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Abstract— Has the integration of European, North American and Asian natural gas markets been fostered over the last few years by growing LNG export capacities and an increasing market share of spot transactions? This is the key question that this article sets out to answer. For this purpose, we develop bivariate error correction models with structural breaks and asymmetric responses among gas references prices, oil prices, and coal prices. We use daily prices of all reference prices spanning from January 12, 2004, to January 12, 2018, for the North American, Asian and European areas. We show that if European and U.S. gas prices are co-integrated when multiple breaks are allowed, their respective markets cannot be considered integrated. However, our results show that the degree of interdependence between European and American prices is increasing, whereas the degree of interdependence between gas and crude oil prices is decreasing. More surprisingly, we also highlight that reversions to long-term equilibria both between the Henry Hub (HH) and the National Balancing Point (NBP) and between the HH and the Japan Korean Marker (JKM) are highly asymmetric, a pattern that could be intuitively interpreted as the consequence of market arbitrage strategies by exporting countries in a context of oversupplied markets.

Keywords: Natural gas, LNG, integration, convergence, structural breaks, TECM

Code JEL: D40, L95

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1. Introduction

The gas market is undoubtedly experiencing profound changes due not only primarily to the development of production and export capacities for liquefied natural gas (LNG), particularly in the United States, but also to the emergence of more-flexible commercial agreements and the growing presence of physical traders. These ongoing processes might potentially have major consequences for the gas market. Through the strengthening of the LNG market, lower transaction costs and increasing flexibility, an internationally integrated gas market would clearly be a revolution. This statement would be true not only in economic terms with the assertion of new players and, most likely, a profound change in comparative advantages, but also and above all in geopolitical terms. In the short and medium term and in the economic field, two questions appear unavoidable: could these profound ongoing changes foster market arbitrage? Would they, in turn, fuel the emergence of a more integrated natural gas marketplace on a world scale? This paper sets out to answer these two interrelated central

questions as an extension of the studies already conducted on this topic over the past few years.

There are several approaches to apprehending the reality of market integration. Kalman filters, convergence tests and cointegration measures are among the most frequent procedures used in this respect. Albeit cointegration is a statistical concept that cannot be assimilated *per se* with market integration, it appears reasonable to assume that prices that are determined on integrated markets should display a long-term relationship. In other words, cointegration tests can be used to measure market integration. In some cases, however, practical interpretation remains questionable. Indeed, if there is a relationship of mutual dependence between the variables studied and another variable, there might be statistical cointegration but without providing undisputable evidence that markets are integrated. Based on this approach, seminal works on natural gas market integration suggest that intra-continental markets are indeed often usually integrated (Asche *et. al.* 2002). However, even when cointegration relationships between the major American, European and Asian gas price references might also have been strong over a given period, such strength cannot be construed *per se* as a sign of a growing interconnection between markets (Brown and Yücel, 2009; Siliverstos *et. al.*, 2005). The determining factor behind joint movements by gas prices observed in the past in the United States, Europe and Asia was not that of arbitrage between two markets but rather a certain dependence upon oil prices.

Dedicated to the analysis of natural gas market integration, this article builds directly on the groundwork laid in the above-mentioned articles by relying on cointegration measures and error correction models with three notable differences. First, our panel encompasses a very large set of natural gas daily price references in the U.S., Europe and Asia, whereas most studies considered only three prices (NBP, Henry Hub and the JKM). Second, we use the econometric procedures that allow for multiple break cointegration tests (Maki, 2012) and threshold error-correction models (Enders and Siklos, 2001). Threshold models have the advantage, contrary to Markov switching models which assume that the state process giving rise to regime switching is latent, of allowing that the nonlinear effect is driven by observable variables (Chan *et al.*, 2017). Furthermore, cointegration tests with multiple breaks allow to detect endogenously the date of a structural change in the relationship between gas prices, and therefore, of apprehending the changing nature of the gas market over the recent period. To our knowledge, this article is the only one to date applying such econometric techniques to analyse the integration of regional gas markets. Third, our period ranges from 12/01/2004 to 12/01/2018. This difference is anything but anecdotal, because it allows to us to consider the latest developments affecting energy markets: (1) the sharp slump in oil prices observed since the second half of 2014, which in particular is linked to the boom in unconventional gas production in the United States; (2) massive investments in the LNG industry in recent years, which translated into a growing number of liquefaction (export) plants and regasification (import) units that will enhance the capacity of international buyers to source natural gas through LNG carriers; and (3) an increased flexibility concerning LNG international trade in terms of LNG import and exports, which have historically been characterized by a high degree of rigidity, whether in terms of logistic conditions, contractual practices (incoterms) or

pricing mechanisms. This last assertion requires a reminder of the reality of physical trade and contractual practices relating to the LNG sector. The historical structuring of natural gas markets around long-term contracts could largely be explained by the product's physical characteristics and infrastructural requirements imposed by international transportation, similar to the case of onshore gas (Asche *et al.*, 2002). The industry's high development costs, linked significantly to the need for both liquefaction and gasification terminals and LNG carriers to transport gas by sea, create an interdependence effect between producers and users and explain the existence of long-term trade relations (Hirschhausen and Neumann, 2008; Ritz, 2014). Importing countries, largely dependent upon fossil fuels and unable to fully benefit from gas pipeline systems, thus secure their supplies, whereas for exporters, this long-term relationship is a guarantee of future revenue and the wherewithal to envision necessary logistical investments with peace of mind. Crude oil indexation is explained from two standpoints. On one side of the Atlantic, Continental Europe historically has had no gas price benchmark, with gas defined as an alternative energy to oil in the sectors of urban heating, electricity production and other industrial applications. Thus, the "oil" component in supply contracts in Europe constituted a widely accepted method of valuation for imported gas. On the other side of the Atlantic, the bridging of U.S. gas prices with oil prices is explained more by a physical connection than by any contractual requirements. As stated earlier, gas can replace oil products in a wide number of applications (for example, domestic oil and gasoil). Accordingly, the competition existing in gas markets with oil products produced the "gas" and "oil" relationship in the United States. Working under this sort of system, the LNG market has never been actually off-balance to the extent that investments in production/exportation capacities were made only when sales outlets were ensured. Fostered by the growth in anticipated long-term growth, by the idea that environmental arbitrage would favour natural gas in European countries (to the detriment of oil and coal), and by the wish of certain countries to eliminate the geopolitical restrictions that supply via gas pipelines impose, the prospects of brighter days ahead prompted producers to finance additional supply, whose price was to take shape on the spot market, most notably in the United States.

The idea was also, in certain geographic regions, to compete with the pipeline supply of natural gas, with the result that the price of LNG, through arbitrage, would be equal to the price of onshore gas once transportation and gasification were accounted for. However, once again the plot did not quite unfold as anticipated. The conjunction of the shale gas revolution in the United States, upscaling operations from historic producers such as Qatar and Australia combined with an environmental policy now much kinder to renewable energy sources than to fossil fuels, and low growth in Europe effectively created the conditions for a glut in supply that logically translated to a significant fall in gas prices and a shift in the power balance between suppliers and demanders (Rogers, 2015). Two largely interdependent consequences could be expected: stronger spot markets through an increasing importance of traded gas hubs, disconnected from oil prices, to the detriment of long-term contracts, and growing interaction between the dynamics of international prices, due not to common practices of oil-related indexation but rather to inter-market arbitrage strategies. Empirical verification that such relationships exist has been central to many articles. As Asche *et al.* (2013) note, there are indeed no clear links between the existence of a spot market and the independence of gas

prices if substitution with oil remains strong. Verifying the scope of this affirmation is therefore at the very heart of this article's ambition. Although to the best of our knowledge, no publicly available data exist that would allow us to understand explicitly the reality of commercial contracts on natural gas or, more particularly, the pricing mechanisms contained therein, there are serious reasons to believe that this trend towards greater flexibility in international trade in natural gas, via the expansion of LNG, is occurring. First, beyond the idea previously developed that excess natural gas supply has favoured the emergence of a spot market, there is indeed an obvious interest for international buyers, particularly electricity producers, in implementing these arbitrage strategies, at least on a regional scale. Such strategies can indeed be driven by not only the seasonality of the demand for gas, which leads to different peaks in demand from one country to the next, but also imperfect substitutability between gas and other energy sources in the production of electricity. This point is even truer for European markets, insofar as the regulators have vowed to foster market transparency, liquidity and completeness by means of the Gas Target Models (GTMs) I and II defined in 2011 and 2014, respectively. Nevertheless, as emphasized by Ritz (2014), producers adopting a policy of price discrimination could inversely limit intensity and thereby the effect on the interdependence of international prices. Second, physical arbitrage is now not only technologically and contractually easier but also less costly. Being by far less expensive than onshore terminals, FRSU (Floating Regasification and Storage Unit) offshore units in importing countries and, even more recently, FLNG (Floating LNG) offshore units in exporting countries, open up new prospects for international gas exchanges. FRSUs and FLNGs are, in a very simplified fashion, infrastructures located at sea to varying degrees (offshore/nearshore/inshore) whose cost[1] and flexibility allow them to be considered attractive alternatives[2]. Third, the rise in U.S. shale gas could, in addition to its depressing effect on world prices, also lead to an "export" of North American contractual practices that are more flexible than in the rest of the world, notably lacking the absence of so-called destination clauses, or the increased use of more flexible Free On Board (FOB) incoterm rather than Delivered Ex-Ship (DES) or Delivery at Terminal (DAT) incoterms[3]. For the International Energy Agency (IEA), the evidence is clear: "*a new gas order is emerging, with U.S. LNG helping to accelerate a shift towards a more flexible, liquid, global market. Ensuring that gas remains affordable and secure, beyond the current period of ample supply and lower prices, is critical for its long-term prospects. LNG accounts for almost 90% of the projected growth in long-distance gas trade to 2040; with few exceptions, most notably the route that opens up between Russia and China, major new pipelines struggle in a world that prizes the optionality of LNG"* (IEA, 2017). In a context of sufficiently supplied markets, this new paradigm, if it were to materialize, would enshrine the role of physical traders. Drawing on their ability to

[1] Approximately USD 450 million, including USD 250–300 million for the "vessel" alone. An FRSU might also result from the transformation of a tanker, but the cost difference is small compared with the development of a new unit when, of course, the tanker used is new.

[2] The first FRSUs were launched in 2008 in Argentina (Bahia Blanca GasPort), Brazil (Pecemport) and the United States (Northeast Gateway Deepwater Port).

[3] The use of the Incoterm DAT incoterm requires the definition of a delivery port, which de facto limits the buyer's capacity for physical arbitrage. An FOB incoterm or the introduction of so-called revision clauses, in contrast, allows the buyer to change the place of delivery, allowing him to limit the risk on the volume of imported gas that the seller imposes on him under a take-or-pay contract.

operate these arbitrage operations to protect traditionally low intermediation margins, they would most likely make price competitiveness a key variable in the functioning of markets, which would most likely not be to the advantage of new producers[4]. In this context, the essential question raised by this article is not so much whether this flexibility of trade will prevail, because it is, in fact, quite consistent with the history of commodity markets, but whether it has already materialized to the point of being reflected in the joint dynamics of regional gas prices and in their links with that of oil. Linear error correction models are not sufficiently sophisticated to capture the long-term price relationships that can prevail on energy markets. Hence, many of the latest articles on gas price dynamics favour different types of regime-switching models. However, they are, to the best of our knowledge, rather focussed on the cointegrating relationships between a given crude oil price reference (West Texas Intermediate or Brent) and its "corresponding" natural gas price, primarily Henry Hub (HH) and National Balancing Point (NBP), rather than among natural gas prices themselves. Using an error correction model with structural breaks and asymmetries in the convergence process to long-term equilibrium, this article aims at filling this gap by considering a large original dataset with information on North American, European and East Asian reference prices (i.e., the Japan Korean Marker – JKM). Oil prices are also considered to distinguish the fact that natural gas prices can display a common dependence upon crude oil rather than a "real" price comovements due to growing gas market integration. Using nonlinear error correction models that allow for both structural breaks and thresholds, we provide further evidence that European and North American markets were cointegrated prior to October 2010. However, their common cointegration with oil prices does not allow us to assert that these markets were integrated. We also demonstrate that this convergence process towards long-term equilibrium is asymmetric both between HH and NBP and between HH and the JKM, possible evidence of existing market arbitrage strategies by exporting countries.

This article is structured as follows. We initially present a rapid review of the literature focussing on the integration of gas markets and the long-term relationship between natural gas and oil prices. Next, we describe the data used for our study and specify our econometric modelling. Findings and the interpretations thereof are covered in the subsequent section. Finally, we conclude.

2. Literature review

The question of the integration of gas markets is not new, but no-one can deny that the selected geographic perimeter has expanded, initially favouring a national or continental dimension but now asserting itself more on a worldwide scale. In this respect, the article by Neumann (2009) is evocative of the incidence of the development of LNG production capacities on the gas market internationally.

Accordingly, the question of interconnection between gas markets for pipeline gas is anything but recent. Following Spulber and Doane (1994), Kleit (1998) effectively questioned the

[4] Among the most recent evidence of this increase in international traders' market power is the agreement reached between Trafigura and Chenière Energy to deliver to the independent trader one million tons of LNG per year for 15 years based on the Henry Hub spot price. This agreement is in addition to the contracts signed between Gunvor and Yamal LNG in Russia or the one allowing Glencore to source Angolan LNG.

integration of gas markets within all of the various producer regions in the United States (the Rockies, Oklahoma, Texas, Louisiana and the Appalachians), a move made further to the lifting of regulations sought by the Federal Energy Regulation Commission (FERC) by way of an approach aimed at assessing the dynamics of inter-regional transaction costs. He suggested that the suppression of trade barriers does not necessarily promote the advent of a unified market. For their part, Asche *et al.* (2002) focussed on the integration of the German gas market by studying the dynamics of import prices from the Netherlands, Norway and Russia. Although the very idea of integration presupposes that these prices should entail virtually identical dynamics, both the nature and the diversity of international trade contracts nevertheless render more complex any apprehension of such a reality. The dominance of so-called "take-or-pay" contracts, which not only allow producers to secure commercial revenue but also provide buyers with a degree of flexibility in terms of supply volumes, has effectively led to the prevalence of price formulas that in part index the price of gas on that of gas substitutes. This indexing might explain the differences in price observed with imports, independently of the reality of market integration.

Are gas markets moving towards greater integration? This question, which implicitly queries the effect of contractual specifics tied to gas reception/delivery operations on relationships uniting the prices of gas and crude oil, actually strikes at the very heart of articles written on this subject. In this same line of thought, Brown and Yücel (2009) develop an error correction model and test the meaningfulness of cause-and-effect relationships between the prices of North American and British gas (HH and NBP) and those of WTI and Brent over the period from June 13, 1997, to May 9, 2008. Specifically, they document the asymmetry of the explanatory power of the prices of gas and oil, in which WTI and Brent prove to be explanatory variables for HH and NBP prices, respectively, but with no verification of reciprocity. Using a multi-varied model using as an explanatory variable the price of European gas (American), American gas (European), oil prices (WTI and Brent) and the vectors of joint integration between oil and gas prices, the authors show that gas prices adjust to the discrepancies in the long-term relationship maintained with WTI. In other words, the joint dynamic of gas prices on either side of the Atlantic is explained more by a shared dependency upon the price of crude oil than on arbitrage operations due to LNG between the United States and the United Kingdom, in accordance with the previous findings of Brown and Yücel (2009). Although Li *et al.* (2014) also question the international integration of gas markets by extending their analysis to the Asian zone (Japan, South Korea and Taiwan), the econometric procedures they use are different because of the intrinsic limitations of co-integration analyses in addressing issues of convergence. Adopting the Philips-Sul test and the Kalman filter to apprehend the (gradually) changing nature of relationships between several series, the authors show that there is no global integration of the markets. They show that integration is rather gaining strength, between not only the three Asian markets under consideration but also these markets and the British gas market, thereby leaving the North American market to adopt its own specific dynamic.

The question of market integration is by its nature a structural one and should consequently be considered in the long term, which in turn raises questions about the stability of the

cointegrating relationships not only between oil and gas prices but also between gas prices themselves. This point is even truer when one examines the last decade, in which oil prices severely decoupled from gas prices[5] in the aftermath of the 2008 financial crisis and the U.S. shale gas revolution, as they did in the U.S. in the eighties and the nineties. Technological changes, notably the growing role of not only combined cycle gas turbines since the 1990s but also the more recent horizontal drilling and rock fracturing techniques, could indeed explain that the relative prices of natural gas to crude oil change considerably over time. This change implies that any studies based on linear error correction models could be methodologically flawed (Ramberg and Parsons, 2012). Regime-switching models have therefore been adopted to overcome this type of misspecification. For instance, Brigida (2014) develops an error correction model with endogenous shifts in cointegrating vector determined by a first-order Markov process. Considering the period from September 1997 to September 2012, the author tests the fact that the long-term relationship between the WTI front month prices and HH gas price can experience structural breaks, once variables such as temperature variations or the U.S. field production of crude oil are controlled for. One of the main conclusions of this article is that oil and gas prices did not permanently decouple in the 2000s but rather exhibited a disconnection from August 2000 to May 2009 during which HH prices outperformed oil prices.

Asche *et al.* (2017) also criticize the conventional "error correction model approach" but for its inability to consider the fact that natural gas prices periodically decouple from oil prices during fall and early winter seasons at a time when immediate demand for heating can be sufficiently high to reach the maximum utilization pipeline capacity, allowing for specific gas pricing and consequently leaving little room for oil indexation to influence prices. Using both a linear error correction model that averages natural gas prices and a Markov-switching model, in line with Bridiga (2014) methodology but which allows for potential peak loading pricing, the authors consider the dynamics of the InterContinental Exchange (ICE) front month gas prices[6] and the Brent front month prices on a weekly basis. They show that the use of a linear model combined with the prevalence of decoupling underestimates not only the adjustment to deviations from the equilibrium relationship but also the long-term equilibrium relationship between oil and natural gas prices. Addressing these biases through a regime-switching model that allows for a two-state dependency (gas pricing being either oil driven or specific), the authors demonstrate that oil and UK gas markets appear to be integrated for the majority of the considered period.

The approach developed by Barnes and Bosworth (2015) prefers a radically different form of modelling based on equations of gravity that is very widely seen in the empirical analysis of international trade flows. The authors' approach is to identify the determinants of import and export flows of LNG and compressed natural gas (CNG) to estimate the incidence of the "distance" variable on the intensity of bilateral trading and thereby apprehend the regional, or inversely the international, dimension of the gas market. The results obtained by Barnes and Bosworth (2015) confirm the importance of distance as an explanatory component of CNG

[5] As measured by the crude oil to natural gas price ratio.
[6] The ICE natural gas contracts delivery point is at the UK National Balancing Point Hub.

trading, as opposed to LNG. Two conclusions can be drawn here: LNG might well be a global market, something the CNG market cannot claim to be, and its strong growth is aiding the internationalization of the natural gas market. Ritz (2014) adopts an idea that is equally different from those based on the analysis of co-integration relationships between gas prices observed at reference hubs. He effectively considers that due to the adoption of strategic behaviours by producers in certain markets, there are intrinsic limits to arbitrage operations. If producers embark upon a third-order policy of price discrimination, in principle, there is therefore no reason to consider that the integration of gas markets should translate to an equalization of prices once transportation costs have been accounted for.

3. Data and empirical methodology

3.1. Data

Our aim is to evaluate both the integration of the European gas market and the world gas market, controlling for the relationship between gas and oil prices. For this purpose, we use daily data at business frequency, expressed in euro per megawatt-hour (MWh)[7], from Thomson Reuters for the NBP in the United Kingdom and all other European gas prices, such as the Central European Gas Hub (CEGH[8]) in Austria, the Title Transfer Facility (Netherlands), the French "Points d'Echange de Gaz[9]" (North and South), the Net Connect Germany (NCG), the Gaspool (Germany) and the Zeebrugge hub in Belgium. Referred to collectively as "hubs", they have neither the same economic role nor the same economic importance; the historical domination of the NBP explains why almost all empirical papers addressing European gas markets have neglected the aforementioned European continental hubs. Heather (2012, 2015) thus distinguishes between trading (NBP and TTF), transmission (NCG, and PEG North and South) and transit (ZEE and CEGH) hubs. Albeit other hub prices could have been considered[10], this study thus encompasses the vast majority of continental gas prices and distinguishes itself from existing studies in this respect. We also use daily data for the HH, the Japan-Korean marker, oil and coal prices. A point must be made concerning the oil price series chosen here. In contrast to existing empirical papers relying on weekly or monthly time series of Brent or WTI front month prices, we opt for a "long-term oil index", which is simply a six-month moving average of Brent daily prices. The primary reason for this choice is that long-term sales agreements on natural gas, which are indexed on crude oil prices, largely rely on a price formula and not on weekly or monthly oil prices as such. Based on industry practices, this six-month moving average time series appears to be a much more reliable indicator of a potential common dependence upon oil prices than are the raw data[11].

[7] NBP, Henry Hub and JKM prices are converted into euro using the daily pound-euro exchange rate and the daily euro-dollar exchange rate.
[8] Formerly known as Baumgarten.
[9] Literally "Gas Exchange Point".
[10] Such as the "Punta di Scambio Virtuale" in Portugal.
[11] Hence, according to a "6.1.6 sell/purchase agreement", natural gas is bought at t_0 by an electricity producer at a six-month moving average price and sold at the same price (+margin) for next six months, the deal being on the table for one month.

We also choose to consider the API2 coal price[12] whereas previous studies do not. The main reason for that choice is that, akin to oil, natural gas has proved a substitute to coal-fired thermal plants. According to the so-called clean dark spread (CDS) and clean spark spread, *i.e.*, the difference between the price at which electricity can be sold to the grid and the costs to produce it either by consuming natural gas or coal once the environmental aspects are considered, there is a price for natural gas under which power companies will favour natural gas rather than coal. The time span of this rich dataset differs according to the prices under consideration. For most prices, we use data from 12/05/2004 to 12/01/2018. For PEG North, NCG, CEGH and PEG South however, our time series start respectively with 02/12/2005, 02/10/2007, 15/09/2009 and 09/29/2009. Note that Coal data only start from the 18/08/2006.

Table 1 presents descriptive statistics of the logarithm of the different prices under consideration in this paper, and Figures 1, 2, and 3[13] present the evolution of the different prices in the level.

Table 1. Descriptive statistics of natural gas, oil and coal prices

	Mean	Median	Max.	Min.	Std. Dev.	Skew.	Kurtosis	JB	Obs.	Start Date
Belgium (ZEE)	2.893	2.947	4.565	0.908	0.350	-0.277	3.210	67.851	4648	12/01/2004
Netherlands (TTF)	2.885	2.950	4.060	0.875	0.326	-0.490	2.615	215.022	4648	12/01/2004
U.K. (NBP)	2.891	2.937	4.569	0.742	0.359	-0.305	3.342	94.923	4648	12/01/2004
Germany (Gaspool)	2.890	2.958	4.054	0.916	0.324	-0.480	2.586	211.510	4648	12/01/2004
Germany (NCG)	2.986	3.067	3.711	1.939	0.294	-0.915	3.196	474.585	3365	02/10/2007
France (PEG-North)	2.970	3.045	4.190	1.841	0.320	-0.593	2.993	234.346	4000	02/12/2005
France (PEG-South)	3.052	3.094	3.773	1.821	0.290	-0.568	3.245	151.010	2682	26/09/2009
Austria (CEGH)	3.034	3.084	3.689	2.327	0.243	-0.773	2.698	278.156	2693	15/09/2009
U.S. (Henry Hub)	2.770	2.659	3.963	2.021	0.362	0.619	2.899	298.375	4648	12/01/2004
Japan-Korean	3.243	3.237	3.928	2.220	0.435	-0.330	2.094	151.770	2903	02/02/2009
Oil	3.124	3.125	3.565	2.197	0.319	-0.699	3.184	384.687	4648	12/01/2004
Coal	4.164	4.120	4.956	3.631	0.250	0.434	2.866	120.634	3754	18/08/2006

Note: All variables are expressed in the logarithmic form. JB denotes the Jarque-Bera statistic

European gas prices blatantly exhibit very similar characteristics, particularly German (Gaspool), Belgium (ZEE), Dutch (TTF) and British (NBP) natural gas prices, suggesting that the difference between those prices could be marginal. The existence of continental interconnectors combined with the fact that some hubs play a leading role in gas contract pricing compared to others, is one of the obvious explanations for this similarity. The pricing role of natural gas exchanges, such as Powernext, the European energy exchange (EEX) or

[12] *i.e.*, the benchmark price reference for coal imported into northwest Europe.
[13] See Appendix.

the ICE in Europe, is also part of the answer. In contrast, Figure 2 suggests a different evolution for NBP, Henry Hub and the JKM. We can remark on a similar pattern for NBP and Henry Hub until 2010, with a higher volatility for NBP. However, at the end of 2010, Henry Hub, the JKM and NBP appear to decouple and exhibit very different patterns. Finally, after 2015, these three prices appear to recouple and to follow a similar evolution. Figure 3 offers evidence of a similar trend between NBP and oil prices, whereas the relationship with coal prices appears more difficult to identify.

3.2. Empirical methodology

In this paper, we are interested in the integration of the world gas market. In particular, we aim to distinguish a cointegration relationship between natural gas and oil prices due to world market integration. Furthermore, the paper is also dedicated to a potential effect of LNG on the European gas market. To achieve this purpose, we rely on different econometric approaches, from linear cointegration tests to a vector error-correction model with structural breaks. We also implement threshold cointegration. All models considered in this study are bivariate models. However, before using cointegration methods, we must test the order of integration of gas, oil, and coal prices.

3.2.1. Structural change and unit root tests

Before proceeding to the cointegration tests, the properties of the time series must be studied. For this purpose, we apply Augmented Dickey-Fuller (ADF) to test the order of integration of each variable retained in the analysis. For a robustness check, we complement this test with the stationarity test developed by Kwiatkowski, Phillips, Schmidt and Shin (1992), which tests the null hypothesis of stationarity instead of the existence of a unit root as in the ADF and PP tests. Using both types of test is important because the ADF test has low power if the process is stationary, but with a root close to the non-stationary boundary, the test tends to reject the non-stationarity hypothesis too often. The KPSS complements the ADF test because, in contrast to the latter, which assesses the null hypothesis of the unit root, the former tests the null hypothesis of stationarity. It is a very powerful test, but it cannot catch non-stationarity due to a volatility shift.

Because we employ data on a very long-time span (14 years), gas, oil and coal prices series can however contain a variety of structural changes due to economic, political or external shocks in the long term. Figures 1, 2, and 3 confirm multiple structural changes in the series under scrutiny. However, if the presence of structural breaks in the series is not considered when using unit root tests, this can lead to misspecification errors (Ketenci, 2016). Consequently, we rely on the Perron and Yabu (2009) test to determine whether there are any structural changes in the deterministic components of a univariate time series. This test can be applied when whether the series (here different prices) is trend stationary or contains an autoregressive unit root is a priori unknown. Perron and Yabu (2009) develop a test of the null hypothesis of no structural change in the deterministic components and employ the test statistic Exp-W_{FS} based on robust quasi-flexible generalized least squares (FGLS). Three models can be used for the estimation: the first model testing for the presence of a structural break in the level of a variable (model I), the second model testing for a shift in the slope of

trend (model II) and the third model testing for structural changes in both the level and the slope of the time trend.

If the presence of a structural break is detected in the deterministic components, standard unit root tests such as ADF or KPSS can lead to inconsistent results. Several tests have been implemented in the empirical literature to consider the existence of breaks in time series. The most commonly used tests are those from Zivot and Andrews (1992), allowing for one break, and from Lee and Strazicich (2003), allowing for two breaks. However, both tests assume that the break occurs only under the alternative hypothesis of stationarity. This result is undesirable, particularly if the Perron and Yabu test suggests a structural change in time series. Kim and Perron (2009) propose a new method that allows a break at an unknown time under both the null and the alternative hypotheses. Carrion-i-Silvestre *et al*. (2009) extend this methodology and develop a test that permits up to five breaks at unknown times in both the level and slope of the time trend. Their test is based on a quasi-generalized least squares (GLS) detrending method proposed by Elliott *et al.* (1992) that allows tests to have a local asymptotic power function close to the local asymptotic Gaussian power envelope. Therefore, if the presence of a structural change in a time series is confirmed by the test of Perron and Yabu (2009), we rely on the Carrion-i-Silvestre *et al.* (2009) unit root test.

In this paper, we use the model III of the Perron and Yabu (2009) test, which corresponds to the model III of the Carrion-i-Silvestre *et al.* (2009) test. Indeed, as depicted in Figures 1, 2, and 3, it appears that all series have experienced multiple structural changes in both intercept and time trend.

3.2.2. Structural breaks and cointegration

Standard cointegration tests enable verification of the existence of the law of one price (LOP) and thus the perfect integration of markets. Under this approach, identical goods traded at different locations in an integrated market must have the same long-term price once transport and other transfer costs are considered. However, explanatory power of standard linear cointegration tests could nonetheless be strongly affected by the presence of breaks in the level, trend, or slope coefficients in the cointegration relationship because it changes the asymptotic distribution of the test (Perron, 1989). Moreover, Gregory and Hansen (1996a) have demonstrated that the null hypothesis of no cointegration might not be rejected when the cointegrating relationship is unstable. Therefore, standard cointegration tests could lead to accepting the null hypothesis of no cointegration between gas prices only because there is a break in the level function in the long-term relationship. Therefore, the test could lead to rejecting the hypothesis of an integration of the natural gas market. Indeed, as depicted in Figures 1, 2 and 3 in the Appendix, gas prices have experienced structural changes; the relationships between these prices could have evolved through time, for instance with a decrease in transportation costs.

Consequently, Gregory and Hansen (1996a, 1996b) have developed a residual-based test that allows addressing shifts in both level and trend. The procedure tests the null hypothesis of no cointegration against the alternative of cointegration in the presence of level shift (Model 1); level shift with trend (Model 2); and regime shift, in which intercept and slope coefficients

change (Model 3). Furthermore, Gregory and Hansen (1996b) add a more general formulation of the test by specifying a regime shift in which intercept, slope coefficients and trend change (Model 4) in the alternative hypothesis. In the case of testing cointegration between two prices, the model can be written as follows:

$$P_t^1 = \beta_1 + \beta_2 \varphi_{tk} + \alpha_1 t + \alpha_2 t \varphi_{tk} + \mu_1^T P_t^2 + \mu_2^T P_t^2 \varphi_{tk} + \varepsilon_t \quad (1)$$

where P_t^1 and P_t^2 are the logarithm of prices (gas, oil or coal), β_1, μ_1 and α_1 the intercept, slope coefficients, and trend coefficient, respectively, before the regime shift, and β_2, μ_2 and α_2 are the corresponding changes after the break. Note that:

$$\begin{cases} \varphi_{tk} = 0 \; if \; t \leq [n\tau] \\ \varphi_{tk} = 1 \; if \; t > [n\tau] \end{cases}$$

where τ denotes the timing of the changing point, and [] denotes integer part.

The test statistics for the Augmented Dickey Fuller (ADF) and Z_a and Z_t of Perron are:

$$ADF^* = Inf_{\tau \epsilon T} ADF(\tau), \; Z_a^* = Inf_{\tau \epsilon T} Z_a(\tau) \text{ and } Z_t^* = Inf_{\tau \epsilon T} Z_t(\tau).$$

In this paper, we initially rely on the test proposed by Gregory and Hansen (1996b) based on model 4.

However, the test developed by Gregory and Hansen only allows testing for one structural break in the alternative hypothesis. Maki (2012) proposed a new cointegration test that allows identifying up to five different unknown breaks. The test is a residual-based model that assumes that the maximum number of breaks of the cointegrating vector is less than or equal to the maximum number of breaks. Maki (2012) provides evidence that the case of one break is consistent with the cointegration models of Gregory and Hansen (1996a, 1996b), whereas the case of two breaks is similar to the model of Hatemi-J (2008). Furthermore, using Monte Carlo simulations, Maki (2012) shows that the proposed tests perform better than do the tests of Gregory and Hansen (1996, 1996b) and Hatemi-J (2008) when three breaks or more are considered in the cointegration relationship.

Maki (2012) proposes four different models to test for cointegration with multiple breaks. The first one assumes multiple breaks in the intercept without trend, the second one assumes multiple breaks in both intercept and slope coefficients without trend, the third model assumes multiple breaks in intercept and slope coefficients with a time trend, and the fourth one assumes multiple breaks in intercept, slope coefficients and trend. The last model can be expressed as follows:

$$P_t^1 = \beta_1 + \sum_{i=1}^{k} \beta_{2,i} \, \varphi_{i,t} + \alpha_1 t + \sum_{i=1}^{k} \alpha_{2,i} t \, \varphi_{i,t} + \mu_1^T P_t^2 + \sum_{i=1}^{k} \mu_{2,i}^T P_t^2 \varphi_{i,t} + u_t \quad (2)$$

where $\varphi_{i,t}$ represents dummy variables equal to 1 if $t > T_{B,i}$ and $T_{B,i}$ denotes the period of the break. Note that k is the maximum number of breaks, which is set to 5. Finally, all variables must be I(1) for the implementation of the Maki (2012) cointegration test.

However, the assumption of a perfect integrated market, i.e. the verification of the LOP, must also be tested. If the LOP is verified, any differences between prices will lead to arbitrage opportunities, and prices will consequently converge a single value (Nick and Tischler, 2014). Nevertheless, although this theory assumes no transaction costs, they are of high importance, particularly in the gas market. Therefore, a price spread between two markets will converge towards transaction costs. In this case, there exist arbitrage opportunities if the price in market *i* is different from the price in market *j* once transaction costs are considered, such as:

$$\begin{cases} P_i > P_j + \varphi \\ P_i < P_j - \varphi \end{cases}$$

Thus, any decrease in transaction and transfer costs (φ), such as innovations that permit drop-in transportation costs, will decrease the price spread between two markets. Indeed, transportation costs can justify differences in natural gas prices between two different geographic areas, for example the Asian and European markets. Following Asche *et al.* (2002) and Siliverstos *et al.* (2005), we construct a Wald test and restrict the cointegrating vector between a pair of prices as $\beta = (1; -1)$, including an intercept in the long-run relationship, to test this hypothesis.

3.3.3. Threshold cointegration and asymmetric Error Correction Model (ECM)

Testing for a structural break using the method developed by Maki (2012) allows identifying changing coefficients in the long-term relationship between prices. Nevertheless, although we consider only one long-run equilibrium, it is also important to assess the possibility of an asymmetric adjustment towards this equilibrium. Indeed, the standard linear method assumes that the adjustment mechanism to reach equilibrium is symmetric. However, in some cases, there could be non-linearity in the relationship and, therefore, asymmetric adjustment. This point is particularly true when assessing the arbitrage dynamics between prices when transaction costs exist. This phenomenon could be tested using threshold cointegration tests and threshold error correction models (TECM). Balke and Fomby (1997) introduce a method that combines both non-linearity and cointegration to test for the presence of a threshold effect. In the empirical literature, several tests have been implemented for threshold cointegration (see Enders and Silkos, 2001; Lo and Zivot, 2001; Hansen and Seo, 2002). In this paper, we rely on the test procedure proposed by Enders and Siklos (2001). In the standard Engle and Granger (1987) two-step method, the existence of cointegration is tested using an ADF test on the residuals (ε_t) of the equation describing the long-term relationship. However, this approach is not consistent if the adjustment mechanism is nonlinear. Therefore, Enders and Siklos (2001) propose modifying the test on the residuals to allow for non-linear adjustment as in the following:

$$\Delta\varepsilon_t = I_t \rho_1 \varepsilon_{t-1} + (1 - I_t)\rho_2 \varepsilon_{t-1} + \sum_{i=1}^{k} \gamma_i \Delta\varepsilon_{t-1} + u_t \quad (3)$$

where ρ_1, ρ_2 and γ_i are the coefficients, k is the number of lags and I_t is the Heaviside indicator function such that:

$$I_t = \begin{cases} 1 \; if \; \varepsilon_{t-1} \geq \tau \\ 0 \; if \; \varepsilon_{t-1} < \tau \end{cases}$$

where τ is the threshold value. These two equations define the threshold autoregression (TAR) model. This model allows non-linear "deep" movements in the residuals. As an alternative adjustment process, Enders and Siklos (2001) also propose the momentum threshold (MTAR) model in which only the Heaviside function differs as in the following:

$$I_t = \begin{cases} 1 \; if \; \Delta\varepsilon_{t-1} \geq \tau \\ 0 \; if \; \Delta\varepsilon_{t-1} < \tau \end{cases}$$

In the MTAR model, the ε_t series exhibits more "momentum" in one direction than in the other. This model is more accurate for price changes that display more momentum in one direction than in another (positive or negative).

Note that there are two approaches to determine the threshold value. The first one is to set exogenously the threshold to zero (*i.e.*, $\tau = 0$). The second one is to determine the value of τ endogenously by the dataset. In this case, the models are called consistent-TAR and consistent-MTAR. In this paper, we rely on the second method and set the threshold endogenously using the search method developed by Chan (1993). According to this procedure, ε_{t-1} for the TAR model and $\Delta\varepsilon_{t-1}$ for the MTAR model are sorted in ascending order, and the lowest and highest 15% of the threshold values are excluded. Then, on the remaining 70% band, we consistently estimate the threshold value if given by the lowest residual sum of squares. In this paper, we want to test for asymmetric cointegration using consistent-TAR and consistent-MTAR models. The choice between the two types of model is made using the AIC and BIC information criteria as in Enders and Siklos (2001). Finally, we examine the existence of a non-linear cointegration relationship between different prices using two tests. First, the F-statistics, called Φ_u and Φ_{u^*}, are used to test the null hypothesis of no-cointegration ($\rho_1 = \rho_2 = 0$) in the TAR and MTAR models, respectively. If the hypothesis of no-cointegration is rejected, we test for the null hypothesis of symmetry ($\rho_1 = \rho_2$) using a standard F-test.

We rely on this approach to test for threshold cointegration. If threshold cointegration is confirmed by the test provided by Enders and Siklos (2001), we can estimate the following asymmetric error correction model with threshold cointegration as developed in this study:

$$\Delta P_t^1 = \alpha + \vartheta^+ ECM_{t-1}^+ + \vartheta^- ECM_{t-1}^- + \sum_{i=1}^{k} \beta_i^+ \Delta P_{t-i}^{1,+} + \sum_{i=1}^{k} \beta_i^- \Delta P_{t-i}^{1,-} + \sum_{i=1}^{k} \delta_i^+ \Delta P_{t-i}^{2,+} + \sum_{i=1}^{k} \delta_i^- \Delta P_{t-i}^{2,-} + \mu_t \quad (4)$$

where ΔP_t^1 and ΔP_t^2 are the natural gas prices in the U.K., Asia or the U.S. in the first difference, and μ_t is the error term. Following Sun (2011), all of the lagged gas price

variables in the first difference are split into positive and negative components (superscripts + or – in the equation). For example, $\Delta P_{t-1}^{1,-} = P_{t-1}^{1} - P_{t-2}^{1}$ if $P_{t-1}^{1} < P_{t-2}^{1}$, and 0 otherwise. Note that the optimal lag value (k) is chosen according to the minimum value of the BIC and according to the Ljung-Box Q_{test} to have no serial autocorrelation in the residuals. Finally, the error correction term (ECM) is constructed according to the value of the threshold and using the Heaviside function[14]. Note that one of the main drawbacks of this approach is that it only allows one threshold. However, it could be sufficient to assess the existence of market arbitrage between natural gas prices.

It should be noted that the existence of explosive behaviour in price dynamics and heteroscedasticity affect the size of unit root and cointegration tests and can therefore bias the long-term relationships results. A robustness check using weekly data is therefore imperative to ensure that results are valid. Thus, we first test our weekly time series for explosive behaviour using the recursive test procedure proposed by Phillips, Shi, and Yu (2015), which has proved to be more robust than the Phillips, Wu and Yu (2011) test in the presence of multiple explosive episodes. Second, as the PSY test allows us to reject the hypothesis of an explosive behaviour at the 5 % level for most of the studied prices[15], we apply all unit root and cointegration tests to our weekly data. The results are consistent with the ones using daily data[16].

4. Results

4.1. Time series properties of prices

As discussed in the previous part, we initially investigate the existence of structural changes in the deterministic components of our data using the test proposed by Perron and Yabu (2009)[17]. Table 2 reports the test statistic Exp-W_{RQF} and the date of the structural break detected for each price.

The null hypothesis of absence of a structural break in both the level and slope of the time trend is rejected for series under scrutiny in our study, suggesting that there is at least one structural change in each price series. This break occurs in 11/2010 for ZEE, NBP and PEG North, in 2012 for PEG South, CEGH, TTF, NCG, Gaspool, and JKM, in 2008 for Henry Hub and Coal and in 2013 for oil. Therefore, it is important to account for possible breaks when investigating the stationarity of our variable, and standard unit root tests, suggesting that all prices are integrated of order one, loose their explanatory power[18].

[14] For the analysis, we rely on the R-package APT written by Changyou Sun (2011).
[15] See Table A.3. in the Appendix.
[16] The results of these tests are available in the online Appendix.
[17] We use the GAUSS code kindly provided by Pierre Perron (http://people.bu.edu/perron/code.html).
[18] See Table A.1. in the Appendix for results concerning standard unit root tests.

Table 2. Perron-Yabu test for structural changes in the deterministic components

	Exp- W-RQF	Break date	cv(1%)	cv(5%)	cv(10%)
Panel A: Gas prices					
Belgium (ZEE)	194.683	24/11/2010	4.47	3.12	2.48
U.K. (NBP)	139.704	22/11/2010	4.47	3.12	2.48
France (PEG South)	28.286	01/10/2012	4.48	3.13	2.49
France (PEG North)	54.407	22/11/2010	4.48	3.13	2.49
Austria (CEGH)	130.766	03/04/2012	4.48	3.13	2.49
Netherlands (TTF)	397.085	26/08/2012	4.48	3.13	2.49
Germany (Gaspool)	389.331	03/09/2012	4.48	3.13	2.49
Germany (NCG)	69.432	03/05/2010	4.48	3.13	2.49
U.S. (Henry Hub)	40.186	11/12/2008	4.48	3.13	2.49
Japan-Korean (JKM)	27.221	04/06/2012	4.48	3.13	2.49
Panel B: Oil and Coal					
Oil	116.286	05/05/2013	4.48	3.13	2.49
Coal	19.719	10/10/2008	4.48	3.13	2.49

Note: Trimmer parameter is equal to 0.15. The critical values are taken Table 2c of Perron and Yabu (2009).

Table 3 provides results of the GLS-based unit root test from Carrion-i-Silvestre *et al.* (2009)[19].

Table 3. Results of Carrion-i-Silvestre *et al.* (2009) unit root tests with structural breaks

	P_T^{GLS}	MP_T^{GLS}	MZ_α^{GLS}	MSB^{GLS}	MZ_t^{GLS}	Numbers of breaks
Austria (CEGH)	13.91	12.88	-29.42	0.129	-3.90	4
	[6.77]	[6.77]	[-51.10]	[0.098]	[-5.03]	
Belgium (ZEE)	10.34	8.32	-42.21	0.108	-4.59	4
	[6.91]	[6.91]	[-48.30]	[0.101]	[-4.86]	
Netherlands (TTF)	9.03	7.602	-45.39	0.105	4.76	4
	[6.54]	[6.54]	[-50.32]	[0.099]	[-4.99]	
U.K. (NBP)	10.02	7.86	-44.63	0.105	-4.72	4
	[6.59]	[6.59]	[-50.48]	[0.099]	[-5.01]	
France (PEG North)	12.04	11.06	-24.58	0.142	-3.51	3
	[5.90]	[5.90]	[-44.59]	[0.105]	[-4.70]	
France (PEG South)	5.68	5.58	-29.768	0.129	-3.85	4
	[5.56]	[5.56]	[-28.34]	[0.126]	[-3.79]	
Japan-Korean (JKM)	19.51	18.53	-20.05	0.157	-3.16	4
	[6.99]	[6.99]	[-50.13]	[0.099]	[-4.99]	
U.S. (Henry Hub)	13.39	11.11	-33.82	0.121	-4.11	4
	[6.80]	[6.80]	[-51.05]	[0.099]	[-5.05]	
Germany (Gaspool)	10.141	9.288	-37.13	0.115	-4.304	4
	[6.49]	[6.49]	[-50.43]	[0.099]	[-5.00]	
Germany (NCG)	10.02	9.74	-16.87	0.171	-2.89	1
	[5.21]	[5.21]	[-30.17]	[0.126]	[-3.89]	
Oil (Index)	251.70	237.31	-1.07	0.496	-0.53	5
	[6.79]	[6.79]	[-57.11]	[0.093]	[-5.31]	
Coal	34.96	33.63	-10.25	0.219	-2.25	4

[19] We use the GAUSS code kindly provided to us by Josep Lluis Carrion-i-Silvestre (http://www.eco.ub.es/~carrion/Welcome.html).

[6.75]	[6.75]	[-48.78]	[0.101]	[-4.92]

Note: Critical values for the 1 % level significance are in brackets. The test is implemented for model III, where the structural break affects both the level and the slope of the time trend. P_T^{GLS} *is the feasible point optimal test,* MP_T^{GLS} *is the modified point optimal test,* MZ_α^{GLS} *is the modified Phillips-Perron* MZ_α *test,* MSB^{GLS} *is the modified Sargan-Bhargava test, and* MZ_t^{GLS} *is the modified Phillips-Perron* MZ_t *test.*

It reveals that all of the price series under scrutiny are non-stationary. Indeed, the null hypothesis of the presence of a unit root with *m* structure cannot be rejected for each variable at the 1% level. Nevertheless, the null hypothesis is rejected at the 1% level for the first difference of our variables, suggesting that they are integrated of order one (I(1)), as shown in previous studies (Siliverstos *et al.*, 2005; Ramberg and Parsons, 2015).

4.2. Structural breaks and cointegration tests

Table 4 reports the results of the more general formulation of the Gregory-Hansen test, which allows a regime shift in which intercept, slope coefficients and trend change (Model 4). Panel A displays results concerning the cointegration between European gas prices and HH. According to both Z_t and Z_a statistic tests, the null hypothesis of no cointegration is rejected at the 5% level in all bivariate tests, with the exception of CEGH and HH. Two closely related reasons can be considered to explain this latter result of no cointegration between the CEGH and the HH. First, most of the hubs considered in this study are located in Northern or Western Europe. The CEGH is, on the other hand, positioned in Central Europe, which gives it a particular role, directly or indirectly influenced by the reality of gas flows between Russia, Ukraine and Europe. The manifold tensions that have plagued Russian-Ukrainian relations over the past ten years have resulted in temporary suspensions of Russian gas supplies to Ukraine and, as a result, a temporary change in European gas flows, traditionally oriented from east to west. Secondly, and as Petrovski (2015) points out, physical bottlenecks at Oberkappel (Austria), the interconnection point between the German MEGAL pipeline and the bi-directional WAG pipeline, may explain the disconnection between CEGH and NCG prices in Germany and therefore, in our study, with those of the HH.

Results are very similar for the JKM since the null hypothesis of no cointegration between Asian and American prices cannot be rejected over the period studied. Consequently, it is reasonable to assume that there has been no cointegration between the JKM and Henry Hub since 2009. Conversely, we note that there is a cointegration relationship between European prices and HH, but it exhibits a structural break. This break could be interpreted as the verification of one of the first conditions for demonstrating the integration of these two regional areas. However, this statement should be qualified inasmuch as different causes can be conducive to the same outcome, i.e., a common dependence upon oil prices. In reality, as highlighted by Neumann (2009), Ritz (2014) and Oglend *et al.* (2015), this result testifies to the fact that U.S. gas markets have profoundly changed with the shale gas boom.

Table 4. Results of the Gregory and Hansen (1996b) on cointegration with one structural break

Panel A European gas prices, Japan-Korean price and Henry Hub

	Austria	Belgium	Netherlands	France North	France South	Germany (NCG)	Germany (Gaspool)	U.K. (NBP)	Japan-Korean
ADF	-4.99	-7.10***	-6.43***	-6.45***	-7.16***	-5.75**	-6.39***	-8.03***	-3.73
Z_t	-4.47	-8.68***	-5.46***	-6.01**	-6.93***	-5.70**	-5.36*	-8.47***	-3.64
Z_a	-46.84	-149.63***	-99.77***	-82.87***	-97.97***	-71.44***	-97.84***	-159.95***	-27.37
Break date	03/03/2012	06/10/2010	30/10/2010	27/10/2010	03/03/2012	03/03/2012	28/10/2010	28/10/2010	24/06/2012
Obs.	14/09/2009-12/01/2018	12/01/2004-12/01/2018	12/01/2004-12/01/2018	01/12/2005-12/01/2018	25/09/2009-12/01/2018	01/10/2007-12/01/2018	12/01/2004-12/01/2018	12/01/2004-12/01/2018	02/02/2009-12/01/2018

Panel B European gas prices and Japan-Korean price

	Austria	Belgium	Netherlands	France North	France South	Germany (NCG)	Germany (Gaspool)	U.K. (NBP)
ADF	-5.52*	-7.39***	-6.23***	-6.28***	-8.27***	-5.94**	-6.18***	-6.88***
Z_t	-4.81	-6.92***	-6.43***	-6.12**	-8.26***	-5.72**	-6.33**	-7.14***
Z_a	-61.09**	-95.46***	-94.98***	-86.53***	-135.93***	-75.75***	-88.96***	-105.82***
Break date	28/04/2011	13/05/2010	13/05/2010	13/05/2010	12/04/2011	13/05/2010	13/05/2010	31/10/2014
Obs.	14/09/2009-12/01/2018	02/02/2009-12/01/2018	02/02/2009-12/01/2018	02/02/2009-12/01/2018	25/09/2009-12/01/2018	02/02/2009-12/01/2018	02/02/2009-12/01/2018	12/01/2004-12/01/2018

Panel C Gas and oil prices

	Austria	Belgium	Netherlands	France North	France South	Germany (NCG)	Germany (Gaspool)	U.K. (NBP)	Japan-Korean	Henry Hub
ADF	-5.41*	-8.03***	-7.80***	-7.64***	-6.07***	-6.67***	-7.79***	-8.86***	-3.95	-5.85**
Z_t	-4.75	-9.91***	-7.01***	-6.88***	-7.00***	-6.52***	-6.99***	-10.39***	-3.19	-5.79**
Z_a	-56.67*	-192.34***	-157.56***	-102.84***	-96.75***	-94.76***	-156.93***	-210.13***	-20.08	-68.28**
Break date	12/11/2010	13/03/2006	05/11/2010	13/05/2010	08/03/2014	13/05/2010	11/05/2010	12/03/2006	10/05/2014	23/11/2011

Panel D Gas and coal prices

	Austria	Belgium	Netherlands	France North	France South	Germany (NCG)	Germany (Gaspool)	U.K. (NBP)	Japan-Korean	Henry Hub
ADF	-5.67**	-8.13***	-6.62***	-6.71***	-7.01***	-5.64**	-6.88***	-8.54***	-4.28	-6.33***
Z_t	-5.10	-8.91***	-6.04***	-6.72***	-8.43***	-5.41*	-5.86**	-9.57***	-4.22	-6.16***
Z_a	-62.53**	-157.79***	-116.81***	-94.16***	-139.87***	-65.19**	-112.08***	-179.64***	-30.02	-77.92***
Break date	03/03/2012	02/03/2012	03/03/2012	03/03/2012	08/03/2014	03/03/2012	03/03/2012	03/03/2012	18/04/2014	05/10/2012
Obs.	14/09/2009-12/01/2018	18/08/2006-12/01/2018	18/08/2006-12/01/2018	18/08/2006-12/01/2018	25/09/2009-12/01/2018	01/10/2007-12/01/2018	18/08/2006-12/01/2018	18/08/2006-12/01/2018	02/02/2009-12/01/2018	18/08/2006-12/01/2018

*Note: We consider the test that allows a break in the constant, the slope and the trend. The asterisks ***, ** and *denote the rejection of the null hypothesis at the1%, 5% and 10% levels, respectively. The critical values are taken from Table 1 of Gregory and Hansen (1996b).*

Prior to this "revolution", the integration between gas and oil prices was enabled by substitution possibilities between oil and gas. In the European case, the prevalence of oil-indexed long-term contracts ensured the existence of a long-term relationship. Due to the shale gas revolution, the growth in the U.S. gas supply outpaced the increase in demand. Combined with low LNG export capabilities, this increase led to a surge in inventory levels and pushed gas prices off a cliff, whereas they did not fall so precipitously in other parts of the world. Furthermore, we shed light on the fact that the different breaks detected in the relationship between European and American gas prices appear to coincide. Indeed, for five European gas prices, the break date in the cointegration relationship is identified in October 2010. Consistent with Asche *et al.* (2013), this result provides further evidence of integration of the European market because the break date is identical among almost all European prices and the Henry Hub. A cointegration relationship with a structural break is also confirmed for all European prices with the Japan-Korean Marker. The structural break appears to occur around May 2010 for almost all European prices. However, these results must be interpreted in light of the cointegration relationship between natural gas and oil prices. For the latter, we indeed reject the null hypothesis of no cointegration in almost all cases. Thus, the cointegration relationship between natural gas and oil prices displays a structural change over the period considered. For almost all European gas prices, the break date occurs in 2010, confirming that the relationship between natural gas and oil prices evolves through time and appears to be nonlinear as suggested in particular by Asche *et al.* (2017). Only the JKM appears not to be cointegrated with oil in the period 2009–2018. Finally, we also find that all natural gas prices are cointegrated (with a structural break) with coal prices with the exception of the CEGH. Here, the break for European prices is the same for almost all prices, suggesting that European prices share a common stochastic trend, and is detected for May 2010. For the HH, the break is found in March 2006[20]. Not surprisingly, Table A.2. highlights that all European gas prices are co-integrated around a structural break.

We then use Maki's (2012)[21] approach to test for more than one break in the cointegration relationship between European gas prices, Henry Hub, the JKM, oil and coal prices. Results of Maki's (2012) cointegration test are demonstrated in Table 5.

The results imply that the null hypothesis of no cointegration between almost all European prices and Henry Hub can be rejected at the 5% level, with the exceptions being CEGH and French PEG-North. The test reveals that three structural shifts are detected in the cointegration relationships. The same results are found for natural gas and oil prices, with the exception of the JKM, confirming our previous conclusion that the JKM is not cointegrated with oil, even when multiple breaks are allowed in the cointegration test.

[20] Because this work is not dedicated, as such, to the analysis of the link between natural gas prices and other energy sources, we do not investigate further the significance of this break date.
[21] We are very grateful to Daiki Maki for providing us the GAUSS code to implement cointegration tests.

Table 5. Maki's (2012) bivariate cointegration tests results

European gas prices and JKM with U.S. Henry Hub			
	Statistics	Critical value	Break dates
Belgium (ZEE)	-6.971**	-6.524	03/10/2006; 07/11/2008; 03/06/2014
U.K. (NBP)	-6.600**	-6.524	20/03/2006; 07/11/2008; 20/06/2013
Netherlands (TTF)	-6.775**	-6.524	03/10/2006; 10/11/2008; 03/06/2014
Germany (Gaspool)	-6.877**	-6.524	03/10/2006; 10/11/2008; 30/10/2014
Germany (NCG)	-7.294***	-6.524	20/03/2009; 16/12/2012; 04/06/2014
Japan-Korean	-5.785	-6.524	
Austria (CEGH)	-5.250	-6.524	
France (PEG South)	-7.619***	-6.524	09/12/2012; 20/02/2014; 10/01/2016
France (PEG North)	-4.820	-6.524	
Gas prices with oil			
Belgium (ZEE)	-8.455***	-6.524	20/03/2006; 31/12/2009; 28/03/2013
U.K. (NBP)	-8.138***	-6.524	20/03/2006; 31/12/2009; 20/06/2013
Netherlands (TTF)	-7.514***	-6.524	03/10/2006; 10/11/2008; 22/05/2014
Germany (Gaspool)	-7.646***	-6.524	03/10/2006; 10/11/2008; 22/05/2014
Germany (NCG)	-6.600**	-6.524	06/10/2009; 07/02/2012; 31/10/2013
Japan-Korean	-5.547	-6.524	
Austria (CEGH)	-5.324	-6.524	
France (PEG South)	-7.205**	-6.524	02/10/2011; 12/04/2013; 24/10/2014
France (PEG North)	-7.467***	-6.524	11/03/2008; 08/12/2009; 07/02/2012
United States (HH)	-5.586**	-5.541	28/09/2009
European gas prices with Japan Korean (JKM)			
Belgium (ZEE)	-6.808***	-6.100	05/07/2010; 29/03/2013
U.K. (NBP)	-5.877*	-6.100	21/06/2013; 13/11/2015
Netherlands (TTF)	-6.781***	-6.100	30/09/2001; 29/03/2013
Germany (Gaspool)	-5.821***	-5.541	13/05/2010
Germany (NCG)	-6.303**	-6.100	29/03/2013; 03/04/2016
Austria (CEGH)	-5.239	-6.100	
France (PEG South)	-8.533***	-6.100	02/10/2011; 12/04/2013
France (PEG North)	-6.781***	-6.100	08/06/2010; 10/04/2013

*Note: Critical values at the 0.05 significance level are from Table 1 of Maki (2012). *, **, *** denotes the rejection of the null hypothesis of no cointegration. Break dates are obtained by using Maki's (2012) cointegration test.*

4.3. Long-term estimates

Because the presence of cointegration between natural gas and oil prices has been demonstrated, we can estimate the long-term relationship between all pairs of prices. We employ the Dynamic Ordinary Least Squares (DOLS) approach to estimate all long-term relationships:

$$P_t^1 = \alpha + \beta P_t^2 + \varepsilon_t \quad (5)$$

Note that we allow for the presence of a trend in the long-term relationship, as tested previously using the Gregory and Hansen (1996b) and Maki (2012) cointegration tests.

Tables 6 and 7 report the long-term estimates (Eq. 5), including the test for the LOP that tests the hypothesis that the slope coefficient is equal to one for the pre- and post-structural break periods specific to each pair of prices and detected in Gregory and Hansen (1996b) and Maki's (2012) cointegration tests. Table 6 focusses on the European gas market, and Table 8 emphasizes results for European, U.S. and oil prices.

Table 6. Estimation of long-term coefficients (DOLS, Bartlett Kernel, Newey-West fixed bandwidth)- European natural gas market

	With U.K. NBP			With Netherlands TTF		
	First period	Second period	Break date	First period	Second period	Break date
Austria (CEGH)	0.852***	0.564***	28/05/2016	0.842***	0.908***	06/02:2015
	(0.020)	(0.033)		(0.018)	(0.013)	
LOP	*51.35***	*177.27***		*74.45***	*49.36***	
Belgium (ZEE)	0.852***	0.987***	23/06/2006	1.695***	1.020***	15/12/2006
	(0.041)	(0.006)		(0.087)	(0.006)	
LOP	*13.05***	*3.94***		*63.56***	*10.80***	
Netherlands (TTF)	0.441***	0.960***	04/10/2006			
	(0.048)	(0.009)				
LOP	*135.12***	*17.79***				
Germany (Gaspool)	0.429***	0.945***	04/10/2006	0.985***	0.987***	22/04/2008
	(0.047)	(0.010)		(0.002)	(0.004)	
LOP	*143.84***	*28.82***		*42.61***	*10.14***	
Germany (NCG)	1.018***	0.960***	05/11/2009	0.920***	0.975***	31/03/2009
	(0.021)	(0.012)		(0.016)	(0.004)	
LOP	*0.743*	*9.65***		*22.86***	*32.22***	
France (PEG North)	0.826***	0.957***	28/04/2008	0.535**	0.993***	07/09/2006
	(0.022)	(0.010)		(0.219)	(0.005)	
LOP	*59.53***	*19.14***		*4.47***	*1.945*	
France (PEG South)	0.838***	0.968***	24/10/2014	0.868***	1.010***	21/10/2014
	(0.023)	(0.077)		(0.019)	(0.060)	
LOP	*47.47***	*0.167*		*46.36***	*0.044*	

*Note: The different periods correspond to the break dates detected using the Gregory and Hansen (1996b) cointegration test. *, **, *** significant at the 10%, 5%, and 1% level, respectively. A Wald test of the null hypothesis of $\beta=1$ has been implemented to test for the LOP hypothesis.*

Unsurprisingly, our results show that most of the European gas markets considered in this study have become integrated in recent years, with the CEGH being the exception for the reasons mentioned above. The structural break tests clearly show that 2006 was a pivotal year in this regard for the Belgian, Dutch and German (Gaspool) markets. However, this statement does not apply to all European markets, due in particular to differences in the timeframes of the price series considered here. The estimated cointegrating vectors between these prices (except CEGH) thus range between (1,-0.9) and (1,-1.02) in the second periods of the study. Furthermore, the LOP is accepted between PEG South and NBP, and between PEG South and PEG North and TTF. This result complements the previous analysis of Renou-Maissant (2012) which is based on industrial prices to end-users, using more European prices and for a more recent period. Although there are exceptions, it appears that there is a strong integration of natural gas markets in continental Europe, particularly between France South, Netherlands and Germany (Gaspool). In contrast to Renou-Maissant (2012) however, we find that the Belgian market is integrated with some other continental markets, even including the U.K.

Furthermore, it appears that almost all continental markets are integrated with the NBP, showing what might be interpreted as an increasing convergence process between continental countries and the U.K since the study of Renou-Maissant (2012). Beyond this simple fact, however, much can be said of the nature of this convergence process. The NBP and the TTF (to a lesser extent) have been the most liquid gas hubs in Europe because of the comprehensive liberalization process through which they have been. Hence, one can ask whether this higher degree of price interdependence is the result of an increased reliance in Europe on NBP and TTF as reference market prices or, conversely, the consequence of a deepening of gas continental European markets as a premise of the single European market wanted by regulatory authorities.

If we investigate the integration between the European and the U.S. gas markets, the picture appears to be quite different (Table 7). First, all of the Wald tests reveal that the hypothesis of perfect market integration between Europe and the U.S., and between Europe and Japan-Korea is rejected at the 1% level. This result remains valid in post- and pre-break periods. Unsurprisingly, this point demonstrates that even with the development of LNG and fall in transportation costs, there remains no perfect integration of the natural gas market.

As suggested in the introduction, the rise of the American LNG could encourage this integration. However, the first U.S. LNG exports began in 2016; thus, it remains too early to measure their effects. This point is even truer given that cost logic must naturally be considered and that, from this point of view, American LNG remains on average more expensive than land-based gas delivered to Europe. However, results suggest that the degree of integration between Europe and the U.S. has increased, particularly in the last period of study (since May 2014). Indeed, the long-term coefficient has recorded shifts over the whole period as revealed by cointegration tests. Until 2006 (first period), European and U.S. gas prices appears to co-evolve, and on average, this coefficient was approximately 0.5. Nevertheless, this coefficient is not significant for NBP and Gaspool in this first period (2004–2006). For all European prices, with the exception of NBP, the long-term coefficient is small until 2014, suggesting a weak integration of markets. However, after 2014 (fourth period), the cointegrating vector is high, and the long-term coefficient is on average 0.65, revealing a higher degree of integration between European and U.S. gas markets. This point is particularly true for German Gaspool, with a long-term coefficient of 0.876 for the period October 2014–January 2018.

Conclusions concerning co-movements between European and Japan-Korean prices are different. Indeed, our results reveal a strong cointegrating vector in the first period, i.e., between February 2009 and September 2011, for TTF, for instance, followed by a period of decoupling of almost all European prices and the JKM. Then, in the last period, i.e., since March 2013 for almost all prices, the cointegrating vector is again important and on average approximately 0.5.

If we analyse these results in the light of co-movements between natural gas and oil prices, new insights appear (Table 7).

Table 7. Estimation of long-term coefficients (DOLS, Bartlett Kernel, Newey-West fixed bandwidth)

	With U.S. Henry Hub				With Japan Korean (JKM)			With oil index			
	First period	Second period	Third period	Fourth period	First period	Second period	Third period	First period	Second period	Third period	Fourth period
Belgium (ZEE)	0.506***	0.213*	0.214**	0.636***	0.836***	-0.09	0.504**	-2.936***	1.796***	0.407**	0.635***
	(0.144)	(0.122)	(0.091)	(0.075)	(0.147)	(0.044)	(0.033)	(0.683)	(0.089)	(0.165)	(0.082)
LOP	*11.723****	*41.48****	*46.64****	*23.10****	*1.237*	*590.97****	*16.84****				
U.K. (NBP)	-0.131	0.460***	0.680***	0.470***	0.503***	0.269***	0.577***	-3.085***	1.804***	0.376***	0.622***
	(0.192)	(0.131)	(0.118)	(0.077)	(0.067)	(0.093)	(0.035)	(0.716)	(0.091)	(0.155)	(0.084)
LOP	*34.53****	*17.07****	*7.26****	*45.57****	*59.26****	*61.74****	*139.98****				
Netherlands (TTF)	0.109	0.212*	0.202*	0.624***	0.688***	-0.060	0.488***	1.072***	1.115***	1.457***	0.701***
	(0.077)	(0.113)	(0.110)	(0.075)	(0.155)	(0.040)	(0.033)	(0.326)	(0.227)	(0.072)	(0.066)
LOP	*133.45****	*48.65****	*51.79****	*24.93****	*4.053****	*673.803****	*237.17****				
Germany (Gaspool)	0.099	0.252**	0.046	0.876***	0.672***	0.470***		0.986***	1.214***	1.442***	0.681***
	(0.076)	(0.112)	(0.111)	(0.054)	(0.144)	(0.018)		(0.324)	(0.221)	(0.069)	(0.064)
LOP	*139.43****	*44.46****	*73.79****	*5.25***	*5.17***	*896.77****					
Germany (NCG)	0.559***	0.489***	0.083	0.621***	0.517***	0.290***	0.454***	1.215***	0.862***	0.032	0.702***
	(0.089)	(0.070)	(0.078)	(0.075)	(0.072)	(0.059)	(0.037)	(0.058)	(0.362)	(0.331)	(0.071)
LOP	*23.91****	*51.00****	*129.57****	*25.30****	*45.05****	*144.05****					
France (PEG South)	0.559***	0.498***	0.083	0.621***	0.099	0.070	0.669***	2.011	-0.097	-0.184	1.004***
	(0.089)	(0.070)	(0.078)	(0.075)	(0.131)	(0.062)	(0.042)	(1.364)	(0.131)	(0.906)	(0.085)
LOP	*23.90****	*51.00****	*129.57****	*25.30****	*47.37****	*222.17****	*60.68****				
France (PEG North)	1.100***	0.319***			0.737***	-0.051	0.494***	2.414***	0.924***	0.419	0.661***
	(0.054)	(0.069)			(0.142)	(0.041)	(0.033)	(0.355)	(0.067)	(0.329)	(0.072)
LOP	*3.34**	*97.17****			*3.43**	*644.93****	*233.55****				
U.S. Henry Hub								0.944***	0.013		
								(0.052)	(0.045)		

*Note: The different periods correspond to the different break dates that have been selected by Maki's (2012) cointegration test for each pair of prices. *, **, *** significant at the 10%, 5%, and 1 % level, respectively. A Wald test of the null hypothesis of β=1 has been implemented to test for the LOP hypothesis.*

Indeed, results in Table 7 highlight a less intense long-term relationship between some natural gas and oil prices in the last period, i.e. since May 2014 (TTF and Gaspool), and in the third period, i.e. since December 2009 (ZEE and NBP). Overall, it seems that the long-run relationship between gas and oil prices is less intense in the last two periods that in the first two periods. On the one hand, we find a stronger cointegrating vector between European and U.S. gas prices on average. On the other hand, we find a lower cointegrating vector between European gas and oil prices. The association of these two phenomena is, in our view, indicative of the deep transformation of the market towards greater integration or, at the very least, of an increase in physical arbitrage strategies.

4.4. Threshold cointegration and asymmetric ECM

Table 8 reports the results of the asymmetric cointegration test proposed by Enders and Siklos (2001), which tests the null hypothesis of no cointegration against the alternative of threshold cointegration (Eq. 3). Notice that we present only results for the consistent-MTAR (or TAR) models selected according to the minimum value of AIC and BIC.

Table 8. Threshold cointegration tests for natural gas (Enders and Siklos, 2001)

	NBP and Henry Hub	Henry Hub and JKM	TTF and Henry Hub	NBP and TTF	NBP and JKM	TTF and JKM
Model	Consistent MTAR	Consistent TAR	Consistent MTAR	Consistent MTAR	Consistent MTAR	Consistent MTAR
Lag	2	1	2	2	2	2
Threshold	0.032	-0.143	0.027	-0.021	-0.005	-0.004
ρ_1	-0.054***	-0.015***	-0.026***	-0.059***	-0.022***	-0.035***
	(-8.667)	(-3.872)	(-4.080)	(-6.590)	(-3.590)	(-6.242)
ρ_2	-0.006*	-0.005	-0.009***	-0.153***	-0.041***	-0.011*
	(-1.793)	(-1.417)	(-3.060)	(-12.235)	(-5.376)	(-1.693)
AIC	-11594.04	-13702.55	-13283.78	-14252.86	-10536.16	-11595.58
BIC	-11561.23	-13678.66	-13251.57	-14220.64	-10506.30	-11595.72
$Q_{LB}(4)$	0.00	0.234	0.00	0.00	0.068	0.00
Φ: $\rho_1 = \rho_2 = 0$	39.070	8.489	12.992	92.86	20.945	20.904
Critical values (10 %)	6.47	6.41	6.47	6.47	6.47	6.47
Critical values (5 %)	7.53	7.39	7.53	7.53	7.53	7.53
Critical values (1 %)	9.76	9.66	9.76	9.76	9.76	9.76
F: $\rho_1 = \rho_2$	47.449***	3.152*	5.829**	39.828***	3.791*	7.967***

*Note: t-statistics are in parentheses. Q_{LB} is the Ljung–Box statistic for 4 lags. Critical values for the distribution of Φ come from Table 1 of Wane et al. (2004). Lags are chosen according to the BIC. *, **, *** denote significance at the 10%, 5%, and 1% levels, respectively.*

First, the Φ statistics lead us to reject the null hypothesis of no cointegration at the 5% level for all specifications. Furthermore, the null hypothesis of symmetric adjustment towards long-term equilibrium is rejected at the 10% level in all cases, according to the F-statistic. Thus, our results strongly suggest that for NBP and HH, HH and the JKM, TTF and HH and TTF and the JKM, the adjustment mechanism is asymmetric (nonlinear). In contrast to our previous results, we find that U.S. and Japan-Korean markets have been co-integrated since

2009, but the relationship is asymmetrical. Moreover, if we analyse the value and significance of ρ_1 and ρ_2, particularly interesting results can be highlighted. For instance, if we consider the relationship between NBP and HH, we find that the estimated threshold is 0.032 and that the point estimate for the adjustment is -0.054 for positive shocks and -0.006 for negative shocks. This outcome reveals that positive discrepancies from long-term equilibrium arising from an increase in U.K. prices or a decrease in American prices (such that $\Delta\varepsilon_{t-1}>0.032$) are eliminated more quickly, at a rate of 5.4% per day. In contrast, negative deviations from long-term equilibrium resulting from decreases in the U.K. prices or increases in the HH take more time to be adjusted (0.6% per day). Consequently, there is substantially slower convergence for deviations below the threshold than for deviations above the threshold. This result is consistent with fact that the relationship between NBP and HH is highly asymmetric and that U.K. prices take more time to adjust below the threshold. We can identify a similar threshold for TTF (0.027), but the point estimate for positive shocks is only -0.026, suggesting that TTF adjusting to HH requires more time than for the U.K. NBP to do so. Caution is clearly necessary when interpreting such results, but it must be acknowledged that this difference could indicate that market arbitrage opportunities are more important between NBP and HH than between TTF and HH.

Our results are different for the relationship between HH and the JKM. In spite of a higher threshold (-0.143) and although ρ_2 is not significant at the 5% level, ρ_1 is indeed significant at the 1% level and equal to -0.015. Thus, only deviations from long-term equilibrium resulting from an increase in American prices or a decrease in the JKM are eliminated and at a lower rate than between HH and NBP or between HH and TTF. We also find that asymmetric cointegration prevails between European prices (NBP and TTF) and the JKM. Providing at this stage of our work an undisputable economic interpretation of these econometric results appears an arduous task and would require further investigation. Intuitively, a greater role played by spot markets could however be part of the explanation. In a recent context of rather oversupplied markets in which East-Asia and, to a lesser extent, Europe were the most resilient areas, any departure from long-term equilibria in the form of a short-term increase in NBP or JKM prices might have been viewed by exporting countries as a source of profitable arbitrage. This arbitrage could in turn have led to an important flow of natural gas to these countries, contributing to greater price interdependency.

Because we have demonstrated that there is a cointegration relationship between these four natural gas prices using the methodology proposed by Enders and Siklos (2001), we can estimate the corresponding TECM (Eq. 4). Tables 9 and 10 report the results. Table 9 focuses on the analysis of European and U.S. markets, whereas Table 10 analyses the integration of European and U.S. gas markets with the Japan-Korean market.

Table 9. Results of the asymmetric error correction model with threshold cointegration (European and U.S. markets)

	U.K NBP (ΔP_t^1)	U.S. HH (ΔP_t^2)	Netherlands TTF (ΔP_t^3)	U.S. HH (ΔP_t^2)	U.K NBP (ΔP_t^1)	Netherlands TTF (ΔP_t^3)
ΔNBP_{t-1}^{+}	-0.188***	0.003			-0.113***	-0.009
	(0.023)	(0.008)			(0.028)	(0.023)
ΔNBP_{t-2}^{+}	-0.020	-0.004			-0.050*	0.071***
	(0.024)	(0.008)			(0.028)	(0.023)
ΔNBP_{t-1}^{-}	0.066***	-0.008			0.070**	0.303***
	(0.023)	(0.008)			(0.029)	(0.023)
ΔNBP_{t-2}^{-}	-0.252***	-0.024***			-0.216***	-0.061***
	(0.022)	(0.008)			(0.028)	(0.023)
ΔHH_{t-1}^{+}	-0.309***	-0.040*	-0.308***	-0.043*		
	(0.064)	(0.023)	(0.053)	(0.023)		
ΔHH_{t-2}^{+}	-0.091	-0.002	-0.169***	0.003		
	(0.064)	(0.023)	(0.053)	(0.023)		
ΔHH_{t-1}^{-}	0.383***	-0.077***	0.353***	-0.070***		
	(0.073)	(0.026)	(0.060)	(0.026)		
ΔHH_{t-2}^{-}	0.103	0.076***	0.306***	0.065**		
	(0.073)	(0.026)	(0.061)	(0.026)		
ΔTTF_{t-1}^{+}			-0.286***	0.016	-0.076**	-0.285***
			(0.024)	(0.010)	(0.034)	(0.028)
ΔTTF_{t-2}^{+}			-0.043**	0.005	0.079**	-0.093***
			(0.023)	(0.010)	(0.033)	(0.028)
ΔTTF_{t-1}^{-}			-0.242***	-0.010	0.018	-0.417***
			(0.021)	(0.009)	(0.033)	(0.027)
ΔTTF_{t-2}^{-}			-0.260***	-0.002	-0.117***	-0.235***
			(0.022)	(0.009)	(0.033)	(0.027)
ECM_{t-1}^{+}	-0.050***	-0.006***	-0.025***	0.000	0.005	-0.053***
	(0.006)	(0.002)	(0.006)	(0.003)	(0.012)	(0.010)
ECM_{t-1}^{-}	-0.009**	0.000	-0.009***	-0.001	-0.173***	-0.006
	(0.003)	(0.001)	(0.003)	(0.001)	(0.017)	(0.014)
Intercept	0.007***	0.000	0.007***	0.000	0.000	0.000
	(0.002)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)

*Note: Lags are chosen according to the BIC. *, **, *** denote significance at the 10%, 5%, and 1% levels, respectively.*

Our results confirm not only that there is a long-term relationship between NBP and HH but also that the adjustment process towards long-term equilibrium is highly asymmetric. Furthermore, we find that $|\vartheta^{+}| > |\vartheta^{-}|$, which indicates that positive deviations from long-term equilibrium are eliminated more quickly than are negative deviations. They also confirm that the adjustment speed between NBP and HH is greater than that between TTF and HH, suggesting better arbitrage opportunities between NBP and HH. Note that the adjustment speed is higher when NBP reacts to a variation of HH (-0.050) than when HH reacts to a variation of NBP (-0.006). Thus, European markets are more affected by variation in the U.S. market than the reverse. If we compare these results with those related to the integration of two European markets (TTF and NBP), we show that there is a higher adjustment speed both for positive and negative discrepancies for European gas prices.

Table 10 highlights the dependence of European gas prices upon the JKM. Indeed, we find a significant adjustment speed for NBP and TTF, for both negative and positive discrepancies from long-term equilibrium (-0.038 and -0.020 for NBP, and -0.035 and -0.018 for TTF),

although adjustment speed for the JKM to NBP or TTF is never significant. This result shed light on the fact that the JKM remains unaffected by variations of European gas prices in the short term. The same result applies to HH, for which only positive deviations from long-term equilibrium are eliminated. However, these results also stress the fact that market arbitrage opportunities exist between European, U.S. and Japan-Korean natural gas prices.

Table 10. Results of the asymmetric error correction model with threshold cointegration (European, U.S. and Japan-Korean markets)

	U.K NBP (ΔP_t^1)	JKM (ΔP_t^3)	U.S. HH (ΔP_t^2)	JKM (ΔP_t^3)	Netherlands TTF (ΔP_t^2)	JKM (ΔP_t^1)
ΔNBP_{t-1}^{+}	-0.050	0.029				
	(0.031)	(0.027)				
ΔNBP_{t-2}^{+}	0.004	0.000				
	(0.024)	(0.026)				
ΔNBP_{t-1}^{-}	-0.071**	-0.046				
	(0.030)	(0.031)				
ΔNBP_{t-2}^{-}	-0.176***	0.062**				
	(0.029)	(0.032)				
ΔJKM_{t-1}^{+}	-0.032	0.117***	0.184***	0.055*	0.004	0.039
	(0.078)	(0.040)	(0.045)	(0.028)	(0.064)	(0.028)
ΔJKM_{t-2}^{+}	-0.085	0.014			-0.123*	0.092***
	(0.078)	(0.040)			(0.064)	(0.028)
ΔJKM_{t-1}^{-}	0.233***	0.067	0.072	0.124***	0.256***	0.120***
	(0.080)	(0.042)	(0.047)	(0.029)	(0.066)	(0.029)
ΔJKM_{t-2}^{-}	0.207***	0.119***			0.189***	0.130***
	(0.080)	(0.042)			(0.066)	(0.029)
ΔHH_{t-1}^{+}			-0.055*	0.022		
			(0.029)	(0.018)		
ΔHH_{t-2}^{+}						
ΔHH_{t-1}^{-}			-0.104***	0.007		
			(0.032)	(0.020)		
ΔHH_{t-2}^{-}						
ΔTTF_{t-1}^{+}					-0.162***	-0.011
					(0.031)	(0.014)
ΔTTF_{t-2}^{+}					-0.057	0.019
					(0.032)	(0.014)
ΔTTF_{t-1}^{-}					0.035	0.021
					(0.029)	(0.013)
ΔTTF_{t-2}^{-}					0.034	-0.013
					(0.030)	(0.013)
ECM_{t-1}^{+}	-0.020***	-0.001	-0.016***	-0.004	-0.035***	0.003
	(0.005)	(0.005)	(0.004)	(0.003)	(0.006)	(0.003)
ECM_{t-1}^{-}	-0.038***	-0.004	-0.004	0.004	-0.018***	0.004
	(0.010)	(0.003)	(0.004)	(0.003)	(0.006)	(0.003)
Intercept	0.000	0.000	0.000	0.001	0.004***	0.000
	(0.001)	(0.001)	(0.001)	(0.000)	(0.001)	(0.000)

*Note: Lags are chosen according to the BIC. *, **, *** denote significance at the 10%, 5%, and 1% levels, respectively.*

5. Conclusion

Based on a fourteen-year period ending in January 2018, this paper provides new empirical evidence on the relationships between North American, European, and East Asian gas prices. Using not only cointegration tests with one or more structural breaks but also threshold cointegration tests and threshold error-correction models, we highlight several interesting findings and make a useful contribution to the literature on gas market integration from this perspective. In particular, we show that the integration of gas markets has increased in recent years in the sense that long-term relationships between gas prices have, for most of them, strengthened while those between gas prices and oil prices have weakened. Although our results confirm that there is a very strong integration among most of the European gas markets, but clearly no perfect integration between the European and American markets, we do indeed point out that the degree of integration between these two regions has increased, especially after 2014. Concerning Asia, we show that most European markets are, for the most part, cointegrated with the JKM while the latter is not with the HH, when the Gregory and Hansen (1996b) test is used. The increase in the cointegrating vector between U.S. and European gas prices would not have allowed us to conclude that international gas market is getting more and more integrated if it had not been accompanied by a decrease in the cointegrating vector between gas prices and oil. We demonstrate that this is the case. Testing for threshold cointegration, we also reach an interesting result on the existence of an asymmetric adjustment to long-term equilibrium between HH and NBP, but also between HH and the JKM, any positive discrepancies from long-term equilibriums in the form of an increase in the NBP or JKM price requiring a greater time to adjust than negative ones. We suggest that market arbitrages from exporting countries resulting from a growing share of spot transactions could be one of the possible explanations for such an asymmetric convergence.

These various results make this article a useful contribution to the literature on gas market integration, but our approach is not without limitations. Several suggestions about future research that might enrich this paper should therefore be mentioned as concluding remarks. First, considering that European gas hubs play different roles, greater scrutiny should be placed on the causality relationships among European prices to determine whether there is any “dominance effect” of some hubs over the others and to check whether what appears from our results to be an integrated European gas market is not a “trompe l’oeil”. Second, further investigation would obviously be required to apprehend the effect of soaring LNG export capacities from the United States, which are expected to be at full capacity in 2018, on the integration of world natural gas markets. Finally, a greater focus should be placed on the asymmetric nature of the reversion to long-term equilibrium between gas prices.

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Appendix

Figure 1. Prices for the European market (In euro per megawatt-hour, MWh)

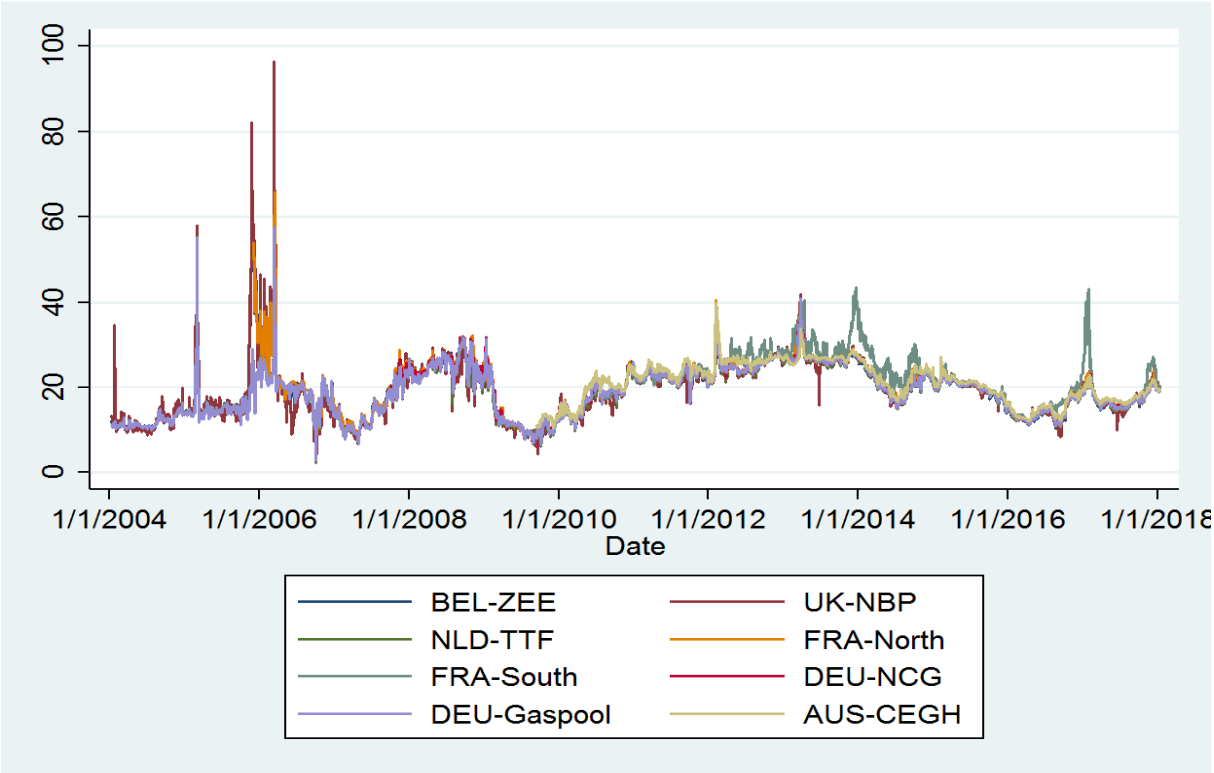

Figure 2. Prices for UK National Balancing Point, US Henry Hub and Japan-Korean Marker (In euro per megawatt-hour, MWh)

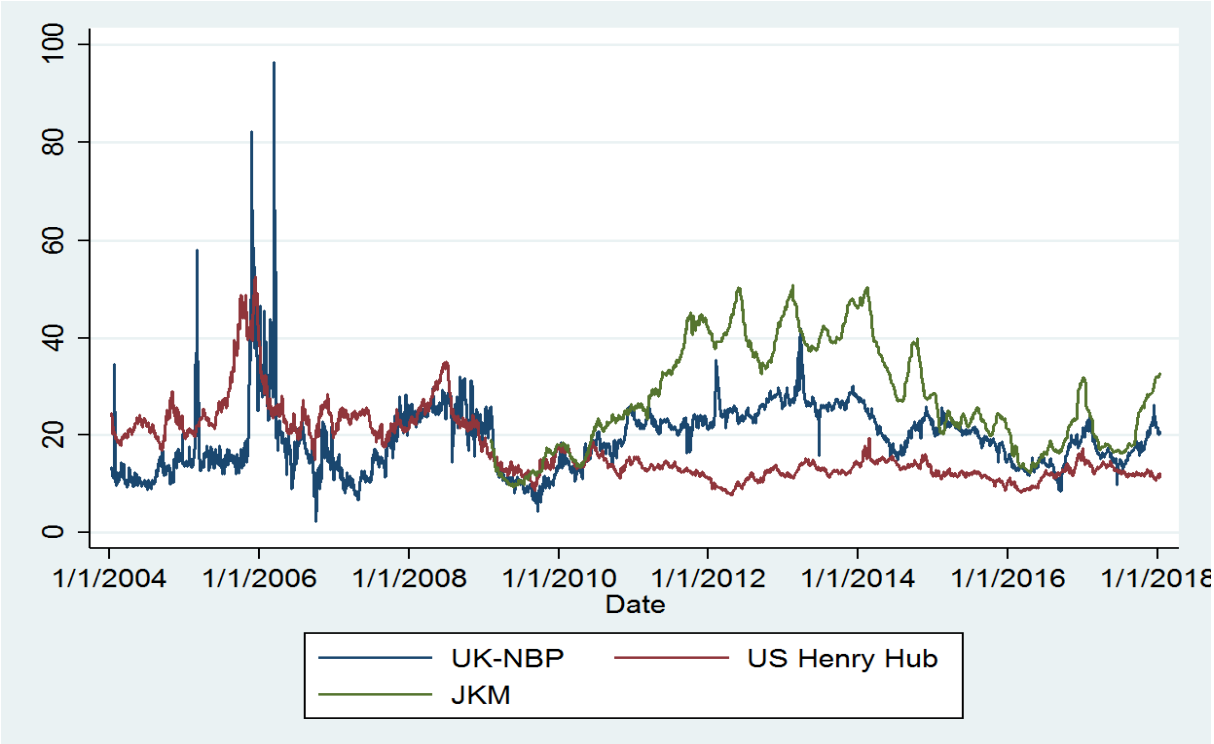

Figure 3. Prices for NBP (Euro per MWh), Henry Hub (Euro per MWh), Coal (Euro per ton and Oil (Index)

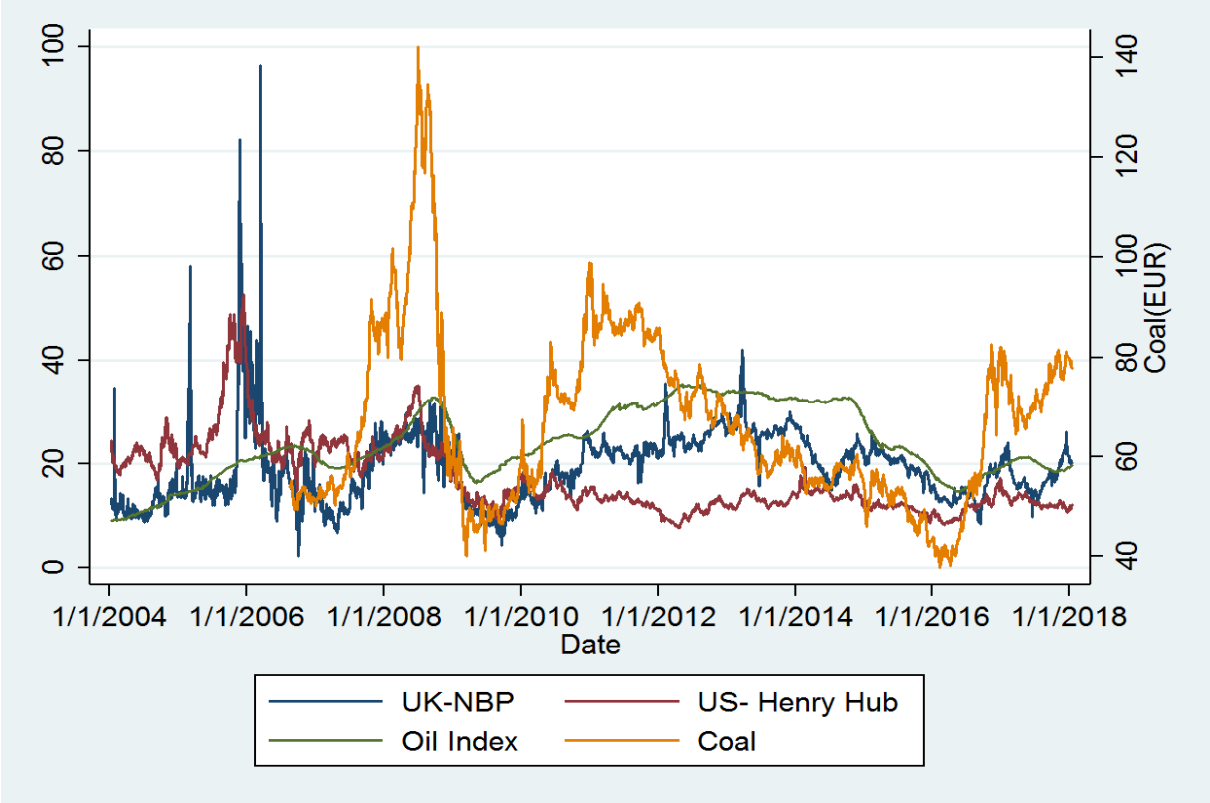

Table A.1. Standard unit-root tests

	ADF				KPSS			
	Level		First diff.		Level		First diff.	
Prices	Intercept	Intercept and trend	Intercept	Intercept and trend	Intercept	Intercept and trend	Intercept	Intercept and trend
Austria (CEGH)	-3.090**	-3.334*	-61.064***	-61.069***	1.340***	1.089***	0.241	0.072
Belgium (ZEE)	-4.738***	-4.821***	-36.099***	-36.103***	0.954***	0.384***	0.027	0.0198
Coal	-1.871	-1.917	-55.348***	-55.353***	0.911***	0.350***	0.104	0.104
Germany (Gaspool)	-4.246***	-4.371***	-26.616***	-26.618***	1.479***	0.504***	0.035	0.020
Germany (NCG)	-2.869**	-2.878	-63.348***	-63.357***	0.651***	0.656***	0.038	0.037
France (PEG North)	-4.335***	-4.349***	-49.927***	-49.931***	0.460***	0.444***	0.117	0.073
France (PEG South)	-3.451***	-3.478**	-26.783***	-26.782***	1.173***	1.160***	0.113	0.032
Japan-Korean (JKM)	-1.499	-1.489	-16.354***	-16.348***	1.444***	1.419***	0.118	0.112
Oil (Index)	-3.314**	-3.139*	-4.365***	-4.319***	2.746***	1.290***	1.018	0.117
Netherlands (TTF)	-3.247**	-3.316*	-19.483***	-19.482***	1.404***	0.477***	0.033	0.021
U.K. (NBP)	-5.166***	-5.310***	-36.585***	-36.589***	1.072***	0.356***	0.021	0.019
U.S. (Henry Hub)	-2.231	-3.405*	-72.047***	-72.052***	5.893***	0.530***	0.0257	0.023

Note: *The lag parameters for ADF tests are selected based on the Schwartz information criteria. Critical values for the null hypothesis of stationarity (KPSS test) are taken from Kwiatkowski et al. (1992, Table 1).*

Table A.2. Results of the Gregory and Hansen (1996b) on cointegration with one structural break for the European gas market

	ADF	Z_t	Z_a	Break date	Observations
ZEE-NBP	-17.33***	-20.33***	-837.07***	23/06/2006	12/01/2004-12/01/2018
TTF-NBP	-13.70***	-24.40***	-1159.48***	04/10/2006	12/01/2004-12/01/2018
PEG North-NBP	-11.96***	-22.07***	-878.53***	28/04/2008	01/12/2005-12/01/2018
PEG South-NBP	-10.15***	-10.83***	-278.23***	24/10/2014	25/09/2009-12/01/2018
NCG-NBP	-14.87***	-17.79***	-750.36***	05/11/2009	01/10/2007-12/01/2018
Gaspool-NBP	-13.64***	-23.72***	-1112.41***	04/10/2006	12/01/2004-12/01/2018
CEGH- NBP	-8.09***	-9.74***	-216.39***	28/05/2016	14/09/2009-12/01/2018
ZEE-TTF	-11.03***	-21.56***	-981.06***	15/12/2006	12/01/2004-12/01/2018
PEG North-TTF	-13.55***	-21.87***	-968.25***	07/09/2006	01/12/2005-12/01/2018
PEG South-TTF	-7.51***	-10.91***	-296.26***	21/10/2014	25/09/2009-12/01/2018
NCG-TTF	-13.37***	-30.22***	-1468.06***	31/03/2009	01/10/2007-12/01/2018
Gaspool-TTF	-15.13***	-33.84***	-1894.50***	22/04/2008	12/01/2004-12/01/2018
CEGH-TTF	-10.15***	-11.95***	-312.98***	06/02/2015	14/09/2009-12/01/2018
ZEE-Gaspool	-11.11***	-20.96***	-935.59***	15/12/2006	12/01/2004-12/01/2018
PEG North- Gaspool	-13.34***	-21.85***	-966.24***	06/10/2008	01/12/2005-12/01/2018
PEG South- Gaspool	-7.48***	-10.66***	-286.53***	21/10/2014	25/09/2009-12/01/2018
NCG-Gaspool	-15.20***	-33.70***	-1764.24***	31/03/2009	01/10/2007-12/01/2018
CEGH-Gaspool	-9.65***	-13.17***	-367.23***	06/02/2015	14/09/2009-12/01/2018
ZEE-NCG	-19.28***	-27.61***	-1238.96***	07/11/2009	01/10/2007-12/01/2018
PEG North-NCG	-15.11***	-28.06***	-1316.64***	20/09/2010	01/10/2007-12/01/2018
PEG South-NCG	-7.40***	-10.87***	-295.60***	21/10/2014	25/09/2009-12/01/2018
CEGH-NCG	-9.64***	-11.93***	-331.54***	24/05/2016	14/09/2009-12/01/2018
ZEE-PEG North	-14.36***	-28.86***	-1376.92***	27/09/2007	01/12/2005-12/01/2018
PEG South-PEG North	-7.75***	-12.34***	-367.58***	21/10/2014	25/09/2009-12/01/2018
CEGH-PEG North	-8.35***	-11.24***	-306.84***	28/05/2016	14/09/2009-12/01/2018
ZEE-PEG South	-7.44***	-11.07***	-303.99***	21/10/2014	25/09/2009-12/01/2018
CEGH-PEG South	-6.79***	-9.12***	-211.93***	08/10/2014	25/09/2009-12/01/2018
ZEE-CEGH	-8.21***	-11.83***	-294.13***	08/02/2011	14/09/2009-12/01/2018

*Note: We consider the test that allows a break in the constant, the slope and the trend. The asterisks ***, ** and *denote the rejection of the null hypothesis at the1%, 5% and 10% levels, respectively. The critical values are taken from Table 1 of Gregory and Hansen (1996b).*

Table A.3. Test for explosive behaviour of Phillips, Shi and Yu (2015) based on weekly data

Prices	Test statistic	Critical value (1%)	Critical value (5%)	Critical value (10%)	Model
Austria (CEGH)	2.089	4.108	3.514	3.233	None
Belgium (ZEE)	1.218	1.962	1.495	1.314	Intercept and trend
Coal	2.761	4.258	3.617	3.314	None
Germany (Gaspool)	1.313	1.962	1.495	1.314	Intercept and trend
Germany (NCG)	1.936	4.058	3.619	3.351	None
France (PEG North)	1.032	1.988	1.460	1.193	Intercept and trend
France (PEG South)	2.870	3.991	3.494	3.258	None
Japan-Korean (JKM)	0.816	1.912	1.440	1.193	Intercept and trend
Oil (Index)	9.297	4.033	3.546	3.189	None
Netherlands (TTF)	0.804	1.962	1.495	1.314	Intercept and trend
U.K. (NBP)	0.749	1.962	1.495	1.314	Intercept and trend
U.S. (Henry Hub)	0.254	1.962	1.495	1.314	Intercept and trend

Note: The lag parameters for the test are selected based on the Schwartz information criteria. Critical values for the null hypothesis are obtained after 500 Monte Carlo simulations. The choice of the model retained is based on the significance of the trend and/or the intercept at the 5% level.

Table A.4. Perron-Yabu test for structural changes in the deterministic components based on weekly data

	Exp- W-RQF	Break date	cv(1%)	cv(5%)	cv(10%)
Panel A: Gas prices					
Belgium (ZEE)	*15.011*	*2nd 11/2010*	*4.47*	*3.12*	*2.48*
U.K. (NBP)	*23.302*	*3rd 11/2010*	*4.47*	*3.12*	*2.48*
France (PEG South)	*19.003*	*3rd 02/2014*	*4.48*	*3.13*	*2.49*
France (PEG North)	*8.123*	*1st 12/2010*	*4.48*	*3.13*	*2.49*
Austria (CEGH)	*31.614*	*4th 10/2011*	*4.48*	*3.13*	*2.49*
Netherlands (TTF)	*13.964*	*3rd 11/2010*	*4.48*	*3.13*	*2.49*
Germany (Gaspool)	*15.185*	*3rd 11/2010*	*4.48*	*3.13*	*2.49*
Germany (NCG)	*14.376*	*1st 05/2010*	*4.48*	*3.13*	*2.49*
U.S. (Henry Hub)	*4.977*	*1st 12/2008*	*4.48*	*3.13*	*2.49*
Japan-Korean (JKM)	*7.958*	*1st 06/2012*	*4.48*	*3.13*	*2.49*
Panel B: Oil and Coal					
Oil	*13.932*	*3rd 12/2014*	*4.48*	*3.13*	*2.49*
Coal	4.263	2nd 10/2008	4.48	3.13	2.49

Note: Trimmer parameter is equal to 0.15. The critical values are taken Table 2c of Perron and Yabu (2009).

Table A.5. Results of Carrion-i-Silvestre *et al.* (2009) unit root tests with structural breaks based on weekly data

	P_T^{GLS}	MP_T^{GLS}	MZ_α^{GLS}	MSB^{GLS}	MZ_t^{GLS}	Numbers of breaks
Austria (CEGH)	11.98	11.59	-31.76	0.125	-3.98	4
	[6.99]	[6.99]	[-49.59]	[0.100]	[-4.96]	
Belgium (ZEE)	15.84	13.44	-25.54	0.139	-3.73	4
	[6.83]	[6.83]	[-47.84]	[0.101]	[-4.84]	
Netherlands (TTF)	13.78	13.46	-25.75	0.139	-3.57	4
	[6.41]	[6.41]	[-50.66]	[0.099]	[-5.01]	
U.K. (NBP)	9.105	8.57	-42.13	0.109	-4.59	4
	[6.67]	[6.67]	[-50.28]	[0.099]	[-5.01]	
France (PEG North)	20.61	19.11	-18.43	0.165	-3.03	4
	[6.52]	[6.52]	[-50.27]	[0.099]	[-5.00]	
France (PEG South)	14.87	11.92	-29.63	0.130	-3.85	4
	[6.69]	[6.69]	[-49.63]	[0.100]	[-4.97]	
Japan-Korean (JKM)	13.36	12.70	-18.44	0.164	-3.02	3
	[5.04]	[5.04]	[-44.13]	[0.107]	[-4.68]	
U.S. (Henry Hub)	67.51	59.22	-6.52	0.276	-1.80	4
	[6.96]	[6.96]	[-51.12]	[0.099]	[-5.04]	
Germany (Gaspool)	14.18	13.86	-24.97	0.141	-3.52	4
	[6.41]	[6.41]	[-50.66]	[0.099]	[-5.01]	
Germany (NCG)	23.35	21.69	-16.58	0.174	-2.88	4
	[6.67]	[6.67]	[-50.57]	[0.099]	[-5.02]	
Oil (Index)	55.67	50.96	-8.48	0.241	-2.04	5
	[6.92]	[6.92]	[-56.94]	[0.093]	[-5.33]	
Coal	40.65	38.58	-9.26	0.231	-2.14	4
	[7.07]	[7.07]	[-47.25]	[0.112]	[-4.83]	

Note: Critical values for the 1 % level significance are in brackets. The test is implemented for model III, where the structural break affects both the level and the slope of the time trend. P_T^{GLS} *is the feasible point optimal test,* MP_T^{GLS} *is the modified point optimal test,* MZ_α^{GLS} *is the modified Phillips-Perron* MZ_α *test,* MSB^{GLS} *is the modified Sargan-Bhargava test and* MZ_t^{GLS}*, is the modified Phillips-Perron* MZ_t *test.*

Table A.6. Results of the Gregory and Hansen (1996b) on cointegration with one structural break based on weekly data

Panel A European gas prices, Japan-Korean price and Henry Hub

	Austria	Belgium	Netherlands	France North	France South	Germany (NCG)	Germany (Gaspool)	U.K. (NBP)	Japan-Korean
ADF	-4.77	-5.60**	-5.90**	-4.08	-5.61**	-4.49	-5.88**	-6.67***	-3.80
Z_t	-5.61	-6.29***	-5.30*	-5.18	-6.32***	-4.75	-5.22*	-6.57***	-5.55**
Z_a	-34.61	-69.68***	-51.47	-48.47	-56.87*	-41.74	-50.67	-77.27***	-32.65
Break date	3rd 01/2015	3rd 10/2010	3rd 10/2010	4th 10/2010	4th 02/2014	1st 11/2011	3rd 10/2010	3rd 10/2010	1st 08/2012

Panel B European gas prices and Japan-Korean price

	Austria	Belgium	Netherlands	France North	France South	Germany (NCG)	Germany (Gaspool)	U.K. (NBP)
ADF	-5.17	-5.80**	-5.64**	-5.65**	-6.56***	-5.55**	-5.60**	-5.87**
Z_t	-5.39*	-6.16***	-6.22***	-6.14**	-7.39***	-6.17**	-6.17***	-6.44***
Z_a	-45.63	-54.08*	-52.68	-55.01*	-85.37***	-52.22	-51.42	-58.68**
Break date	1st 09/2010	2nd 12/2014	2nd 12/2014	2nd 12/2014	3rd 04/2011	2nd 12/2014	2nd 12/2014	2nd 12/2014

Panel C Gas and oil prices

	Austria	Belgium	Netherlands	France North	France South	Germany (NCG)	Germany (Gaspool)	U.K. (NBP)	Japan-Korean	Henry Hub
ADF	-4.99	-6.18***	-5.55**	-5.84**	-5.75**	-5.98**	-5.57**	-6.15***	-5.38*	-6.05***
Z_t	-5.31*	-6.84***	-6.08***	-6.65***	-6.17***	-6.02**	-6.08**	-7.20***	-6.85***	-6.95***
Z_a	-41.17	-85.02***	-70.51***	-62.70**	-58.67**	-59.38*	-70.85***	-92.39***	-38.55	-59.81**
Break date	4th 12/2014	1st 03/2006	4th 04/2010	4th 12/2014	4th 02/2014	2nd 05/2010	3rd 05/2010	1st 03/2006	2nd 05/2014	4th 10/2011

Panel D Gas and coal prices

	Austria	Belgium	Netherlands	France North	France South	Germany (NCG)	Germany (Gaspool)	U.K. (NBP)	Japan-Korean	Henry Hub
ADF	-4.86	-6.48***	-5.41*	-5.78**	-6.74***	-5.25*	-6.38***	-6.06***	-4.39	-6.35***
Z_t	-4.86	-6.33***	-5.72**	-5.88**	-7.33***	-4.88	-5.58*	-6.42***	-6.45***	-6.87***
Z_a	-38.74	-69.46***	-56.26*	-55.80*	-83.57***	-41.73	-54.44*	-72.74***	-38.34	-63.80***
Break date	3rd 02/2014	2nd 02/2012	2nd 02/2012	2nd 02/2012	3rd 02/2014	1st 02/2012	2nd 02/2012	2nd 02/2012	2nd 04/2014	2nd 10/2012

*Note: We consider the test that allows a break in the constant, the slope and the trend. The asterisks ***, ** and *denote the rejection of the null hypothesis at the1%, 5% and 10% levels, respectively. The critical values are taken from Table 1 of Gregory and Hansen (1996b).*

Table A.7. Results of the Gregory and Hansen (1996b) on cointegration with one structural break for the European gas market based on weekly data

	ADF	Z_t	Z_a	Break date
ZEE-NBP	-10.02***	-14.53***	-319.56***	1st 06/2006
TTF-NBP	-11.11***	-12.33***	-252.13***	4th 09/2006
PEG North-NBP	-10.47***	-10.66***	-190.54***	3rd 09/2007
PEG South-NBP	-8.14***	-7.45***	-95.07***	1st 11/2014
NCG-NBP	-9.87***	-9.90***	-165.86***	1st 11/2009
Gaspool-NBP	-10.81***	-11.93***	-238.81***	3rd 09/2006
CEGH- NBP	-6.07***	-6.21***	-66.96**	4th 08/2016
ZEE-TTF	-11.65***	-10.33***	-189.04***	2nd 03/2006
PEG North-TTF	-9.73***	-11.41***	-179.31***	3rd 07/2008
PEG South-TTF	-6.78***	-6.91***	-83.10***	1st 11/2014
NCG-TTF	-11.70***	-12.05***	-224.50***	1st 04/2009
Gaspool-TTF	-13.06***	-13.55***	-287.46***	1st 04/2008
CEGH-TTF	-5.85**	-8.03***	-107.13***	1st 02/2015
ZEE-Gaspool	-10.90***	-10.52***	-193.63***	2nd 03/2006
PEG North- Gaspool	-12.75***	-11.25***	-175.30***	1st 11/2008
PEG South- Gaspool	-7.70***	-7.08***	-82.10***	1st 10/2014
NCG-Gaspool	-12.82***	-13.38***	-261.18***	1st 04/2009
CEGH-Gaspool	-5.24*	-8.40***	-117.19***	4th 01/2015
ZEE-NCG	-13.05***	-13.40***	-265.67***	2nd 11/2009
PEG North-NCG	-11.66***	-11.88***	-221.54***	4th 09/2010
PEG South-NCG	-7.77***	-6.66***	-80.77***	3rd 10/2014
CEGH-NCG	-5.52**	-7.95***	-105.56***	2nd 05/2016
ZEE-PEG North	-12.26***	-12.15***	-243.28***	2nd 09/2007
PEG South-PEG North	-8.05***	-6.80***	-85.79***	3rd 09/2014
CEGH-PEG North	-5.48*	-7.66***	-100.70***	2nd 09/2016
ZEE-PEG South	-6.97***	-6.77***	-84.69***	4th 10/2014
CEGH-PEG South	-6.79***	-9.12***	-211.93***	4th 09/2014
ZEE-CEGH	-6.21***	-7.57***	-100.38***	1st 02/2011

*Note: We consider the test that allows a break in the constant, the slope and the trend. The asterisks ***, ** and *denote the rejection of the null hypothesis at the1%, 5% and 10% levels, respectively. The critical values are taken from Table 1 of Gregory and Hansen (1996b).*

Table A.8. Maki's (2012) bivariate cointegration tests results based on weekly data

European gas prices and JKM with U.S. Henry Hub			
	Statistics	Critical value	Break dates
Belgium (ZEE)	*-6.874***	*-6.524*	*4th 09/2006; 3rd 02/2009; 2nd 01/2014*
U.K. (NBP)	*-6.604***	*-6.524*	*4th 05/2006; 1st 11/2008; 4th 03/2013*
Netherlands (TTF)	*-6.759***	*-6.524*	*2nd 09/2006; 2nd 02/2009; 2nd 01/2014*
Germany (Gaspool)	*-6.357**	*-6.524*	*2nd 09/2006; 1st 02/2009; 4th 10/2014*
Germany (NCG)	*-6.141*	*-6.524*	*3rd 02/2009; 2nd 08/2015; 1st 12/2016*
Japan-Korean	*-4.561*	*-6.524*	
Austria (CEGH)	*-5.519*	*-6.524*	
France (PEG South)	*-6.432**	*-6.524*	*2nd 10/2011; 3rd 04/2013; 1st 01/2016*
France (PEG North)	*-5.343*	*-6.524*	
Gas prices with oil			
Belgium (ZEE)	*-6.805***	*-6.524*	*3rd 10/2006; 4th 12/2009; 4th 03/2013*
U.K. (NBP)	*-7.060***	*-6.524*	*3rd 10/2006; 4th 12/2009; 4th 03/2013*
Netherlands (TTF)	*-7.112****	*-6.524*	*4th 10/2006; 1st 03/2011; 1st 06/2015*
Germany (Gaspool)	*-7.178****	*-6.524*	*4th 04/2007; 1st 10/2009; 3rd 03/2013*
Germany (NCG)	*-5.460*	*-6.524*	*2nd 10/2009; 2nd 02/2012; 2nd 04/2014*
Japan-Korean	*-3.119*	*-6.524*	
Austria (CEGH)	*-4.782*	*-6.524*	
France (PEG South)	*-6.228*	*-6.524*	*4th 10/2010; 1st 02/2012; 2nd 01/2017*
France (PEG North)	*-6.470**	*-6.524*	*1st 10/2009; 2nd 02/2012; 3rd 04/2014*
United States (HH)	*-5.334**	*-5.541*	*3rd 09/2012*
European gas prices with Japan Korean (JKM)			
Belgium (ZEE)	*-5.609***	*-5.541*	*4th 11/2010*
U.K. (NBP)	*-6.276**	*-6.524*	*3rd 09/2010; 4th 03/2013; 3rd 12/2015*
Netherlands (TTF)	*-5.507**	*-5.541*	*4th 11/2010*
Germany (Gaspool)	*-5.454**	*-5.541*	*4th 11/2010*
Germany (NCG)	*-5.400**	*-5.541*	*4th 11/2010*
Austria (CEGH)	-4.480	-6.100	
France (PEG South)	*-6.853****	*-6.100*	*4th 02/2011; 2nd 04/2013*
France (PEG North)	-5.649**	*-5.541*	*4th 11/2010*

*Note: Critical values at the 0.05 significance level are from Table 1 of Maki (2012). *, **, *** denotes the rejection of the null hypothesis of no cointegration. Break dates are obtained by using Maki's (2012) cointegration test.*

Table A.9. Estimation of long-term coefficients based on weekly data (DOLS, Bartlett Kernel, Newey-West fixed bandwidth)- European natural gas market

	With U.K. NBP			With Netherlands TTF		
	First period	Second period	Break date	First period	Second period	Break date
Austria (CEGH)	0.867***	0.575***	4th 08/2016	0.844***	0.900***	1st 02/2015
	(0.039)	(0.041)		(0.030)	(0.022)	
LOP	*11.42****	*177.27****		*26.55****	*21.42****	
Belgium (ZEE)	0.979***	0.980***	1st 06/2006	1.483***	1.026***	2nd 03/2006
	(0.007)	(0.008)		(0.120)	(0.011)	
LOP	*7.67****	*5.68***		*16.20****	*5.82***	
Netherlands (TTF)	0.675***	0.966***	4th 09/2006			
	(0.027)	(0.015)				
LOP	*139.08****	*5.36***				
Germany (Gaspool)	0.709***	0.960***	3rd 09/2006	0.982***	0.991***	1st 04/2008
	(0.050)	(0.015)		(0.004)	(0.006)	
LOP	*33.85****	*7.37****		*15.49****	*2.35*	
Germany (NCG)	0.968***	0.963***	1st 11/2009	0.960***	0.976***	1st 04/2009
	(0.016)	(0.022)		(0.015)	(0.007)	
LOP	*3.93**	*2.60*		*7.07****	*10.12****	
France (PEG North)	0.852***	0.953***	3rd 09/2007	1.071***	0.996***	3rd 07/2008
	(0.028)	(0.017)		(0.045)	(0.008)	
LOP	*27.92****	*7.91****		*2.54*	*0.263*	
France (PEG South)	0.999***	0.901***	1st 11/2014	1.049***	0.956***	1st 11/2014
	(0.029)	(0.011)		(0.030)	(0.092)	
LOP	*0.000*	*0.740*		*2.620*	*0.225*	

*Note: The different periods correspond to the break dates detected using the Gregory and Hansen (1996b) cointegration test. *, **, *** significant at the 10%, 5%, and 1% level, respectively. A Wald test of the null hypothesis of $\beta=1$ has been implemented to test for the LOP hypothesis.*

Table A.10. Estimation of long-term coefficients based on weekly data (DOLS, Bartlett Kernel, Newey-West fixed bandwidth)

	With U.S. Henry Hub				With Japan Korean (JKM)			With oil index			
	First period	Second period	Third period	Fourth period	First period	Second period	Third period	First period	Second period	Third period	Fourth period
Belgium (ZEE)	1.312***	0.432	-0.446*	0.786***	1.128***	0.565***		0.807***	1.841***	1.200***	0.716***
	(0.183)	(0.324)	(0.238)	(0.119)	(0.094)	(0.035)		(0.153)	(0.165)	(0.134)	(0.075)
LOP	*2.91**	*3.07**	*38.82****	*3.26**	*1.858*	*156.00****					
U.K. (NBP)	1.344***	0.874***	-0.796***	0.866***	0.824***	0.283***	0.577***	0.740***	1.849***	1.230***	0.682***
	(0.192)	(0.115)	(0.151)	(0.133)	(0.109)	(0.03)	(0.036)	(0.169)	(0.170)	(0.137)	(0.080)
LOP	*3.21**	*1.201*	*141.68****	*1.012*	*2.58*	*60.33****	*137.86****				
Netherlands (TTF)	0.787***	0.376	-0.443*	0.770***	0.800***	0.551***		0.700***	1.826***	0.522***	1.044***
	(0.100)	(0.298)	(0.228)	(0.119)	(0.085)	(0.035)		(0.081)	(0.141)	(0.113)	(0.127)
LOP	*4.55***	*4.37***	*39.94****	*3.70**	*5.41**	*164.81****					
Germany (Gaspool)	0.756***	0.451	-0.347	0.720***	1.085***	0.552***		0.642***	1.657***	1.166***	1.025***
	(0.098)	(0.304)	(0.236)	(0.149)	(0.087)	(0.033)		(0.079)	(0.147)	(0.158)	(0.117)
LOP	*6.14***	*3.25**	*32.48****	*3.50**	*0.956*	*184.55****					
Germany (NCG)	0.201***	-0.326	0.589***	0.580***	1.049***	0.549***		1.461***	0.729***		
	(0.061)	(0.223)	(0.206)	(0.136)	(0.083)	(0.034)		(0.125)	(0.060)		
LOP	*169.64****	*35.40****	*3.98**	*9.52****	*0.343*	*175.33****					
France (PEG South)	0.844*	-0.381***	0.016	0.980***	1.110***	0.467***	0.699***	2.927***	0.754***		
	(0.444)	(0.084)	(0.129)	(0.205)	(0.132)	(0.098)	(0.047)	(0.241)	(0.063)		
LOP	*0.122*	*274.41****	*57.89****	*0.009*	*0.697*	*29.84****	*40.01****				
France (PEG North)	0.054	0.648***			1.064***	0.564***		1.585***	1.617***	0.088	0.550***
	(0.122)	(0.160)			(0.080)	(0.033)		(0.197)	(0.164)	(0.609)	(0.098)
LOP	*60.03*	*4.82***			*0.630*	*171.16****					
U.S. Henry Hub								-0.411***	0.241***		
								(0.109)	(0.043)		

*Note: The different periods correspond to the different break dates that have been selected by Maki's (2012) cointegration test for each pair of prices. *, **, *** significant at the 10%, 5%, and 1 % level, respectively. A Wald test of the null hypothesis of β=1 has been implemented to test for the LOP hypothesis.*

Table A.11. Threshold cointegration tests for natural gas based on weekly data (Enders and Siklos, 2001).

	NBP and Henry Hub	Henry Hub and JKM	TTF and Henry Hub	NBP and TTF	NBP and JKM	TTF and JKM
Model	Consistent MTAR	Consistent TAR	Consistent TAR	Consistent TAR	Consistent MTAR	Consistent MTAR
Lag	2	2	2	0	2	2
Threshold	-0.045	-0.128	0.330	-0.053	0.013	-0.041
ρ_1	-0.017	-0.059***	-0.358***	-0.135***	-0.024	-0.064***
	(-1.343)	(-4.375)	(-4.738)	(-5.442)	(-0.978)	(-3.607)
ρ_2	-0.104***	-0.025*	-0.078***	-0.259***	-0.133***	-0.146***
	(-4.976)	(-1.882)	(-5.056)	(-6.862)	(-6.634)	(-1.693)
AIC	-1250.00	-2596.38	-2144.87	-2022.16	-1987.00	-2137.68
BIC	-1227.06	-2573.43	-2121.92	-2008.38	-1963.53	-2114.74
$Q_{LB}(4)$	0.867	0.199	0.483	0.063	0.967	0.505
Φ: $\rho_1 = \rho_2 = 0$	13.192	11.16	22.790	38.355	22.259	19.012
Critical values (10 %)	6.47	6.44	6.44	6.47	6.47	6.47
Critical values (5 %)	7.53	7.47	7.47	7.53	7.53	7.53
Critical values (1 %)	9.76	9.64	9.64	9.76	9.76	9.76
F: $\rho_1 = \rho_2$	12.563***	3.17*	13.460**	7.623***	12.254***	6.219**

*Note: t-statistics are in parentheses. Q_{LB} is the Ljung–Box statistic for 4 lags. Critical values for the distribution of Φ come from Table 1 of Wane et al. (2004). Lags are chosen according to the BIC. *, **, *** denote significance at the 10%, 5%, and 1% levels, respectively.*

Table A.12. Results of the asymmetric error correction model with threshold cointegration based on weekly data (European and U.S. markets)

	U.K NBP (ΔP_t^1)	U.S. HH (ΔP_t^2)	Netherlands TTF (ΔP_t^3)	U.S. HH (ΔP_t^2)	U.K NBP (ΔP_t^1)	Netherlands TTF (ΔP_t^3)
ΔNBP_{t-1}^{+}	0.082	-0.006			0.007	0.128*
	(0.062)	(0.029)			(0.096)	(0.071)
ΔNBP_{t-2}^{+}	-0.244***	0.037			-0.004	-0.068
	(0.062)	(0.030)			(0.095)	(0.071)
ΔNBP_{t-1}^{-}	0.102	0.029			-0.168*	-0.206***
	(0.066)	(0.031)			(0.101)	(0.075)
ΔNBP_{t-2}^{-}	-0.054	-0.023			0.030	0.153**
	(0.064)	(0.010)			(0.097)	(0.072)
ΔHH_{t-1}^{+}	0.145	0.217***	0.086	-0.218***		
	(0.157)	(0.074)	(0.112)	(0.075)		
ΔHH_{t-2}^{+}	-0.027	-0.076	-0.039	-0.098		
	(0.157)	(0.074)	(0.112)	(0.075)		
ΔHH_{t-1}^{-}	0.132	0.466***	0.148	-0.480***		
	(0.165)	(0.078)	(0.112)	(0.078)		
ΔHH_{t-2}^{-}	-0.062	-0.091	-0.110	-0.085**		
	(0.166)	(0.079)	(0.118)	(0.079)		
ΔTTF_{t-1}^{+}			0.288***	0.047	0.142	-0.028
			(0.067)	(0.045)	(0.131)	(0.097)
ΔTTF_{t-2}^{+}			-0.292**	0.003	-0.485***	-0.283***
			(0.064)	(0.043)	(0.133)	(0.099)
ΔTTF_{t-1}^{-}			-0.233***	-0.002	0.481***	0.495***
			(0.066)	(0.044)	(0.138)	(0.102)
ΔTTF_{t-2}^{-}			-0.164***	-0.013	-0.076	-0.331***
			(0.064)	(0.043)	(0.136)	(0.101)
ECM_{t-1}^{+}	-0.018	-0.000	-0.493***	-0.044	-0.027	0.075**
	(0.013)	(0.006)	(0.079)	(0.053)	(0.048)	(0.036)
ECM_{t-1}^{-}	-0.103**	0.027***	-0.022***	-0.008	-0.326***	-0.050
	(0.021)	(0.010)	(0.009)	(0.006)	(0.074)	(0.055)
Intercept	0.003	0.000	0.002	0.004	0.007	0.005
	(0.008)	(0.001)	(0.005)	(0.004)	(0.005)	(0.004)

*Note: Lags are chosen according to the BIC. *, **, *** denote significance at the 10%, 5%, and 1% levels, respectively.*

Table A.13. Results of the asymmetric error correction model with threshold cointegration based on weekly data (European, U.S. and Japan-Korean markets)

	U.K NBP (ΔP_t^1)	JKM (ΔP_t^3)	U.S. HH (ΔP_t^2)	JKM (ΔP_t^3)	Netherlands TTF (ΔP_t^2)	JKM (ΔP_t^1)
ΔNBP_{t-1}^{+}	0.112	0.066				
	(0.092)	(0.046)				
ΔNBP_{t-2}^{+}	-0.110	0.027				
	(0.093)	(0.047)				
ΔNBP_{t-1}^{-}	0.042	-0.035				
	(0.088)	(0.044)				
ΔNBP_{t-2}^{-}	0.035	0.048				
	(0.087)	(0.044)				
ΔJKM_{t-1}^{+}	-0.057	0.495***	0.077	0.509***	-0.071	0.472***
	(0.160)	(0.080)	(0.118)	(0.078)	(0.141)	(0.079)
ΔJKM_{t-2}^{+}	0.162	-0.031	0.023	-0.049	-0.026	-0.022
	(0.159)	(0.080)	(0.118)	(0.078)	(0.139)	(0.078)
ΔJKM_{t-1}^{-}	0.001	0.465***	-0.083	0.472***	0.046	0.456***
	(0.155)	(0.078)	(0.116)	(0.077)	(0.138)	(0.077)
ΔJKM_{t-2}^{-}	0.144	0.072	0.116	0.079	0.092	0.090
	(0.152)	(0.076)	(0.115)	(0.076)	(0.134)	(0.075)
ΔHH_{t-1}^{+}			-0.296***	-0.005		
			(0.102)	(0.068)		
ΔHH_{t-2}^{+}			-0.146	0.048		
			(0.102)	(0.068)		
ΔHH_{t-1}^{-}			0.339***	0.123*		
			(0.111)	(0.074)		
ΔHH_{t-2}^{-}			-0.139	0.064		
			(0.111)	(0.074)		
ΔTTF_{t-1}^{+}					-0.144	-0.082
					(0.091)	(0.051)
ΔTTF_{t-2}^{+}					0.024	0.062
					(0.092)	(0.052)
ΔTTF_{t-1}^{-}					0.216**	0.165***
					(0.094)	(0.053)
ΔTTF_{t-2}^{-}					-0.166*	-0.054
					(0.094)	(0.053)
ECM_{t-1}^{+}	0.034	-0.020	0.016	-0.018	0.038	-0.019
	(0.032)	(0.016)	(0.0023)	(0.016)	(0.023)	(0.013)
ECM_{t-1}^{-}	0.026	-0.008	0.016	0.015	-0.030	-0.022
	(0.026)	(0.013)	(0.022)	(0.015)	(0.037)	(0.021)
Intercept	0.001	0.002	0.001	0.006*	-0.001	0.002
	(0.006)	(0.003)	(0.005)	(0.004)	(0.005)	(0.003)

*Note: Lags are chosen according to the BIC. *, **, *** denote significance at the 10%, 5%, and 1% levels, respectively.*