$		-0.0805 <sup>b</sup>	0.0403	-1.9970	0.0458
$\Delta Gas_{t-10}$		0.01115	0.0196	0.5910	0.5549
Breusch-Godfrey LM test					0.1083
ARCH (multivariate)					2.2e <sup>-16</sup>

<sup>a</sup>Indicates significance at all levels (1%, 5%, and 10%). <sup>b</sup>Indicates significance at 5% and 10%. <sup>c</sup>Indicates significance at 10%

markets as highly liquid, and if spillovers exist, then their impact should be observed instantly. We use a 10-day horizon (two trading weeks) to capture this kind of impact as liquidity is fair able to pass effects in this short period.

We derive the accumulated impulse response functions from our rolling VARs to obtain impulse response coefficients with their respective bootstrapped error bands with 95% confidence intervals. Furthermore, the computations are for the orthogonalized impulse responses. Our rolling window consists of 250 observations, which account for a whole trading year.

#### 4.4. Volatility Transmission

Information transmission might be passed through volatility transmission. Apart from the bivariate VARs (Tables 1-3), we apply the dynamic conditional covariance (DCC) GARCH (1,1)

model. First, we test for serial correlation in our bivariate VARs with Portmanteau and Breusch-Godfrey statistics. If the serial correlation is rejected then we test for ARCH effects with the ARCH LM test. The DCC GARCH model introduced by Engle and Sheppard (2001), which allows for non-constant correlation between the variables, -consideration by Engle et al. (1990) and Bollerslev (1990) - was also improved by Cappiello et al. (2006) to include asymmetries. The Engle (2002) Dynamic Conditional Correlation starts with:

$$H_t = D_t R_t D_t \quad (7)$$

$H_t$  and  $D_t$  are the conditional correlation matrix and the  $k \times k$  diagonal matrix of the time-varying standard deviations from the univariate GARCH with  $(\sigma_{i,t}^2)^{1/2}$  on the  $i^{\text{th}}$  diagonal respectively.

**Table 3: JKM bivariate VAR**

Variables	$\Delta Oil_t$	$\Delta Gas_t$	Std. error	t-value	Probability
C	0.0001		0.0003	0.3030	0.7616
$\Delta Oil_{t-1}$	-0.0468 <sup>b</sup>		0.0197	-2.3670	0.0180
$\Delta Gas_{t-1}$	0.0268		0.0230	1.1650	0.2440
$\Delta Oil_{t-2}$	-0.0108		0.0197	-0.5480	0.5834
$\Delta Gas_{t-2}$	-0.0506 <sup>b</sup>		0.0231	-2.1870	0.0288
$\Delta Oil_{t-3}$	0.0087		0.0197	0.4440	0.6573
$\Delta Gas_{t-3}$	-0.0543 <sup>b</sup>		0.0231	-2.3460	0.0191
$\Delta Oil_{t-4}$	0.0235		0.0197	1.1930	0.2329
$\Delta Gas_{t-4}$	-0.0177		0.0230	-0.7690	0.4417
C		-0.0001	0.0003	-0.3220	0.7471
$\Delta Oil_{t-1}$		0.0512 <sup>a</sup>	0.0168	3.0340	0.0024
$\Delta Gas_{t-1}$		0.1166	0.0196	5.9340	3.35e <sup>-9</sup>
$\Delta Oil_{t-2}$		-0.0144	0.0168	-0.8550	0.3928
$\Delta Gas_{t-2}$		0.0933 <sup>a</sup>	0.0197	4.7220	2.46e <sup>-6</sup>
$\Delta Oil_{t-3}$		0.0117	0.0168	0.6960	0.4862
$\Delta Gas_{t-3}$		0.0550 <sup>a</sup>	0.0197	2.7840	0.0054
$\Delta Oil_{t-4}$		0.0568 <sup>a</sup>	0.0168	3.3730	0.0007
$\Delta Gas_{t-4}$		0.0831	0.0196	4.2280	2.44e <sup>-5</sup>
Breusch-Godfrey LM test					0.0584
ARCH (multivariate)					2.2e <sup>-16</sup>

<sup>a</sup>Indicates significance at all levels (1%, 5% and 10%). <sup>b</sup>Indicates significance at 5% and 10%. <sup>c</sup>Indicates significance at 10%

**Table 4: Full sample causality tests**

Null hypothesis H <sub>0</sub> no causality	NBP	TTF	JKM	Critical value
From oil to gas	P value	P value	P value	
Wald test	0.0785	0.1407	0.0002	0.05
From gas to oil				
Wald test	0.1628	0.7538	0.0083	0.05

$$D_t = \begin{bmatrix} \sqrt{\sigma_{o,t}^2} & 0 \\ 0 & \sqrt{\sigma_{s,t}^2} \end{bmatrix} \quad (8)$$

with  $R_t$  containing the time varying correlation components

$$R_t = \begin{bmatrix} \varepsilon_{oo,t} & \varepsilon_{os,t} \\ \varepsilon_{so,t} & \varepsilon_{ss,t} \end{bmatrix} \quad (9)$$

Where  $R_t$  is

$$R_t = Q_{os,t}^{*-1} Q_{os,t} Q_{os,t}^{*-1} \quad (10)$$

And  $Q_{os,t}$  is

$$Q_{os,t} = (1 - \theta_1 - \theta_2) Q^* + \theta_1 (\varepsilon_{o,t-1} \varepsilon_{s,t-1}) + \theta_2 (Q_{os,t-1}) \quad (11)$$

$Q_{os,t}$  is the unconditional variance of the  $i$  and  $j$  following a GARCH,  $Q^*$  denotes the unconditional covariance, while  $\theta_1$  and  $\theta_2$  are non-negative parameters which their sum is less than unity:  $\theta_1 + \theta_2 < 1$ .

The parameters are calculated while maximizing the log-likelihood function:

$$L(0) = -\frac{1}{2} \sum_{t=1}^T (k \log(2\pi)) + 2 \log(|D_t|) + \log(|R_t|) + \varepsilon_t' R_t^{-1} \varepsilon_t \quad (12)$$

Last Cappiello et al. (2006) include an asymmetric term  $\theta_3$  to the symmetrical model with  $Q_{os,t}$  to be:

$$Q_{os,t} = (1 - \theta_1 - \theta_2) Q^- - \theta_3 \bar{\xi}_t + \theta_1 (\varepsilon_{o,t} \varepsilon_{s,t-1}) + \theta_2 (Q_{os,t-1}) \quad (13)$$

With  $\bar{\xi}_t = E + \theta_3 (\varphi_{t-1} \varphi_{t-1}')$  and

$$|\overline{\varphi_{ot} \varphi_{st}'}| \text{ and } \overline{\varphi_{ot}} = (I [\varepsilon_{ot} < 0] o \bar{\varepsilon}_{ot})$$

the last is the Hadamard product of the residuals, an element in case the returns are negative and  $\overline{\varphi_{ot}} = 0$  otherwise. Last,  $\theta_3$  includes the periods when the information inflow for the market could be characterized as negative with  $w |\overline{\varphi_{ot} \varphi_{st}'}| = I_t$ .

## 5. EMPIRICAL RESULTS

### 5.1. Time Domain Causality Tests

We start with the NBP as it is the oldest VTP in Europe and a role model for all the later gas hubs. We start with the full sample, and it is only the aggregate between 2009 and 2019. We first examine whether there is causality or price information spillovers from oil to gas returns, and vice-versa. We use 5.00% as the significance level to reject or not reject the hypothesis of price spillovers. Our null hypothesis is that there is no causality between the two commodities. The aggregate of the full sample presents evidence that the NBP is a decoupled market i.e. there are no price spillovers from neither commodity. Both probabilities are over our significance level, 7.85%, and 16.28% respectively. Our first results verify the fundamental pricing of the two commodities since there are no information spillovers from one commodity to the other (Table 4)

As for the NBP, the rolling VAR process presents evidence of no causality from oil to gas. The probabilities that oil returns do not affect gas returns are always over our rejection threshold. The

no influence hypothesis holds even for transient effects. There are only three instances when the probability reaches the level of rejecting the null hypothesis but does not pass it, and these are around between 2010 and 2011, 2016 and 2017, and 2018 and 2019 (Figure 1). These instances can also explain the significant  $\Delta Oil_{t-2}$  coefficient in Table 1 for  $\Delta Gas$ . When the vice versa analysis is studied, we have evidence of transient effects from gas to oil, as probabilities fall well below our threshold. These are three short-lived periods between 2010 and 2011, 2012 and 2013, and 2015. This is evidence that gas pricing leads the information process in a transient way (Figure 2). The general conclusion from our first method is that oil and gas remain largely unaffected from one another and that there are only short periods when gas passes information to oil. These are short-lived periods and the aggregate remains uninfluenced. What can be claimed about the market is that it is integrated and fully efficient since commodities are priced by fundamentals and not by other's movement.

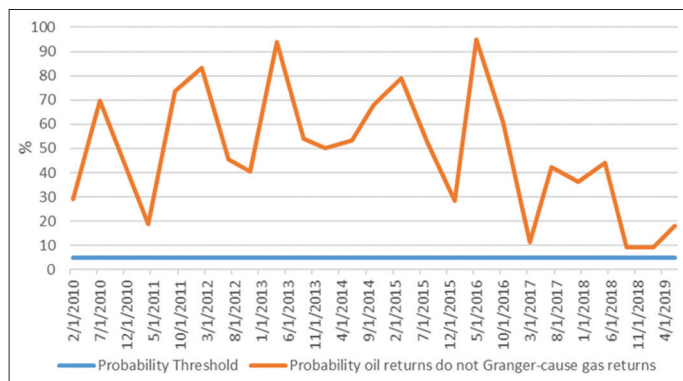
Our second gas hub is the TTF and it is considered as even more liquid than the NBP in recent years. We can not reject the hypothesis that there are no price spillovers from oil returns to gas returns. The probability of no causality from the Brent blend to natural gas is 14.07%. Furthermore, the full sample Wald test suggests that there is no causality or price spillover from gas returns to those of oil too. The probability value is 75.38% not rejecting the null of no causality. From our first empirical study, we can say with confidence there are no causal relationships from oil to gas and vice versa. Our

full sample causality tests verify the independence between the commodities in the European gas hubs (Table 4).

We can conclude that oil does not lead gas in the pricing process of TTF by the rolling VAR methodology (Figure 3). The probability that oil returns do not cause gas returns remains over our rejection threshold. Two time points reach our threshold without passing it. These time points are not sufficient to constitute a price comovement between the commodities. The rolling VAR analysis verifies the full sample result. When we investigate the time-varying relationship from gas to oil, we have only a time point when this kind of relationship holds. The time point is from 2013 to 2014 (Figure 4). The absence of long consecutive periods when the gas market leads the oil price formulation does not verify the assumption of unilateral causality, and our results are in full agreement with the full sample results. Largely the two European markets are integrated with neither commodity leading the pricing process.

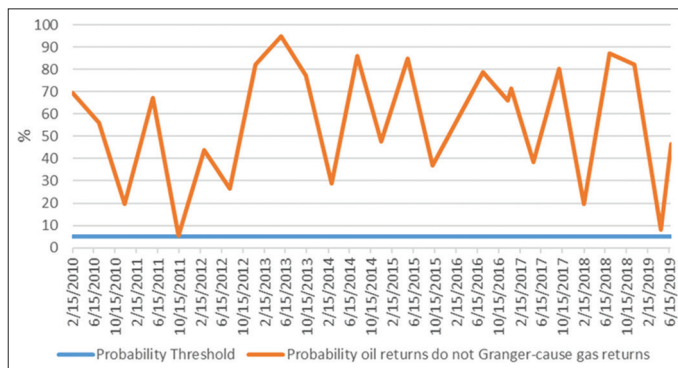
From our full sample causality tests, we can conclude that both oil and gas influence each other (Table 4). The hypothesis of oil returns not causing the gas returns is rejected with confidence as the P value is 0.02%. What is also important is that we do find evidence of gas returns causing oil returns. The probability of gas not causing oil prices is low, 0.83%. This is an interesting result as both commodities have explanatory power over the other. Their bidirectional influence remains to be better explained by the second

Figure 1: NBP (%) oil returns do not Granger-cause gas returns



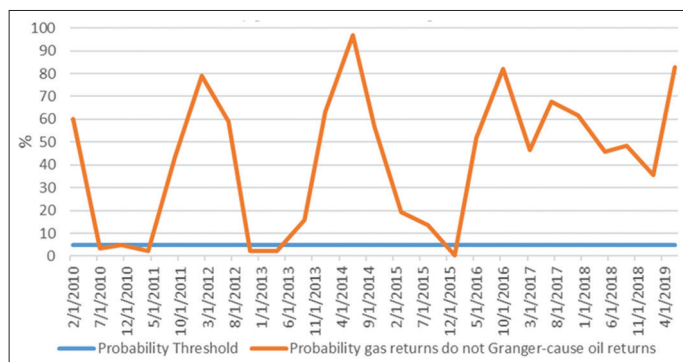
Source: Authors' calculations

Figure 3: TTF probability (%) oil returns do not Granger-cause gas returns



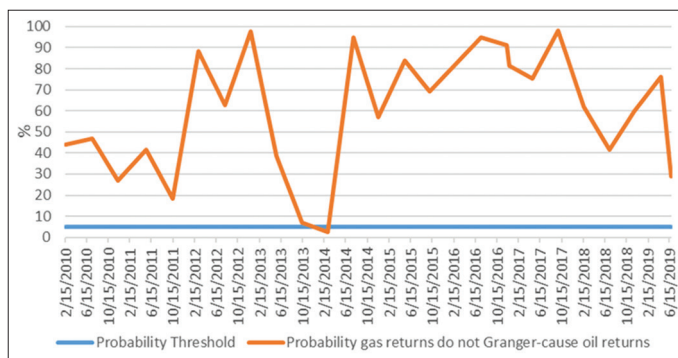
Source: Authors' calculations

Figure 2: NBP probability (%) gas returns do not Granger-cause oil returns



Source: Authors' calculations

Figure 4: TTF probability (%) gas returns do not Granger-cause oil returns



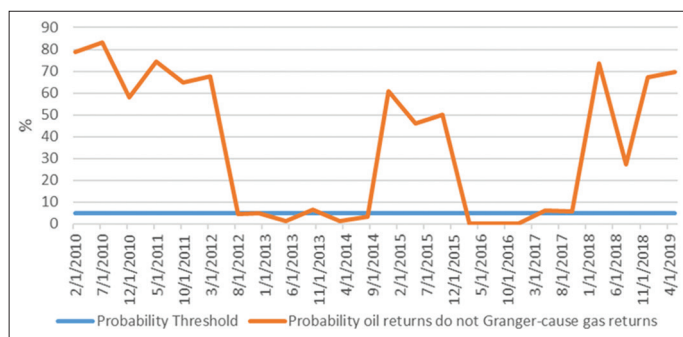
Source: Authors' calculations

method of shorter iterations which will present further evidence of their time-varying linkages.

The rolling VAR analysis presents some useful insights when studying the Asian market. We find strong evidence oil returns cause gas returns for long periods (Figure 5). The oil leads in price formulation between 2012 and 2014, and 2015 and 2016. These periods are of extreme importance as they shed light on their driving causes. In March 2011, an earthquake of 9.0 Richter caused one of the largest nuclear accidents in history. The Fukushima Daiichi nuclear power plants were hit by a giant wave (tsunami) causing instant infrastructure break down. Japan experienced a 10 gigawatt (GW) shortage of energy capacity. The Japanese government not only shut down the damaged reactors but generally suspended all nuclear power generation from 2013 to 2015. It is easily understood that it was the price taker since nuclear energy consisted 27% of the power generation before the 2011 earthquake and since Japan imports all of its fossil fuels. Japan turned to gas imports to generate power to replace nuclear capacity. LNG importers signed mid-term to long-term contracts with several suppliers to hedge, but Japan was already experiencing a currency depreciation against the US dollar making oil and gas imports more expensive. Also, oil and gas prices remained at high levels until 2014. The result was accumulating losses and deficits and increased import prices<sup>3</sup>. Since August 2015 nuclear power generation started partly recovering as one by one

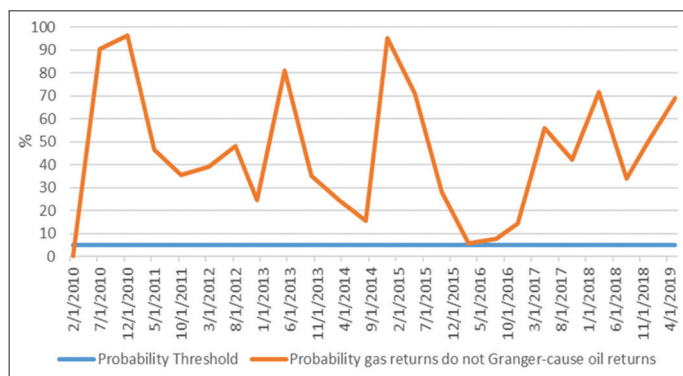
3 [https://www.eia.gov/beta/international/analysis\\_includes/countries\\_long/Japan/japan.pdf](https://www.eia.gov/beta/international/analysis_includes/countries_long/Japan/japan.pdf).

**Figure 5:** JKM probability (%) oil returns do not Granger-cause gas returns



Source: Authors' calculations

**Figure 6:** JKM probability (%) gas returns do not Granger-cause oil returns



Source: Authors' calculations

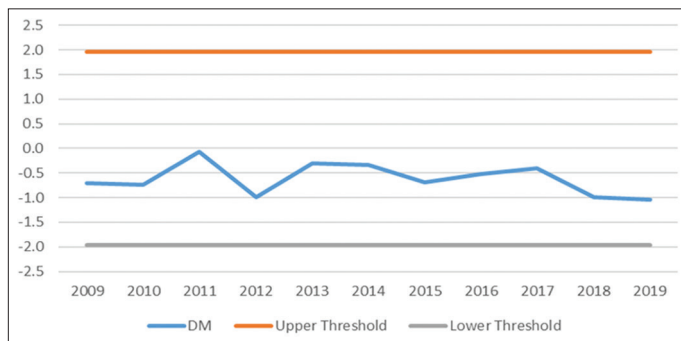
nuclear reactor started to supply power<sup>4</sup>. The two periods of oil leading gas can be attributed to these facts. Oil drove the gas market until nuclear power generation resumed. The increased imports, by mid to long-term contracts, to hedge against potential further price increases, and the tight power market is accountable for our results. On the contrary, we do not find evidence of causality from gas to oil (Figure 6), as within the examined period, there is only 1 time point when gas leads the information process and it is in 2010, and two reaching the threshold without passing it. The time-varying relationship examination does not agree with the full sample result. Finally, we could conclude that by our so far research, there is unilateral causality from oil to gas and not the vice-versa in the JKM market. This is also by our bivariate VARs, since there are oil returns' coefficients which are significant (Table 3).

**5.2 In and Out-of-sample Forecasting Ability Tests**

We compare the predictive ability of one-step-ahead forecasts of the models (1) and (2), to that of models (7) and (8) respectively. If the inclusion of oil coefficients improves the predictive ability for the gas price formulation, then we have a causal relationship from oil to gas, and the vice-versa. If the predictive ability is not improved, then there are no price spillovers. To conclude the predictive ability, we compare our results of the DM tests to the absolute value of 1.96. If the absolute value of our test is <1.96, then

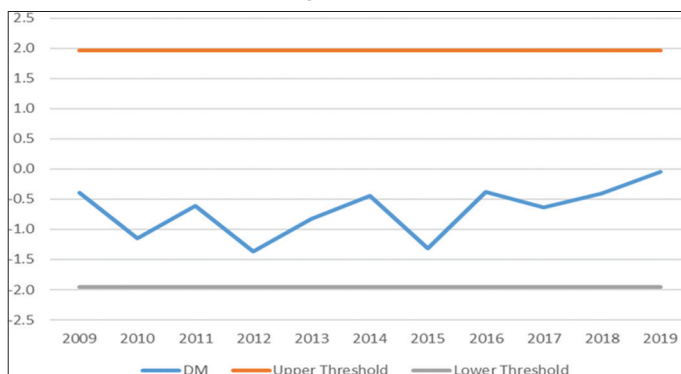
4 <https://www.world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-power.aspx>.

**Figure 7:** NBP the Diebold-Mariano test for forecasting ability from oil to gas



Source: Authors' calculations

**Figure 8:** NBP the Diebold-Mariano test for forecasting ability from gas to oil



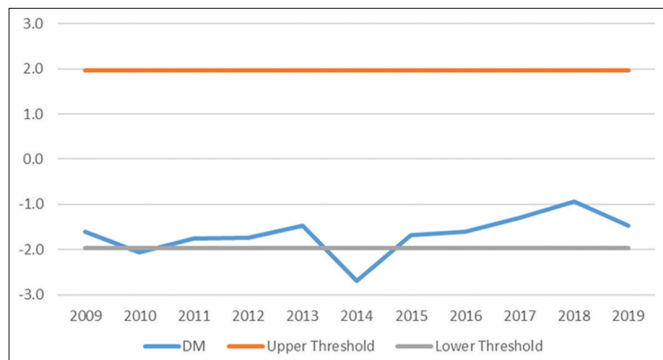
Source: Authors' calculations



**Table 5: Diebold and Mariano tests – In sample**

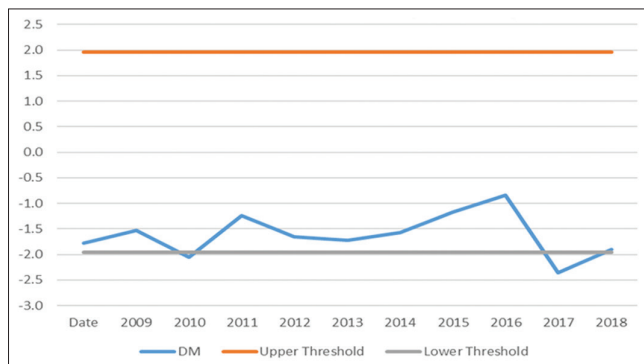
Null hypothesis $H_0$ : no causality	NBP	TTF	JKM	Critical value
From oil to gas	D-M value -0.8954	D-M value -2.2638	D-M value -1.8897	1.96
From gas to oil	-0.7763	-1.5045	-1.5166	

**Figure 9:** TTF the Diebold-Mariano test for forecasting ability from oil to gas



Source: Authors' calculations

**Figure 10:** TTF the Diebold-Mariano test for forecasting ability from gas to oil



Source: Authors' calculations

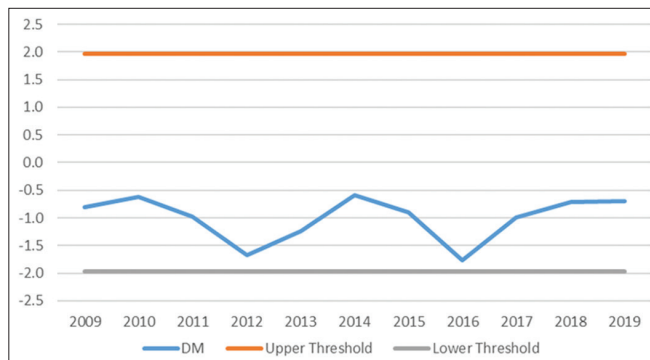
we have models of equal predictive ability i.e. no price spillovers. We first try with the full sample periods (in sample) and then we proceed by dividing them into shorter iterations (out of sample).

The in-sample tests for the NBP market suggest the equal predictive ability of the restricted and unrestricted models i.e. there are no price spillovers from oil to gas and vice-versa (Table 5). Both test values are well below the absolute value of 1.96. The last, further, enhance the assumption of an efficient and integrated market for NBP.

The same results are reached when we proceed with the out-of-sample calculations. The DM values never surpass either the negative or positive thresholds further enhancing our assumption even for transient effects. The results agree with the assumption of market decoupling (Figures 7 and 8).

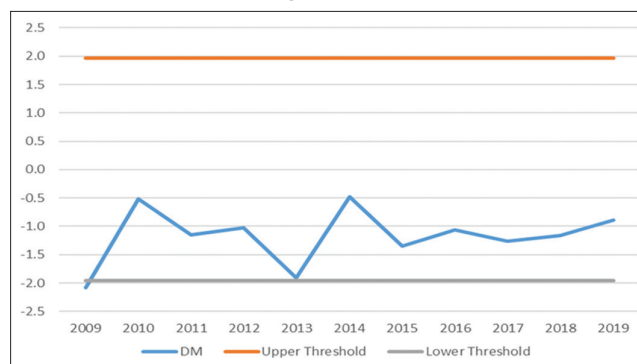
We find evidence of a causal relationship from oil to gas returns when applying the same methodologies for our second

**Figure 11:** JKM the Diebold-Mariano test for forecasting ability from oil to gas



Source: Authors' calculations

**Figure 12:** JKM the Diebold-Mariano test for forecasting ability from gas to oil



Source: Authors' calculations

European market. Our result for the in-sample methodology is -2.2638, which is well over the absolute value of 1.96 (Table 5). The vice versa relationship does not hold according to our full sample DM test. However, these are only the aggregate of the whole period.

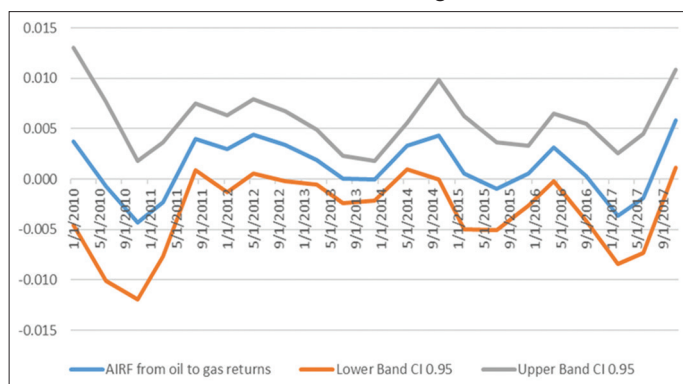
The out-of-sample forecasting ability tests suggest that in two instances oil returns better forecast gas returns and while the same holds also for the vice-versa (Figures 9 and 10). As a matter of fact, and since there are no successive periods of improved predictive ability, we can claim that there are only transient causal relationships in our period. The results further enhance those of the Wald tests. The TTF market is a largely decoupled market with its integration and efficiency to be well suggested.

The in-sample result for the JKM suggests market decoupling (-1.8897) and (-1.5166) (Table 5). However, the DM value for the causality from oil to gas returns is very close to our threshold value. We proceed with the out-of-sample tests since the full

sample DM tests suggest no causal relationship from oil to gas returns and vice versa (Figures 11 and 12).

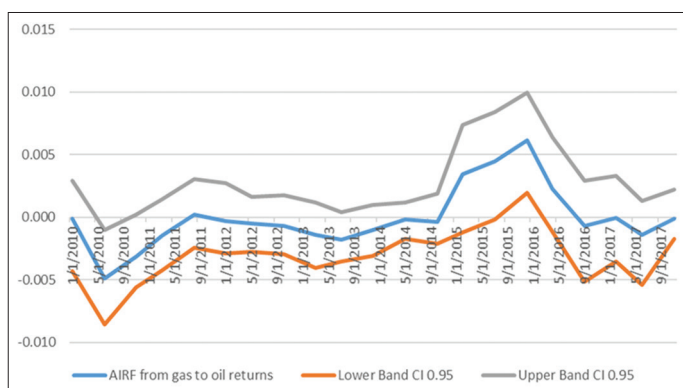
What is noticed is that both DM sequences have instances where they move close to our negative thresholds. However, only once the DM value for the causal relationship from gas to oil exceeds the threshold value. Finally, our results suggest market decoupling for the European gas hubs when we cannot tell the same with confidence for our Asian gas hub.

**Figure 13:** NBP 10-day horizon accumulated impulse response functions from oil to gas



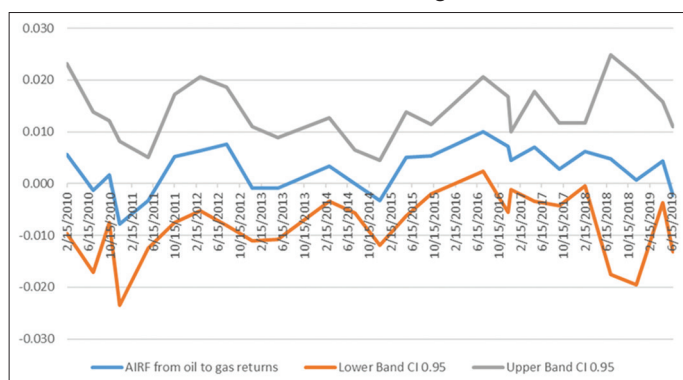
Source: Authors' calculations

**Figure 14:** NBP 10-day horizon accumulated impulse response functions from gas to oil



Source: Authors' calculations

**Figure 15:** TTF 10-day horizon accumulated impulse response functions from oil to gas



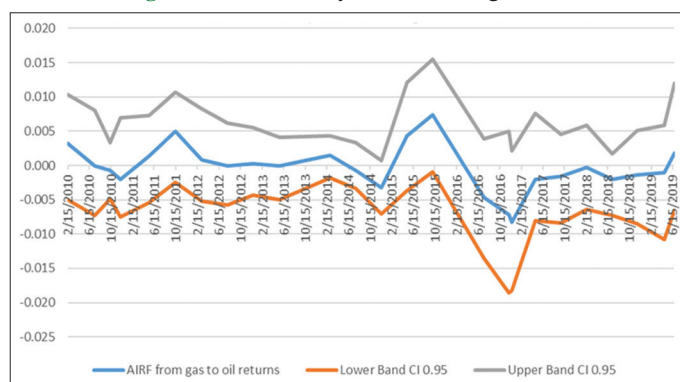
Source: Authors' calculations

### 5.3. Long-term Impacts

The first implication for the NBP is that the impacts' magnitude is very low. After one standard deviation's oil shock, the impact on gas ranges between zero and 0.0050 (Figure 13), while for the vice versa relationship is almost zero except for a spike from 2015 to 2016 (Figure 14). The extremely low effects between the two markets (that of Brent and NBP) verify the hypothesis of market decoupling.

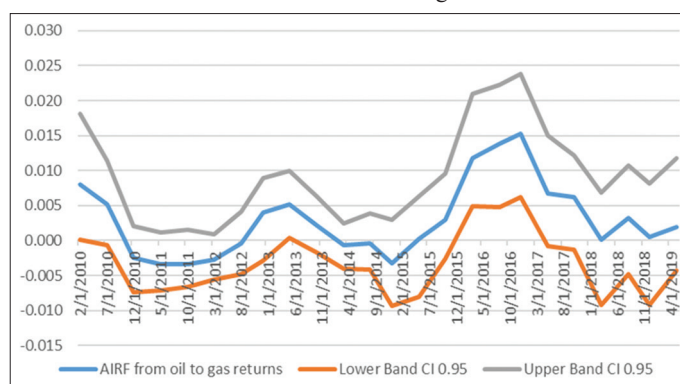
We have similar results for the TTF market. Oil returns cause higher effects to gas returns, as a one standard deviation shock

**Figure 16:** TTF 10-day horizon from gas to oil



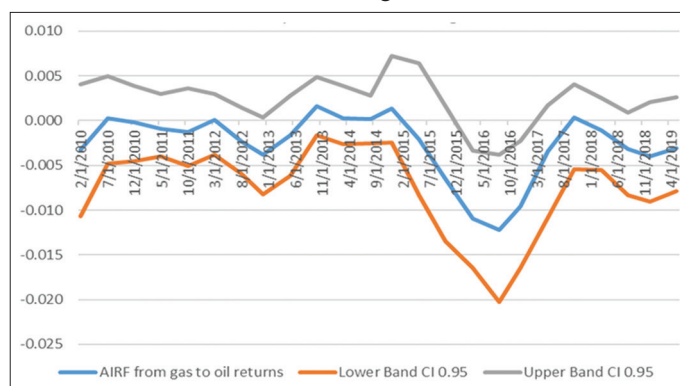
Source: Authors' calculations

**Figure 17:** JKM 10-day horizon accumulated impulse response functions from oil to gas

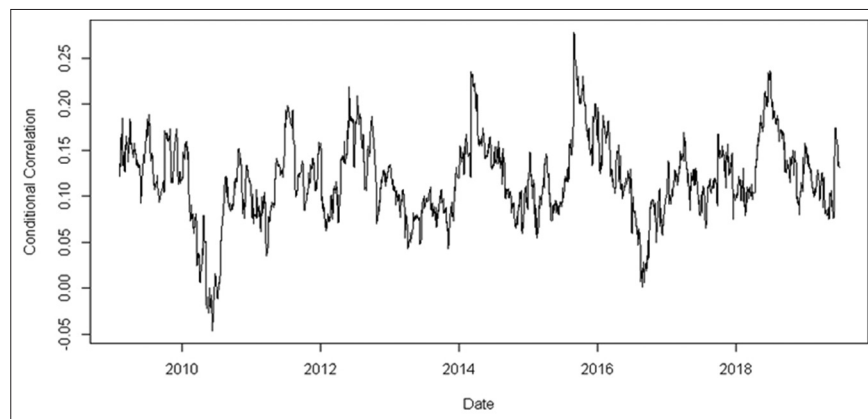


Source: Authors' calculations

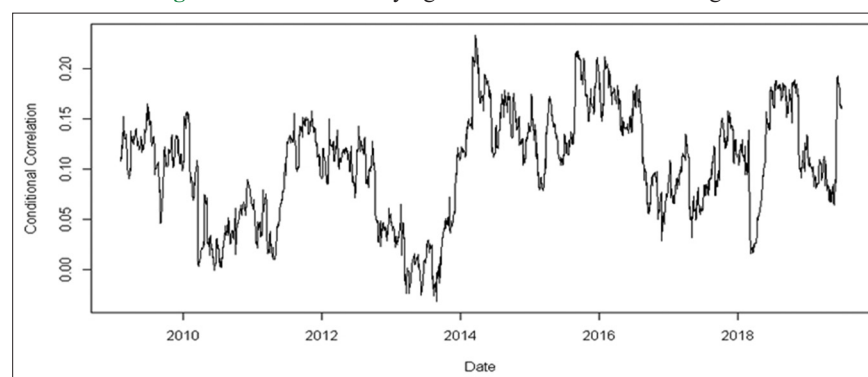
**Figure 18:** JKM 10-day horizon accumulated impulse response functions from gas to oil



Source: Authors' calculations

**Figure 19:** NBP time-varying correlation between oil and gas

Source: Authors' calculations

**Figure 20:** TTF time-varying correlation between oil and gas

Source: Authors' calculations

would cause an impact of 0.0100 to gas price (Figure 15). The vice versa effect is again almost zero (Figure 16). Again, we have evidence of market decoupling in the second European gas market due to the low impacts.

The impact of one standard deviation of oil is greater than any other market when it comes to the JKM market (Figure 17). Its highest impact reaches the level of 0.0150, which is 3 times the highest of NBP and 50% greater than that of TTF. The peak of the impact starts in 2015 and ends in 2018. Before that oil's impact ranges close to zero and it is almost identical in magnitude and pattern with the rest of gas hubs. This development is justified by the successful hedging by mid to long-term contracts. Therefore, the hedging kept the impacts at low levels whether the oil price was increasing or decreasing. However, the peak coincides with the partial nuclear power generation recovery leaving less capacity for other fuels. It is also contemporary with the decreasing oil price from the highest in 2014 to the lowest in 2016. Probably Japanese companies turned to more short-term contracts increasing the impact that oil prices had since the available capacity for other than nuclear power sources was not constant.

On the contrary, the gas had almost zero influence over oil (Figure 18). The accumulated impact response functions move parallel to the X-axis except for the period between 2015 and 2018. It is the same period when nuclear power recovers and the oil price

falls. Gas had a negative impact on oil as it was perceived as the substitute for nuclear energy, oil, and the “bridge fuel.”

#### 5.4. Volatility Transmission

We also study the potential volatility linkages apart from the potential inherent price linkages and information process that might be existent. One commodity might also affect the range within the second commodity's price moves. Volatility transmission is important as it can clarify whether the two commodities can be used as hedging instruments against each other.

We start with our bivariate VARs as Singhal and Gosh (2016) do. We first test our models for serial correlation and ARCH effects. Our Breusch-Godfrey LM test suggests that there is no serial correlation in our residuals, while the ARCH test suggests that there is clustered volatility. Clustered volatility implies that there are periods of low volatility followed by periods of high volatility. The last verifies our assumption that volatility modeling is appropriate for our models.

We can tell that in the NBP market only oil transfers volatility to gas. The last is implied by the VAR's coefficient where oil returns are only explained by their lagged coefficient. On the contrary, it is not the same for gas returns,  $\Delta Oil_{t-2}$  is negative and low explaining gas returns. The oil returns' coefficient is only significant at 5% and 10% levels. The result implies the unidirectional transmission of volatility, but we could consider it as weak due to the negative sign (substitutability) and magnitude ( $-0.0567$ ) (Table 1).

**Table 6: NBP symmetrical DCC GARCH (1,1)**

Coefficient	GARCH (Oil)	GARCH (Gas)	Joint	t-value	Probability
M.U	0.0003			1.3234	0.1856
Ar	-0.0987			-0.2380	0.8118
M.A	0.0510			0.1225	0.9024
$\omega$	0.0000			0.5259	0.5989
$\alpha$	0.0622 <sup>a</sup>			2.7277	0.0063
$\beta$	0.9359 <sup>a</sup>			39.8777	0.0000
M.U		0.0000		0.1383	0.8899
Ar		-0.7962 <sup>a</sup>		-6.1000	0.0000
M.A		0.8221 <sup>a</sup>		6.5669	0.0000
$\omega$		0.0000		1.0368	0.2998
$\alpha$		0.1307 <sup>a</sup>		4.7521	0.0000
$\beta$		0.8682 <sup>a</sup>		29.7702	0.0000
$\lambda$	5.8114 <sup>a</sup>			7.9441	0.0000
DCC $\alpha$			0.0098 <sup>b</sup>	2.0604	0.0393
DCC $\beta$			0.9682 <sup>a</sup>	113.3988	0.0000
Q(50)r		0.8156			0.3665
Q(50)r <sup>2</sup>		0.1663			0.6834
Q(50)r	2.1645				0.1412
Q(50)r <sup>2</sup>	0.5006				0.4792
Akaike					-10.0550

Ljung – Box q statistics correspond to a test of the null of no autocorrelation in residuals, and squared residuals with h=50. <sup>a</sup>Indicates significance at all levels (1%, 5%, and 10%).

<sup>b</sup>Indicates significance at 5% and 10%. <sup>c</sup>Indicates significance at 10%

**Table 7: TTF symmetrical DCC GARCH (1,1)**

Coefficient	GARCH (Oil)	GARCH (Gas)	Joint	t-Value	Probability
M.U	0.0003			1.3326	0.1826
Ar	-0.0581			-0.1478	0.8824
M.A	0.0126			0.0320	0.9744
$\omega$	0.0000			0.5757	0.5648
$\alpha$	0.0559 <sup>a</sup>			3.1854	0.0014
$\beta$	0.9420 <sup>a</sup>			51.5940	0.0000
M.U		-0.0006 <sup>c</sup>		-1.7221	0.0850
Ar		0.4075		1.4771	0.1396
M.A		-0.4761 <sup>c</sup>		-1.7895	0.0735
$\omega$		0.0000 <sup>a</sup>		3.1575	0.0015
$\alpha$		0.1772 <sup>a</sup>		9.0067	0.0000
$\beta$		0.8217 <sup>a</sup>		43.6667	0.0000
$\lambda$	5.9547 <sup>a</sup>			8.0420	0.0000
DCC $\alpha$			0.0082 <sup>b</sup>	2.1491	0.0316
DCC $\beta$			0.9806 <sup>a</sup>	107.2759	0.0000
Q(50)r		1.4473			0.2290
Q(50)r <sup>2</sup>		1.1556			0.2824
Q(50)r	2.119				0.1455
Q(50)r <sup>2</sup>	0.2516				0.6159
Akaike					-9.6304

Ljung – Box q statistics correspond to a test of the null of no autocorrelation in residuals, and squared residuals with h=50. <sup>a</sup>Indicates significance at all levels (1%, 5%, and 10%).

<sup>b</sup>Indicates significance at 5% and 10%. <sup>c</sup>Indicates significance at 10%

We proceed with the fitting of our DCC GARCH (1,1) model as our data (returns) are stationary. We apply both the symmetrical (DCC) and the asymmetrical (ADCC) version of DCC GARCH modeling for all the studied markets. However, the symmetrical are better as thus presented. The NBP results are presented in Table 6. For both the symmetrical and asymmetrical version of our model, the alphas (ARCH coefficients) and betas (GARCH coefficients) are statistically significant at 1% for both commodities. Furthermore, they are positive and their sums-for each commodity separately- is close to one (1) suggesting that the shocks to the conditional variance are highly persistent i.e. volatility shocks have a long memory.

DCC GARCH modeling distinguishes shocks' volatility persistence on the dynamic conditional correlation into short and

long-run components. Again, we have statistically significant DCC coefficients for both versions of our model. Nevertheless, the asymmetric DCC coefficient (DCC $\gamma$ ) is zero (available upon request). Besides, the Akaike criterion advises us that the symmetrical DCC is preferable. It is noticed that the dynamic part of the volatility coming from the DCC $\alpha$  coefficient is close to 0.01 (0.0098), while the long-run persistence of the shock coefficient (DCC $\beta$ ) is almost one (1). They are jointly significant implying that the conditional volatility is not constant over time. The magnitude of the two coefficients implies that there is a systematic correlation between the two energy sources.

The evolution of the time-varying correlation is low and does not present vast fluctuations with only exceptions when the



correlation plummets in 2011 and 2016 (Figure 19). In 2011, oil fully recovered from the drop of 2008 and it remained at high levels until 2014. Profoundly, the oil price recovery had little connection with the UK gas prices and left them unaffected. The change of sign from positive to negative implies the competitive nature of the two commodities for the market. Oil prices plummeted in 2016 reaching its lowest level. Gas prices, on the contrary, increased implying the different pricing mechanisms in the market. Low correlation implies decoupled markets since there is no strong relationship between the markets.

The results for the TTF market are very similar (Table 7). What is different is the time-varying correlation which has extreme swifts (Figure 20). It again turns from positive to zero in 2010 as that of NBP, and it can be explained by the same reasoning. An even more abrupt change is that between 2013 and 2014 when the correlation reached and remained at zero levels. There was a gas crisis in Europe due to the Ukraine crisis. Gas imports were halted from this route and continental Europe had to import gas from various sources. This changed the price mechanism of the market temporarily. In 2018, there is a correlation decline to zero profoundly attributed to the gas price's increase when oil prices remained largely stable. Again, we have the verification of fundamental pricing and not that of spillovers since correlation is low.

Finally, the NBP and TTF pricing mechanisms remain largely unaffected having their fundamentals as oil does (Perifanis and Dagoumas, 2019). The markets are decoupled and let the demand and supply sides to play their important roles. The two commodities can not be used as hedging instruments as there is no strong correlation among them. Further, none commodity precedes the other in the information process.

Unfortunately, our results for the JKM market are not satisfactory as there are insignificant alphas (gas) and DCC coefficients, and this is why we do not present their results and time-varying correlation.

After all, our results (by all methodological approaches) do not present evidence of volatility spillovers in the European markets between oil and gas. Moreover, we do not find bidirectional volatility spillovers between oil and gas as Perifanis and Dagoumas (2018) (Henry Hub). Our results comply with Dahl et al. (2011) who suggest that there is no causal relationship between Brent and NBP prices. Further, the results give support to Misund and Oglend's (2016) view that the UK gas system is endowed with interconnections, which mitigate potential deviations. The market design additionally enhances the hard equipment of the market. All the aforementioned do not agree with Nick and Thoenes (2014), Geng et al. (2016), Geng et al. (2016b). Further, our results do not support the opinion that the European markets failed and remained oil-indexed, and that the US market decoupled from European and Asian ones due to the shale revolution (Erdos, 2012). The interconnection is fading since nuclear power rebounds for the Asian market. We calculate low correlations between the two commodities in the European markets, and we agree with Erdos (2012) who finds that markets decoupled since 2009. The two commodities are no longer useful as hedging instruments against

each other and we confirm Batten's et al. (2017) result who suggest that this is not possible since 2007. The low correlations do not comply with the view of Asche et al. (2012) who suggest that vast differences can exist in the short-run, but there is a long-term equilibrium relationship. We agree with Shaikh et al. (2016) over the importance of source and route diversification for the JKM market since we find unidirectional causality from oil returns to gas returns. However, the policymakers' efforts did not bring results or will in the near future as Vivoda (2014) suggests. The followed hedging strategy in the JKM did not have gas fundamentals as drivers, something which complies with Stern (2014). We can conclude, as Barnes and Bosworth (2015), that the gas market became more integrated. However, integration advances with different paces around the globe. This is why we find fully integrated gas hubs (NBP and TTF), while JKM turned to integration after the nuclear power rebound. Therefore, our findings confirm Jensen's (2004), Bachmeier and Griffin's (2006), and Li's et al. (2014) results for the separation of the global natural gas market into regional ones. The European gas markets succeeded in being efficient and transparent and now lead the gas pricing. Our results verify the results of Kim and Kim (2019). Last, our results do not comply with the claim of "one price law," as now oil and gas, in Europe and the JKM after the nuclear power rebound, are fundamentally determined.

## 6. CONCLUSIONS

The paper examines the linkage among European and Japan-Korea gas markets (NBP and TTF) with Brent crude oil market. In contradiction to the Japan-Korea market, the paper provides evidence that there are no major price spillovers between oil and gas in case of European gas markets, as the two commodities (gas and oil) are priced based on their fundamentals. The law of one price does not hold, since gas and oil are considered as two separate energy commodities.

To achieve this, European countries implemented several regulatory reforms to initiate the introduction of competition into the gas sector. The deregulation process is examined in relevant literature, Joskow (1996) and Newberry (2002). The main regulatory tools are services' unbundling, third party access to the network, and network access pricing regulation. The role of independent regulatory authorities has proved crucial for the liberalization process, enabled with rights to monitor market and competition in gas markets. Those regulatory tools could be useful for any market, such as the Japan-Korea market, in its process of strengthening dynamics of regional gas markets. Therefore, this paper, considering the European gas deregulation experience, supported by the paper results on the de-linkage of European gas markets, provides policy recommendations on the key elements needed for establishing functional gas hubs

More specifically, unbundling has been one of the most important steps implemented in European markets, although implemented in different forms: accounting, operating, legal and ownership. Accounting unbundling concerns the case where network activities are financially monitored separately than sales or upstream activities, while they are sharing operations within the same

## 7. ACKNOWLEDGMENTS

This work has been supported by the Horizon 2020 research project INTERFACE: TSO-DSO-Consumer INTERFACE architecture to provide innovative grid services for an efficient power system (Grant Agreement No. 824330).

## REFERENCES

company. Operational/management unbundling concerns the case where different business divisions operate under the same company, but independently of the rest. Legal unbundling forms different entities, which operate in parallel with production or sales subsidiaries in the holding company. Finally, ownership unbundling separates assets from the dominant corporation and forms a completely different entity.

Third-Party-Access (TPA) to the network is another regulatory tool. Especially, the regulated TPA is more than transparent than the negotiated one. Under the regulated TPA, the network owner publishes major terms of transactions along with tariffs. This makes the entrance of plenty of competitors more feasible in the network. Costs are published and no anti-competition or favorable policies can be followed.

Lifting gas price controls further facilitates market-determined pricing. Demand and supply well can replace regulatory-determined prices. If this is not feasible then monopolistic behaviors can arise. Additionally, one way to remove cost burdens to the competition is Gas Release Programs (GRPs). Dominant companies sell volumes to their competitors at determined prices allowing competition in retail. Market opening i.e. consumers' right to use infrastructure and change suppliers strengthens market pricing. Market opening encourages competition and eliminates potential premium charges by dominant companies.

All the aforementioned-measures are available tools that the East Asian market (JKM) can apply. However, the transition must be smooth and under the trade ethics of the region. "One size does not fit all" when it comes to market designs. Shi and Variam (2018) also propose similar policy tools for market liberalization of Asian markets. Oil indexation was used as a hedging instrument after the Fukushima Daiichi accident, but it cannot be sustainable in the future.

Finally, we provide evidence that the efforts of common infrastructure and regulations in the European Union have been effective concerning gas pricing, as there is gas market coupling among key intra-regional gas hubs. Interconnections in grids, regional hubs, and shared energy strategy accomplished the regionalization of energy pricing initially. The Energy Union with a fully integrated and efficient market will be a reality since these regions become more interconnected. Fundamentals are freed to play their role in commodity pricing leaving exogenous innovations outside the pricing process. However, this process needs to be further enhanced through the implementation of critical infrastructures, such as the Projects of Common Interest (PCIs) in the Balkans and the Baltics regions. On the other hand, severe incidents like nuclear power capacity removal in Japan led to less integration and efficiency. The diversification of energy sources and suppliers is of high importance for operational markets. Having different energy sources in the grid (fossil fuels, nuclear, renewables) and diversified energy suppliers (gas pipelines from different routes, LNG with increased liquefaction capacity, storage facilities) enables market fundamentals to work by removing information asymmetries and extreme incidences' impact, while they bring energy security.

- Asche, F., Oglend, A., Osmundsen, P. (2012), Gas versus oil prices the impact of shale gas. *Energy Policy*, 47, 117-124.
- Bachmeier, L.J., Griffin, J.M. (2016), Testing for market integration: Crude oil, coal, and natural gas. *International Association for Energy Economics*, 27(2), 55-71.
- Barnes, R., Bosworth, R. (2015), LNG is linking regional natural gas markets: Evidence from the gravity model. *Energy Economics*, 47, 11-17.
- Batten, J.A., Ciner, C., Lucey, B.M. (2017), The dynamic linkages between crude oil and natural gas markets. *Energy Economics*, 62, 155-170.
- Bernstein, P., Tuladhar, S.D., Yuan, M. (2016), Economics of U.S. Natural gas exports: Should regulators limit U.S. LNG exports? *Energy Economics*, 60, 427-437.
- Bollerslev, T. (1990), Modelling the coherence in short-run nominal exchange rates: A multivariate generalized ARCH model. *The Review of Economics and Statistics*, 72(3), 498.
- Cappiello, L., Engle, R.F., Sheppard, K. (2006), Asymmetric dynamics in the correlations of global equity and bond returns. *Journal of Financial Econometrics*, 4(4), 537-572.
- Dahl, R.E., Oglend, A., Osmundsen, P., Sikveland, M. (2011), Are oil and natural gas going separate ways in the UK? Cointegration tests with structural shifts. *SSRN Electronic Journal*, 5(2), 1-31.
- del Valle, A., Pablo, D., Sonja, W., Javier, R. (2017), A fundamental analysis on the implementation and development of virtual natural gas hubs. *Energy Economics*. 67, 520-532.
- Diebold, F.X., Mariano, R.S. (1995), Comparing predictive accuracy. *Journal of Business and Economic Statistics*, 13, 253-265.
- Engle, R. (2002), Dynamic conditional correlation: A simple class of multivariate generalized autoregressive conditional heteroskedasticity models. *Journal of Business and Economic Statistics*, 20(3), 339-350.
- Engle, R.F., Ito, T., Lin, W. (1990), Meteor showers or heat waves? Heteroskedastic intra-daily volatility in the foreign exchange market. *Econometrica*, 58(3), 525-542.
- Engle, R.F., Sheppard, K. (2001), Theoretical and Empirical properties of Dynamic Conditional Correlation Multivariate GARCH, NBER Working Paper Series. p1-46.
- Erdos, P. (2012), Have oil and gas prices got separated? *Energy Policy*, 49, 707-718.
- Fattouh, B. (2009), The dynamics of crude oil price differentials. *Energy Economics*, 32(2), 334-342.
- Geng, J.B., Ji, Q., Fan, Y. (2014), A dynamic analysis on global natural gas trade network. *Applied Energy*, 132, 23-33.
- Geng, J.B., Ji, Q., Fan, Y. (2016), How regional natural gas markets have reacted to oil price shocks before and since the shale gas revolution: A multi-scale perspective. *Journal of Natural Gas Science and Engineering*, 36, 734-746.
- Geng, J.B., Ji, Q., Fan, Y. (2016a), The impact of the North American shale gas revolution on regional natural gas markets: Evidence from the regime-switching model. *Energy Policy*, 96, 167-178.
- Granger, C.W.J. (1969), Investigating causal relations by econometric models and cross-spectral methods. *Econometrica*, 37(3), 424.
- Hulshof, D., van der Maat, J.P., Mulder, M. (2016), Market fundamentals,

- competition and natural-gas prices. *Energy Policy*, 94, 480-491.
- Jensen, J.T. (2004), *The Development of a Global LNG*. Oxford: The Oxford Institute for Energy Studies.
- Ji, Q., Geng, J.B., Fan, Y. (2014), Separated influence of crude oil prices on regional natural gas import prices. *Energy Policy*, 70, 96-105.
- Joskow, P.L. (1996), Introducing competition into regulated network industries: From hierarchies to markets in electricity. *Industrial and Corporate Change*, 5(2), 341-382.
- Kaufmann, R.K., Ullman, B. (2009), Oil prices, speculation, and fundamentals: Interpreting causal relations among spot and futures prices. *Energy Economics*, 31(4), 550-558.
- Kilian, L. (2009), Not all oil price shocks are alike: Disentangling supply shocks in the crude oil market. *The American Economic Review*, 99(3), 1053-1069.
- Kim, M., Kim, D. (2019), Leading and lagging natural gas markets between Asia and Europe. *OPEC Energy Review*, 43, 1-13.
- Li, R., Joyeux, R., Ripple, R.D. (2014), International natural gas market integration. *Energy Journal*, 35(4), 159-179.
- Lin, B., Li, J. (2015), The spillover effects across natural gas and oil markets: Based on the VEC-MGARCH framework. *Applied Energy*, 155, 229-241.
- Miriello, C., Polo, M. (2015), The development of gas hubs in Europe. *Energy Policy*, 84, 177-190.
- Misund, B., Oglend, A. (2016), Supply and demand determinants of natural gas price volatility in the U.K.: A vector autoregression approach. *Energy*, 111, 178-189.
- Newberry, M. (2002), *Privatization, Restructuring, and Regulation of Network Utilities*. Cambridge: MIT Press.
- Nick, S., Thoenes, S. (2014), What drives natural gas prices? A structural VAR approach. *Energy Economics*, 45, 517-527.
- Nikhalat-Jahromi, H., Bell, M.C.H., Fontes, D.M.M., Cochrane, R., Angeloudis, P. (2016), Spot sale of uncommitted LNG from Middle East: Japan or the UK? *Energy Policy*, 96, 717-725.
- Opolska, I. (2017), The efficacy of liberalization and privatization in introducing competition into European natural gas markets. *Utilities Policy*, 48, 12-21.
- Perifanis, T. (2019), Detecting west Texas intermediate (WTI) prices' bubble periods. *Energies*, 12, 1-16.
- Perifanis, T., Dagoumas, A. (2018), Price and volatility spillovers between the US crude oil and natural gas wholesale markets. *Energies*, 11(10), 2757.
- Perifanis, T., Dagoumas, A. (2019), Living in an Era when market fundamentals determine crude oil price. *The Energy Journal*, 40(1), 317-336.
- Shaikh, F., Ji, Q., Fan, Y. (2016), Assessing the stability of the LNG supply in the Asia Pacific region. *Journal of Natural Gas Science and Engineering*, 34, 376-386.
- Shi, X. (2016), Gas and LNG pricing and trading hub in East Asia: An introduction. *Natural Gas Industry B*, 3(4), 352-356.
- Shi, X., Padinjare, V.H.M. (2016), Gas and LNG trading hubs, hub indexation and destination flexibility in East Asia. *Energy Policy*, 96, 587-596.
- Shi, X., Shen, Y., Wu, Y. (2019), Energy market financialization: Empirical evidence and implications from East Asian LNG markets. *Finance Research Letters*, 30, 414-419.
- Shi, X., Variam, H.M.P. (2018), Key elements for functioning gas hubs: A case study of East Asia. *Natural Gas Industry B*, 5(2), 167-176.
- Singhal, S., Ghosh, S. (2016), Returns and volatility linkages between international crude oil price, metal and other stock indices in India: Evidence from VAR-DCC-GARCH models. *Resources Policy*, 50(C), 276-288.
- Stern, J. (2014), International gas pricing in Europe and Asia: A crisis of fundamentals. *Energy Policy*, 64, 43-48.
- Van Goor, H., Scholtens, B. (2014), Modeling natural gas price volatility: The case of the UK gas market. *Energy*, 72, 1216-1234.
- Vivoda, V. (2014), Natural gas in Asia: Trade, markets and regional institutions. *Energy Policy*, 74(C), 80-90.
- Wakamatsu, H., Aruga, K. (2013), The impact of the shale gas revolution on the U.S. and Japanese natural gas markets. *Energy Policy*, 62, 1002-1009.
- Zhang, D., Shi, M., Shi, X. (2018), Oil indexation, market fundamentals, and natural gas prices: An investigation of the Asian premium in natural gas trade. *Energy Economics*, 69, 33-41.
- Zhang, D., Tiantian, W., Xunpeng, S., Jia, L. (2018), Is hub-based pricing a better choice than oil indexation for natural gas? Evidence from a multiple bubble test. *Energy Economics*, 76, 495-503.