The Law of one Price in Global Natural Gas Markets - A Threshold Cointegration Analysis

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Abstract

The US and UK markets for natural gas are connected by arbitrage activity in the form of imports of liquefied natural gas (LNG). We empirically investigate the degree of integration between the US and the UK gas markets by using a threshold cointegration approach that is in exact accordance with the law of one price and explicitly accounts for the transaction costs of arbitrage. Our estimation results reveal a high degree of market integration for the period 2000-2008 and a lower degree for the period 2009-2012 when US and UK gas prices seemed decoupled. Moreover, in the latter period high threshold estimates indicate impediments to arbitrage that are by far surpassing the LNG transport costs difference between the US and UK gas market.

Keywords: natural gas market, liquified natural gas, law of one price, arbitrage, nonlinear models, threshold error correction

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1. Introduction

In the last decade, trade volumes of liquified natural gas (LNG) have increased strongly and are thought to promote the integration of global markets for natural gas. However, important benchmark prices of natural gas around the globe have diverged at the latest since the financial crisis in the year 2009. This observation is frequently referred to as the "decoupling" of gas markets. Since then, the US Henry Hub (HH) spot price started its descent and the UK National Balancing Point (NBP) spot price started its ascent which resulted in high price spreads between the US and UK natural gas markets (see Figure 1). From the perspective of the law of one price (LOP) theory, we would expect prices to adjust towards each other once the price spread between two markets is larger than the transaction costs of spatial arbitrage. Against this background, the question arises whether the seemingly decoupled benchmark natural gas prices such as the HH spot price and the NBP spot price are still pulled together by arbitrage even if the individual series seem to stay away from each other. Up to now, the relationship between international gas prices was

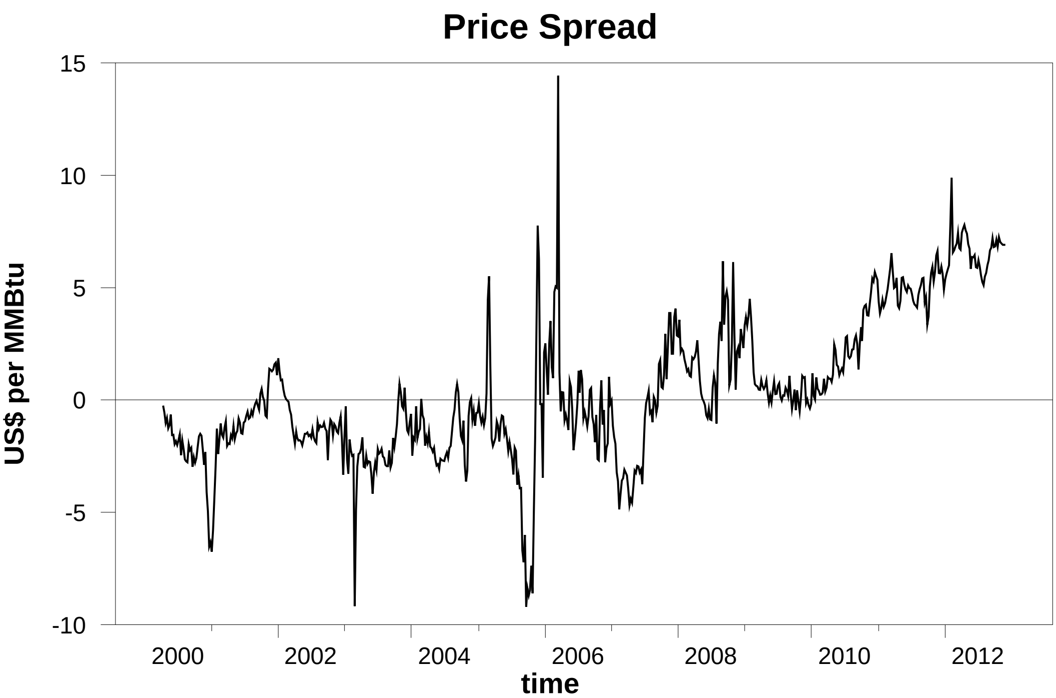

Figure 1: Price difference between UK National Balancing Point and US Henry Hub

mostly analyzed using linear cointegration analysis such as Neumann (2009), Kao and Wan (2009) or Brown and Yücel (2009). Using US and UK gas price data up to the year 2008 all these studies find linear cointegration and, thus, provide evidence for a certain degree integration of US and UK gas markets. However, linear cointegration models are actually unable to capture arbitrage dynamics in a spatial setting adequately since they do not account for transaction costs that can impede arbitrage activity. In contrast to the available literature on the global natural gas markets, we use a threshold cointegration approach to test for price convergence and to estimate how long arbitrage activity between the markets needs to restore an arbitrage free equilibrium situation. As we discuss below in Section 2 a threshold cointegration framework is able to more closely emulate the specifics of the LOP theory and arbitrage behavior in the presence of transaction costs. In our study we focus on the relationship between the US price of natural gas and the UK price of natural gas. First, for comparison with the existing literature we use both linear and threshold cointegration tests to test for price convergence between the US gas price and the UK gas price. In other words, we test whether we can find statistical evidence for both markets being integrated by arbitrage activity in accordance with the LOP. When doing threshold cointegration tests, we also estimate the threshold values which represent transaction costs and other impediments for arbitrage activity. These threshold estimates are compared with data on liquified natural gas (LNG) transport costs to obtain a measure for the size of market inefficiencies that are induced by factors other than transport costs. Second, where we find threshold cointegration, we use a threshold vector error correction model (TVECM) to investigate how the individual price series adjust. The TVECM gives us additional insights about the speed of adjustment of the individual price series during the arbitrage process. Thereby, we obtain an indication of how strongly the Transatlantic gas market was integrated and how effectively arbitrage is pushing price convergence. We conduct all these analytical steps for the period 2000 to 2012 and for the two sub-samples 2000 to 2008 and 2009 to 2012. The former sub-sample roughly corresponds to the samples used in most of the earlier literature and thus enables comparison with older results using linear cointegration approaches. Further, with the start of the latter sub-sample the UK and US price series are often said to start to decouple which seems to be evident when inspecting the movement of the price series. Linear and threshold cointegration tests both imply that natural gas markets are cointegrated in the full sample period 2000 to 2012. Also, in the 2000 to 2008 sub-sample there is strong evidence from linear and threshold cointegration tests for cointegration of the UK and US price series. In the second sub-sample linear cointegration tests reject cointegration. Using threshold cointegration tests which are deemed an improved framework to test for price convergence in accordance with the LOP, we find cointegration also in the second sub-sample. Whilst arbitrage activity can be observed at low price spreads in the first sub-sample, in the second sub-sample arbitrage can be observed only at very high price spreads. Moreover, the comparison of threshold estimates with LNG transport cost data reveals low non-transport cost impediments to arbitrage in the 2000 to 2008 sub-sample, but high non-transport cost impediments in the second sub-sample. The TVECM results reveal that between 2000 and 2008 both markets adjusted when arbitrage was profitable. However, between 2009 and 2012 price convergence was exclusively brought about by a downward pull on the UK price of natural gas. Our contribution to the literature on spatial arbitrage and international gas markets is threefold. First, we improve the econometric framework for studying spatial arbitrage by specifying an econometric model for testing cointegration and investigating individual price adjustment that is more consistent with LOP theory. Second, we empirically apply our framework and show that at least in the 2009 to 2012 sub-sample linear and threshold cointegration frameworks deliver different results with respect to finding price convergence and the intensity of arbitrage activity. Third, we provide evidence that the US and UK gas prices albeit seemingly having decoupled since the year 2009 are still pulled together by arbitrage forces in line with the LOP. Additionally, we present evidence that in recent years impediments to arbitrage have arisen that are not related to transport costs. The remainder of this paper is organized in the following way. In Section 2 we show how the law of one price can be represented by an econometric model. In Section 3 we introduce the econometric procedures necessary to test for price convergence and to estimate the extent of arbitrage activity. We also present and discuss the estimation results in that Section. We conclude in the final Section.

2. Theoretical Framework

2.1. The Law of One Price and its Application to Global Natural Gas Markets

Our study is grounded on the Law of One Price (LOP), stating that the price for the same good should be equal in different markets. In a frictionless world, the law of one price is expected to hold since any price divergence triggers arbitrage and thus is only of transitory nature. Ignoring transaction costs of arbitrage activity, the arbitrage conditions for traders participating in two markets i and j, can be stated as

$$\begin{aligned} P_i > &\quad P_j, \\ P_i < &\quad P_j, \end{aligned} \tag{1}$$

However, in a more realistic framework, arbitrage activity may cause significant transaction costs such as costs for transportation, information or trading fees. Thus, arbitrage may only be triggered if the implied gross profit of the trade covers transaction costs. Denoting the transaction costs by τ, the arbitrage conditions translate to

$$\begin{aligned} P_i > &\quad P_j + \tau \\ P_i < &\quad P_j - \tau. \end{aligned} \tag{2}$$

In our study, we empirically investigate a special case of regional price arbitrage in commodity markets, focusing on the natural gas prices in Great Britain (UK) and the United States (US). One has to keep in mind however, that direct price arbitrage (i.e., exports from the UK to the US or vice versa) is not the driving force of any price convergence since no significant LNG exports neither from the UK nor from the US can be observed during the sample period of our study due to regulatory constraints and the lack of liquefaction capacity. In fact, transatlantic convergence in gas prices may be the result from arbitrage carried out by a third party, namely the trader of LNG rerouting its shipments according to current market conditions, rather than from bilateral trade between the two markets considered.

In the global natural gas market, the majority of LNG shipments is based on long-term contracts

(LTCs). These trade flows thus represent constant deliveries regardless of the current demand and supply balance and can therefore not be regarded as a mean of regional price arbitrage.

However, there is also a growing spot market for LNG where gas volumes are traded on a short-term basis accounting for current regional gas prices and transaction costs. Within the spot market, the exporter of LNG is expected to serve the market where the greatest revenue (adjusted for transportation costs) can be obtained from selling the gas volumes. As a consequence, changes in regional supply and demand balances may represent an incentive for the LNG exporter to divert its spot volumes to other destinations. Thus, the rerouting of LNG spot market deliveries may constitute an effective element of transatlantic price arbitrage in the natural gas market.

Since the price arbitrage is not carried out via bilateral trade but through third parties, the arbitrage condition can be stated in terms of the prices in the potential destination regions and the respective transportation costs. For the sake of simplicity, we assume an exporter having the opportunity to deliver spot LNG volumes to two markets A and B. In addition, market A is assumed to be the more remote market for the exporter, resulting in increased transportation costs when this market is served instead of market B. As long as the regional price differential $P_A - P_B$ does not exceed the difference in transportation costs, $\Delta TC_{A,B}$, all spot volumes are shipped to market B. In contrast, market A is exclusively served when the transportation cost differential is covered by the greater revenues that can be generated by selling the gas to market B. Equation (3) states the indifference condition for the arbitrageur with regard to the potential destinations:

$$\Delta TC_{A,B} = P_A - P_B \tag{3}$$

with

$$\Delta TC_{A,B} = TC_A - TC_B \tag{4}$$

where TC_A and TC_B denote the transportation costs for the exporter to market A and market B, respectively. The situation when switching from market A to market B is profitable for the arbitrage player in our simplified example is illustrated in Figure 2.

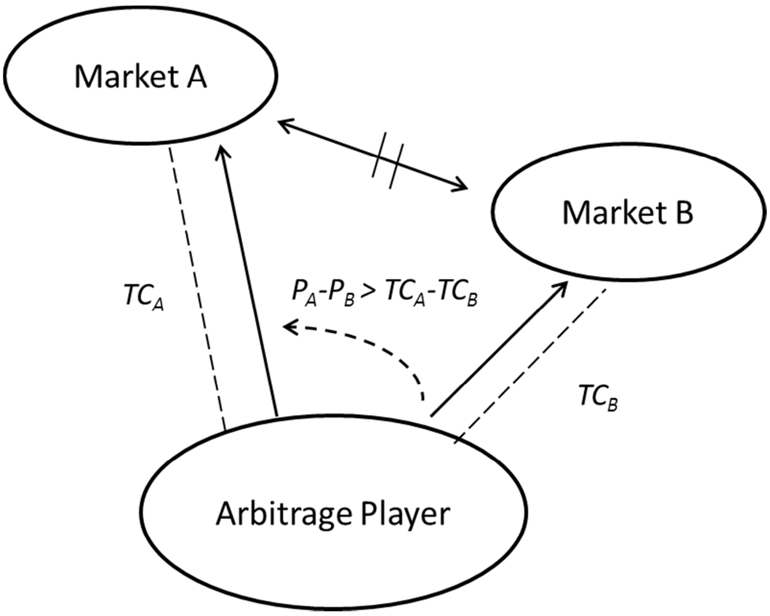

Figure 2: Regional Price Arbitrage in the Global Natural Gas Market

2.2. Econometric Approach

Disregarding transaction costs, the LOP requires that any deviation from the LOP is corrected by instantaneous arbitrage activity. Based on this assumption, deviations of the prices in the two markets considered cannot be persistent. From an econometric perspective, this translates into stationary behavior of the price spread, $s_t = P_i - P_j$. Since the LOP calls for the unity of prices in the long-run equilibrium, the price spread reverts to an expected value of zero. The time series behavior of the price spread can be represented by the following autoregressive process:

$$s_t = (\varrho + 1)(s_{t-1}) + \epsilon_t \tag{5}$$

or equivalently

$$\Delta s_t = \varrho(s_{t-1}) + \epsilon_t \tag{6}$$

with $\varrho < 0$ to ensure stationarity of the process.

The existence of transaction costs causes a "band of no arbitrage" between both markets as stated in Equation (2). Within this band, the price spread s_t does not cover the transaction costs of the arbitrage activity τ. In contrast, if the absolute value of s_t exceeds τ arbitrage is profitable resulting in adjustment of the prices towards a price spread of zero. "Towards zero" here means that the price spread only reverts towards that value, but never actually reaches it as price adjustment stops as soon as arbitrage is not profitable anymore. Thus, in the presence of transaction costs, the short-run behavior of s_t may be more adequately captured by a threshold autoregressive model (TAR):

$$\Delta s_t = \begin{cases} \gamma_1(s_{t-1} - \mu) + \epsilon_{1t}, & \text{if } s_{t-1} > \tau \\ \epsilon_{2t}, & \text{if } |s_{t-1}| < \tau \\ \gamma_1(s_{t-1} + \mu) + \epsilon_{3t}, & \text{if } s_{t-1} < -\tau \end{cases} \tag{7}$$

The representation in Equation (7) shows that within the band of no arbitrage, the price spread follows a random walk without drift, that is, it does not exhibit any mean reverting behavior. In contrast, in the outer regimes, the price spread follows a stationary process reverting to the so-called "attractor" μ. To be even more particular about the adjustment, in the spatial arbitrage case, the price spread is normally not expected to revert to zero, but to revert until its absolute value is equal to the threshold. In this case, the attractor μ equals the threshold τ. Arbitrage activity will lead to reversion of the (absolute value) of the price spread to exactly the transaction costs if we assume the possibility to transport very small quantities of the good (relative to the overall market volume) by the arbitrageurs. This is because each unit that is imported with revenues that are lower than per unit transaction costs would lead to shrinking profits. Balke and Fomby (1997) who first introduced this type of TAR-model call the corresponding stochastic process a band threshold autoregressive (BAND-TAR) process.

One has to keep in mind that the model specified above assumes symmetry in the adjustment process with regard to the direction of the deviation from the equilibrium. That means, no matter whether the price spread s_t is negative or positive, as long as its absolute value is larger than transaction costs τ, Equation (7) implies that the price spread will converge to μ (or $-\mu$) at the same speed γ_1. One may relax this symmetric adjustment assumption by using the following specification:

$$\Delta s_t = \begin{cases} \gamma_1(s_{t-1} - \mu) + \epsilon_{1t}, & \text{if } s_{t-1} > \tau \\ \epsilon_{2t}, & \text{if } |s_{t-1}| \leq \tau \\ \gamma_3(s_{t-1} + \mu) + \epsilon_{3t}, & \text{if } s_{t-1} < -\tau \end{cases}, \tag{8}$$

where the adjustment coefficients γ_1 and γ_3 may be statistically different from each other. Equation (8) allows that the price spread converges at different speeds γ_1 and γ_3 to μ (or $-\mu$ when the spread is negative) depending on whether the price spread is positive or negative.

The models just presented constitute an appropriate framework not only to estimate the threshold value τ, but also to investigate its role for the autoregressive behavior of the price spread. Moreover, the framework allows to test whether the prices follow a stationary long run equilibrium relationship as implied by the LOP (cointegration) and whether the adjustment process is linear or whether transaction costs introduce threshold nonlinear adjustment. However, these specifications do not allow for an empirical assessment of the adjustment behavior of the individual prices in the markets considered. For this purpose, multivariate models have to be applied. Since we operate in a cointegration framework, the usage of a multivariate vector error correction models (VECM) is straightforward. Abstaining from the consideration of transaction costs, the corresponding frictionless arbitrage dynamics can be represented by a linear VECM:

$$\begin{aligned} \Delta P_{t,1} &= \gamma_1 s_{t-1} + \epsilon_{1t}, \\ \Delta P_{t,2} &= \gamma_2 s_{t-1} + \epsilon_{2t}, \end{aligned} \tag{9}$$

where $s_{t-1} = P_{t-1,1} - P_{t-1,2}$ denotes the price differential between both markets. However, accounting for transaction costs, the threshold vector error correction model (TVECM) seems more suitable for the empirical investigation of arbitrage between two markets. We thus specify the following TVECM to investigate arbitrage dynamics between the two markets:

$$\Delta P_{t,1} = \begin{cases} \gamma_1^{(1)}(s_{t-1} - \mu) + \epsilon_{1t}, & \text{if } s_{t-1} > \tau \\ \epsilon_{1t}, & \text{if } |s_{t-1}| \leq \tau \\ \gamma_1^{(3)}(s_{t-1} + \mu) + \epsilon_{1t}, & \text{if } s_{t-1} < -\tau \end{cases} \tag{10}$$

$$\Delta P_{t,2} = \begin{cases} \gamma_2^{(1)}(s_{t-1} - \mu) + \epsilon_{2t}, & \text{if } s_{t-1} > \tau \\ \epsilon_{2t}, & \text{if } |s_{t-1}| \leq \tau \\ \gamma_2^{(3)}(s_{t-1} + \mu) + \epsilon_{2t}, & \text{if } s_{t-1} < -\tau \end{cases}, \tag{11}$$

where the threshold τ equals the estimate of τ from the a univariate TAR model of the price spread.

In Equation (10) and (11) prices stop to adjust towards the long run equilibrium when the price spread has decreased as much as to equal the transaction cost threshold. When the attractor μ is set equal to τ we obtain a BAND-TVECM. Hence, when the attractor is the threshold value τ prices - in order to restore the equilibrium - are assumed to change in proportion to the difference of the price spread and the attractor.

We further differentiate the basic model by specifying a symmetric and an asymmetric adjustment case for the BAND-TVECM. To estimate a case of symmetric adjustment we restrict $\gamma_1^{(1)} = \gamma_1^{(3)}$ and $\gamma_2^{(1)} = \gamma_2^{(3)}$. With this restriction in place, we assume that prices in both markets adjust with the same speed irrespective of whether the price spread is positive or negative, that is, irrespective of whether the prices in market A are above the prices in market B or vice versa. The asymmetric adjustment case is readily represented by the equations (10) and (11). Here adjustment of each individual price is allowed to differ with respect to the sign of the price spread. In our empirical application, we estimate both the symmetric and the asymmetric case as economic theory does not make a clear statement on whether symmetric or asymmetric adjustment should be expected in the LNG arbitrage case.

3. Empirical Application

This Section comprises four subsections and presents the econometric estimation and testing procedures as well as the estimation results. The first subsection presents the data and variables. In the second subsection we test for cointegration in the presence of threshold effects as implied by the LOP. In the third subsection we estimate threshold vector error correction models to investigate how the US and the UK prices adjust in order to restore equilibrium. Finally, we interpret the estimation results from an economic perspective, draw conclusions on the degree of integration of Atlantic gas markets and discuss how much efficiency is promoted by arbitrage activity.

3.1. Data

We use weekly price data for the period April 2000 to November 2012. The Henry Hub (HH) spot price which is measured in US-dollar per million British thermal units (MMBtu) is used as the US price of natural gas. The National Balancing Point (NBP) spot price which is measured in pound sterling per kilowatt-hour is used as the UK price. For better comparability the UK price is converted to US dollars per MMBtu using appropriate physical conversion factors and the weekly pound-sterling-to-US-dollar exchange rate as published by the Bank of England.

To investigate whether or not there is still price convergence after the "decoupling of gas prices" and to examine whether the workings of arbitrage are different in recent years we perform all analytical steps for the full sample and for the sub-samples 2000 to 2008 and a 2009 to 2012. The starting date of the latter sub-sample coincides roughly with the so called "decoupling" of the US and UK gas market and still leaves us with enough observations for the estimation.

In contrast to other studies of spatial arbitrage such as Lo and Zivot (2001) or Neumann (2009) we do not use the logarithm of the natural gas prices as variables. Using the logarithms of the variables is often done to get data that are somewhat more in line with the assumptions needed to get (asymptotically) efficient estimates. However, taking the logarithms of both prices effectively assumes an isoelastic relationship between the variables. In our view, an isolelastic relationship is not in complete accordance with the LOP, most likely not even locally in the range of values of our data. Further, as can be seen in Lo and Zivot, a log-log specification implies arbitrage conditions that we do not consider as a convincing representation of the real circumstances.[1] Only a level-level specification in our view is in line with LOP theory. LOP theory implies that in the long run prices should be equal and thus they are tied together by a linear relationship.

[1] In Lo and Zivot (2001) the arbitrage conditions imply that the threshold - generally representing transaction costs and other frictions - is proportional to the revenues from arbitrage.

3.2. Threshold Estimation and testing for (threshold) cointegration

First and foremost, it has to be determined whether UK and US natural gas prices are in a long run equilibrium relationship. Without the two time series being cointegrated any further analysis of adjustment processes of individual price series would be in vain. Only when UK and US prices are cointegrated then there is error correction, price convergence and market integration. For comparability and to illustrate the performance of the different approaches, we use linear as well as threshold cointegration tests. The analysis involves several sequential steps. First, unit root tests are used to determine whether both price series are integrated of the same order as this is the prerequisite for cointegration. Table (1) shows the results from augmented Dickey-Fuller (ADF) unit root tests for the levels and the first differenced versions of the natural gas prices. The results imply that each of the prices is integrated of order one.

Table 1: Unit root tests for US and UK natural gas spot prices

	UK price	Δ UK price	US price	Δ US price
ADF	-1.101	-23.61 ***	-1.12	-23.44 ***

Notes: Time period April 14 2000 to November 30 2012. Results for unit root tests with a null hypothesis of a unit root and a maximum lag length of $T^{1/3} = 9$ The Schwarz Criterion is used to select the lag lengths for the ADF unit root test. A rejection of the null hypothesis of a unit root at the 1, 5 and 10 percent significance level is denoted by ***, ** and *, respectively.

As a second step cointegration tests are used to determine whether the prices are tied together by a long run relationship over the sample periods. Initially, linear cointegration tests are used to make our results comparable with studies using older data (see literature in the introduction) and to have a point of reference when we test for threshold cointegration. When testing for cointegration we use the structural information that according to LOP theory the prices are at least in expectation equal in the long run equilibrium. The corresponding prespecified cointegration vector is (1,-1). In other words, if the prices are tied together as implied by the LOP the price spread should be a stationary series that reverts to a mean of zero. Therefore, we can test for cointegration by testing whether the price spread series contains a unit root.[2] In our case the null hypothesis that the price

[2]We abstain from using Johansen and Juselius (1992) or Engle and Granger (1987) cointegration tests. These

spread $s_t = p_{UK,t} - p_{US,t}$ is a non-stationary, unit root process is tested against the alternative hypothesis of a linear autoregressive process. Thus, the cointegration test is essentially an ADF test that is based on the estimation of the following equation.

$$\Delta s_t = \varrho(s_{t-1}) + \sum_{i=1}^{M} \Delta s_{t-i} + \epsilon_t \tag{12}$$

with $\varrho < 0$ to ensure stationarity of the process.

If ϱ is not significantly different from zero then the price spread s_t is essentially only explained by the current error term. In other words, s_t follows an unit root process and the US and the UK prices are considered as not cointegrated. If ϱ is different from zero at conventional significance levels then we reject the null hypothesis of non-stationarity and accept the alternative hypothesis of stationarity. Stationarity of the price spread means that the cointegration vector (1,-1) or a price spread of zero represents a long run equilibrium relationship for the two prices. According to the Engle and Granger (1987) representation theorem whenever there is cointegration then there is an error correction process. Error correction - in our case - means that whenever a shock drives the prices out of their long run equilibrium then at least one of the prices adjusts in order to restore the equilibrium.

Table 2: Cointegration test for prespecified cointegration vector (1,-1)

	price spread 2000-2012	price spread 2000-2008	price spread 2009-2012
Linear Cointegration	-3.4325 ***	-5.8921 ***	-0.0859

Notes: Time period April 14 2000 to November 30 2012. Results for unit root tests with a null hypothesis of a unit root and a maximum lag length of $T^{1/3} = 9$ The Schwarz Criterion is used to select the lag lengths for the ADF unit root test. A rejection of the null hypothesis of a unit root at the 1, 5 and 10 percent significance level is denoted by ***, ** and *, respectively.

Table (2) shows the cointegration test results on the prespecified cointegration relationship $s_t = p_{UK,t} - p_{US,t}$. The tests for the full period 2000 to 2012 and for the first subsample 2000 to

tests ignore that theory clearly states a cointegration vector of (1,-1) and estimate the parameters of the long run relationship. Thereby additional uncertainty is introduced that is reflected in too conservative test critical values. In our case the testable longrun relationship (1,-1) can clearly be derived from LOP theory. Therefore, in order to optimally test for cointegration, we should not estimate the longrun relationship, but directly test the known relationship for (non-)stationarity as suggested by Horvath and Watson (1995).

2008 reject the null hypothesis of a unit root at the 1 percent significance level and thus provide sound evidence for cointegration. In contrast, the results for the period 2009 to 2012 indicate no cointegration.

As we have just demonstrated, standard testing for cointegration with known cointegration vectors can be done by testing the null hypothesis of a unit root against the alternative hypothesis of linear cointegration. Particularly, linear here means that independent of the size of the deviation from the equilibrium a price adjusts proportionally to the size of the deviation.

In contrast, LOP theory suggests that if the absolute value of the price difference between two markets is smaller than transaction costs arbitrage is not profitable. Therefore, in such time periods there will be no arbitrage and no price adjustment. Thus, there should be a set of "small" price spreads where no error correction occurs. As outlined in Section (2) this set of price combinations constitutes a symmetric band around the long run relationship that is confined by two symmetric thresholds that represent transaction costs and other impediments to arbitrage. Only if the price spread is larger (if it is positive) than the threshold value or smaller (in case the spread is negative) than the negative threshold value there should be reversion of the price spread towards the long run relationship. Balke and Fomby (1997) and Enders and Granger (1998) show that traditional tests for unit roots and cointegration have low power in the presence of asymmetric adjustment. Particularly, if a process is characterized by threshold cointegration and threshold error correction this is strongly decreasing the power of conventional linear cointegration tests that ignore threshold nonlinearity in the alternative hypothesis. In order to use a test that explicitly takes account of cointegration in the presence of threshold error correction we follow Enders and Granger (1998) and employ a cointegration test that is based on the band threshold autoregressive process. First, the BAND-TAR equations, the estimation procedure and how this framework is used to test for threshold cointegration is outlined. Then the estimation and test results are presented.[3] The econometric representation of the BAND-TAR model is shown in Equation (13).

$$\Delta s_t = \rho_1(s_{t-1} - \tau)[s_{t-1} > \tau] + \rho_2(s_{t-1} + \tau)[s_{t-1} < -\tau] + \sum_{k}^{K} \Delta s_{t-k} + \epsilon_t \tag{13}$$

[3]For a general economic discussion of the results the reader is refered to subsection "General Discussion".

Equation (13) resembles the BAND-TAR Equation (7). The first differenced price spread Δs_t is explained by a tripartite process. In each time period Δs_t follows only one of the three "sub"-processes. Either Δs_t follows the autoregressive process $\rho_1(s_{t-1} - \tau)$ if the lagged price spread s_{t-1} is above the threshold value τ, the autoregressive process $\rho_2(s_{t-1} + \tau)$ if s_{t-1} is smaller than minus τ or a random walk if the absolute value of s_{t-1} is smaller than τ, respectively. A number of lags of the dependent variable is included to prevent residual autocorrelation that would render the parameter estimation inconsistent.

The parameters of Equation (13) including the value of the threshold parameter τ are estimated with the iterative grid search method proposed by Chan (1993). Accordingly, the equation is estimated several times with OLS - each time using a different value of the threshold variable s_{t-1} for τ.[4] Each time the sum of squared residuals (SSR) is stored. The value of the threshold variable that yields the lowest SSR is regarded as the final estimate of τ. This value of τ is used to actually estimate the parameters. The number of lags of the dependent variable is chosen by the Schwarz information criterion. The approach gives consistent estimates of the parameters of Equation (13) and a super-consistent estimate of the threshold parameter τ.

After estimating Equation (13) with Chan´s grid search procedure the presence of threshold cointegration can be tested. Testing for threshold cointegration is similar to testing for linear cointegration. Basically, Equation (13) is the BAND-threshold nonlinear counterpart of the ADF equation used for the linear cointegration tests. If the price spread, that is, the assumed long run relationship (1,-1) between the UK and US natural gas price were non-stationary then - as a null hypothesis - we would expect that $\rho_1 = \rho_2 = 0$. Accordingly, the price spread then is only explained by the error term, s_t is a unit root process and the US price and the UK price of natural gas are not cointegrated. The alternative hypothesis is that $\rho_1 \neq 0$ and $\rho_2 \neq 0$. The threshold cointegration test is performed using an F-Test for the joint restrictions implied by the null hypothesis. The critical values with which the F-test statistics have to be compared are non-standard. Unfortunately, no critical values for the general version of the test equation (13) are available. Yet, approximate critical values are available when we use a more restricted version of

[4]As recommended by Chan, the lowest and the highest 15 percent of the values of s_{t-1} are not used as potential threshold values to provide meaningful results.

the equation for the test that resembles the two regime threshold cointegration test developed by Enders and Granger (1998). In order to use the critical values published in Enders and Granger (1998) we restrict equation (13) by setting $\rho_1 = \rho_2 = \rho_{arbitrage}$ and hence effectively create a two regime threshold cointegration test. $\rho_{arbitrage}$ is the autoregressive coefficient for the arbitrage regime and the inner, no arbitrage regime follows a random walk.[5] This restriction is equivalent to the mild assumption that the speed of adjustment of the price spread to the attractor τ is equal regardless of whether the price spread is positive or negative (unless the absolute value of the price spread is larger than the threshold value).

Further, if evidence for cointegration could be found we can test whether the corresponding error correction process is indeed threshold nonlinear. Linear adjustment as opposed to threshold non-linear adjustment means that the speed of adjustment in all regimes is equal. So, we have to test whether the speed of the adjustment in the arbitrage regime is equal to the speed of adjustment in the no arbitrage, random walk regime. The speed of adjustment in the no arbitrage regime is zero as implied by the random walk. Accordingly, we effectively have to test the null hypothesis of zero adjustment in the arbitrage regime which is the same as the null hypothesis in the threshold cointegration test. Hence, the corresponding test statistic is the same F-statistic that we obtained for cointegration test. However, after we found threshold cointegration we now have to compare the F-statistic to critical values of the standard F-distribution. If the null of no adjustment $\rho_{arbitrage} = 0$ can be rejected this is regarded as evidence for threshold nonlinear error correction.

In the following the threshold estimates and test results are presented. A comprehensive economic discussion of the results follows below in subsection (3.4). The threshold estimates for the full sample 2000 to 2012 and the two sub-samples 2000 to 2008 and 2009 to 2012 are given in the top row of Table (3). The estimates for the other parameters of equation (13) are left out for conciseness. In the full sample arbitrage activity and reversion of the price spread to the threshold only happens when the price spread is above 4.72 US-Dollar per MMBtu in absolute terms. The

[5]Even with this restriction in place our test equation is not perfectly equal to the equation used by Enders and Granger. However, we conjecture the critical values for our case will not differ greatly from the Enders Granger critical values. At least, given the size of all our threshold cointegration test statistics obtained in the estimations small deviations from the appropriate critical values should not be of importance for the validity of the test results.

threshold estimate for the first sub-sample 2000 to 2008 is low at 2.89 US-Dollar per MMBtu. In contrast, the threshold estimate for 2009 to 2012 is far higher at 6.56 US-Dollar per MMBtu implying that only very high price spreads in absolute terms lead to reversion of the price spread towards the long run equilibrium.[6]

Table 3: Tests for cointegration and threshold non-linearity

		2000-2012	2000-2008	2009-2012
Threshold value		4.72	2.89	6.56
Threshold cointegration test	test statistic	67.18	72.51	14.27
	significance level	1%	1%	1%
Threshold nonlinearity test	test statistic	67.18	72.51	14.27
	significance level	1%	1%	1%

Notes: The estimates of the threshold values are measured in US-Dollar per MMBtu. The critical values used to obtain the significance levels for the threshold cointegration test are from Enders (2001). The critical values for the threshold non-normality test correspond with the usual F-distribution.

The second and the third row of Table (3) show the test statistics and the significance levels of the threshold cointegration tests. Accordingly, there is strong evidence for cointegration in the full sample and each of the sub-samples as the null hypothesis of a unit root can be rejected at the 1 percent and the 2.5 percent significance levels, respectively. The fourth and fifth row of Table (3) show the results for the threshold non-linearity tests. The null hypothesis of a linear process can clearly be rejected at the 1 percent significance level in all sample periods. This can be regarded as strong evidence for threshold non-linearity and, hence, threshold cointegration of the US and UK natural gas prices.

3.3. TVECM Estimation - Adjustment of individual prices

Up to now we have found evidence that UK and US natural gas prices are cointegrated. To get a better understanding of the adjustment process of the two individual price series we estimate a threshold vector error correction model. This model allows us to estimate how single prices, say the UK gas price, adjusts when the UK and the US prices are not in the long equilibrium and arbitrage is profitable. According to the LOP with transaction costs there should only be arbitrage

[6] When performing Chan´s grid search the threshold estimates partly vary with respect to the share of the excluded observations at the upper and the lower value range of the threshold variable. However, even in the presence of this phenomenon the estimates can still be considered as determined at least in a partially endogenous fashion.

and, hence, statistically significant adjustment of at least one of the two price series if the absolute value of the price spread is larger than the threshold value representing the transaction costs. The following system of equations represents our TVECM model.

$$\begin{aligned}
\Delta p_{UK,t} &= \gamma_{UK,high}(s_{t-1}-\tau)[s_{t-1}>\tau] + \gamma_{UK,low}(s_{t-1}+\tau)[s_{t-1}<-\tau] + \sum_{k=1}^{K}\Delta p_{UK,t-k} \\
&\quad + \sum_{j=1}^{L}\Delta p_{US,t-j} + \epsilon_{UK,t} \\
\Delta p_{US,t} &= \gamma_{US,high}(s_{t-1}-\tau)[s_{t-1}>\tau] + \gamma_{US,low}(s_{t-1}+\tau)[s_{t-1}<-\tau] + \sum_{m=1}^{M}\Delta p_{US,t-m} \\
&\quad + \sum_{l=1}^{N}\Delta p_{UK,t-l} + \epsilon_{US,t}
\end{aligned} \tag{14}$$

Equation (14) resembles the BAND-TVECM Equations (10) and (11). The first differenced natural gas prices for UK and US are each explained by two error correction terms and a set of lagged explanatory variables. The "high" and "low" regimes are defined by the price spread being larger than the positive threshold value τ or smaller than the negative threshold value $-\tau$. In accordance with the procedure outlined in Enders (2008) the value of τ in each sample period is equal to the threshold estimates from the TAR model given in Table (3). We do not allow for arbitrage and adjustment if the absolute value of the price spread is smaller than the threshold value τ. We estimate a symmetric adjustment and an asymmetric adjustment version of the BAND-TVECM described above as economic theory does not make a clear a priori case for one of the two model versions. The more general, asymmetric adjustment specification is readily represented by Equation (14) above. For the symmetric adjustment version we restrict $\gamma_{l,high} = \gamma_{l,low}$. The set of lags of the dependent variable and the other explanatory variables in each equation of the system of equations is determined by the sequential elimination algorithm (SE) as outlined in Lütkepohl (2004). The SE procedure leads to a reduced number of parameters that have to be estimated and, thus, to a more efficient estimation. The SE procedure first estimates the system of equations by generalized least squares (GLS) with a certain maximum lag length for the explanatory variables. Hereafter, the explanatory variable whose elimination leads to the largest decrease in an information criterion is eliminated from the system and the system is estimated again with a zero restriction placed on the respective variable.[7] This procedure is repeated until no further reductions in the information criterion are possible by eliminating any variable lags. The model specification that results from the SE procedure is used in the actual estimations. For each TVCEM we start the sequential elimination procedure with 18 initial lags of the lagged dependent and the other lagged explanatory variables in each equation. Due to the partly long lag structure the final specification is not shown here, but can be obtained from the authors. The final model is estimated by GLS.[8] The estimated adjustment coefficients for the full sample, the 2000 to 2008 sub-sample and the 2009 to 2012 sub-sample for the final specification after the sequential elimination procedure are shown in Table (4).[9]

The results for the full sample symmetric BAND-estimation show that once the price spread is above the threshold value in absolute terms there is significant adjustment to the long run equilibrium for both the US and the UK prices of natural gas. The adjustment of the UK price of 25 percent per week is much larger than the 5.9 percent adjustment of the US price. The estimates for the more general asymmetric BAND model support the symmetric version in that there is adjustment in both prices. In addition, the asymmetric model provides us with more refined insights about the error correction process. There is strong evidence that adjustment in the UK price only takes place when the price spread is above the threshold. But there is no adjustment if there is a negative price spread, that is, the US price is higher than the UK price (and this spread is also smaller than the negative threshold value). Similarly, the US price only shows significant adjustment when the price spread is negative and below the negative threshold value. The adjustment of the US price in this case is much stronger at 28.9 percent than in the symmteric case.

[7] We use the Schwarz information criterion in the SE procedure. When the lag restrictions placed on the system of equations by the SE procedure using the Schwarz criterion resulted in autocorrelated residuals, then the less restrictive Akaike criterion was employed in the SE procedure. This always resulted in residuals that were free from autocorrelation.

[8] GLS estimation is necessary because OLS would lead to a less efficient estimation in the presence of a set of lagged dependent and other explanatory variables that faces different restrictions in each equation of the system.

[9] All estimated models were tested for residual autocorrelation with LM tests as proposed by Lütkepohl (2004). No evidence for autocorrelation could be detected in any of the regressions. However, residual non-normality tests point to a decreased estimation efficiency. Autocorrelation and non-normality test results are not shown here for conciseness.

Table 4: Results for BAND-TVECM estimations

Period	Model	Regime	Δp_{US}	t-value	Δp_{UK}	t-value
2000-2012	Symmetric		0.059^{***}	(2.307)	-0.250^{***}	(-5.034)
	Asymmetric	high	-0.007	(-0.229)	-0.305^{***}	(-5.264)
		low	0.289^{***}	(6.283)	-0.047	(-0.524)
2000-2008	Symmetric		0.094^{***}	(3.532)	-0.460^{***}	(-8.997)
	Asymmetric	high	-0.037	(-0.789)	-1.000^{***}	(-12.012)
		low	0.152^{***}	(4.84)	-0.154^{***}	(-2.676)
2009-2012	Symmetric		0.009	(0.168)	-0.387^{***}	(-3.264)
	Asymmetric	high	0.009	(0.168)	-0.387^{***}	(-3.264)
		low	–	-	–	-

Notes: Lag order selected with SE algorithm using the by Schwarz information criterion. Where the Schwarz criterion results in autocorrelated error terms the Akaike information criterion was used because it allows for more generous lag lengths. */**/*** attached to coefficients signify that the coefficient is significantly different from zero at the 10%, 5% or 1% level, respectively. t-values are given in brackets.

As in the full sample in the symmetric BAND model for the 2000 to 2008 sub-sample both the US and the UK price adjust significantly. Again the UK price with 46 percent shows much higher error correction than the US price with only 9.4 percent. The results for the asymmetric BAND TVECM for 2000 to 2008 are qualitatively not too different from the results for the full sample. The UK price is significantly adjusting as long as arbitrage is profitable. The adjustment of the UK price in the positive price spread regime is very strong at 100 percent meaning that a positive price spread is fully corrected after one week when the spread was positive and above the threshold value. In contrast, the US price is only significantly adjusting at a rate of 15 percent when arbitrage is profitable and the US price is above the UK price (i.e. the price spread is negative).

The results for the 2009 to 2012 sub-sample differ substantially from the results for the period 2000 to 2008. The results for the symmetric and the asymmetric TVECM are equal as there were no negative price spreads that where below the negative threshold value in the later sub-sample. The estimation results indicate that there is significant and substantial adjustment only in the UK price.

3.4. General Discussion

In this subsection we interpret and discuss the estimation results. As outlined above the LOP implies price convergence which is reflected in threshold error correction and cointegration in econometric modeling. In contrast, linear cointegration tests ignore the potential threshold property of an adjustment process. This is reflected in the results for linear cointegration tests in Table (2) and threshold cointegration tests in Table (3). Whereas both linear and threshold tests find cointegration in the full sample and the 2000 to 2008 sub-sample the test results for the later subsample differ. In contrast to the linear cointegration test that finds no evidence for cointegration the threshold cointegration test strongly supports cointegration in the period 2009 to 2012. This finding provides evidence against the notion of a "decoupling" of gas markets in recent years - at least if decoupling means that the LOP does not hold or that there is no arbitrage driving the prices towards each other. Threshold nonlinearity tests further indicate that a threshold framework indeed is improving on previous linear cointegration approaches in that it is a more appropriate model to capture adjustment dynamics of benchmark gas prices such as the US and UK prices.

Basically, LNG trade is the only way to arbitrage between the US and the UK natural gas market. The typical transport cost differential of LNG transports from usual exporting countries such as Qatar to US destinations compared to UK destinations is below 2 US dollar per MMBtu.[10] In the last decade this LNG transport cost differential has not changed substantially at least in comparison to commonly observed gas price differentials in this period. Therefore a comparison of our threshold values that are estimates of transaction costs and other impediments to arbitrage gives us some indication of the size of non-transport cost impediments for arbitrage activity. Table (3) shows that the threshold estimates (of 2.89 US dollar per MMBtu for the period 2000 to 2008 and 6.56 US dollar per MMBtu for the period 2009 to 2012) differ widely. This can be regarded as evidence that impediments to arbitrage in the Atlantic gas market other than transport costs have increased largely in the later period. Usual candidates for these impediments are capacity limits for LNG import and export. This could be an explanation between 2009 and 2012 when UK LNG imports reached unprecedented levels and possibly also UK LNG import capacity limits. Another potential explanation could be increased Japanese LNG demand and prices after the Fukushima disaster in the year 2011. This could have created higher opportunity costs of delivering LNG

[10]Market information providers such as Platts or ICIS differ somewhat in their measurement of LNG transport cost. However, two US dollar per MMBtu seems to be a reasonable upper bound for the US-UK transport cost differential from the most relevant exporting regions.

quantities to the Atlantic basin and to the high price UK market in particular. But also contractual structures and other non-fundamental factors can be mentioned as a potential explanation. Further, technical constraints in LNG shipping could also play a role as not all types of LNG carriers are capable of delivering gas to all LNG regasification terminals. Market power in the LNG market and the LNG shipping market which is further promoted by the often integrated ownership structure in the LNG supply chain could also be an explanation.

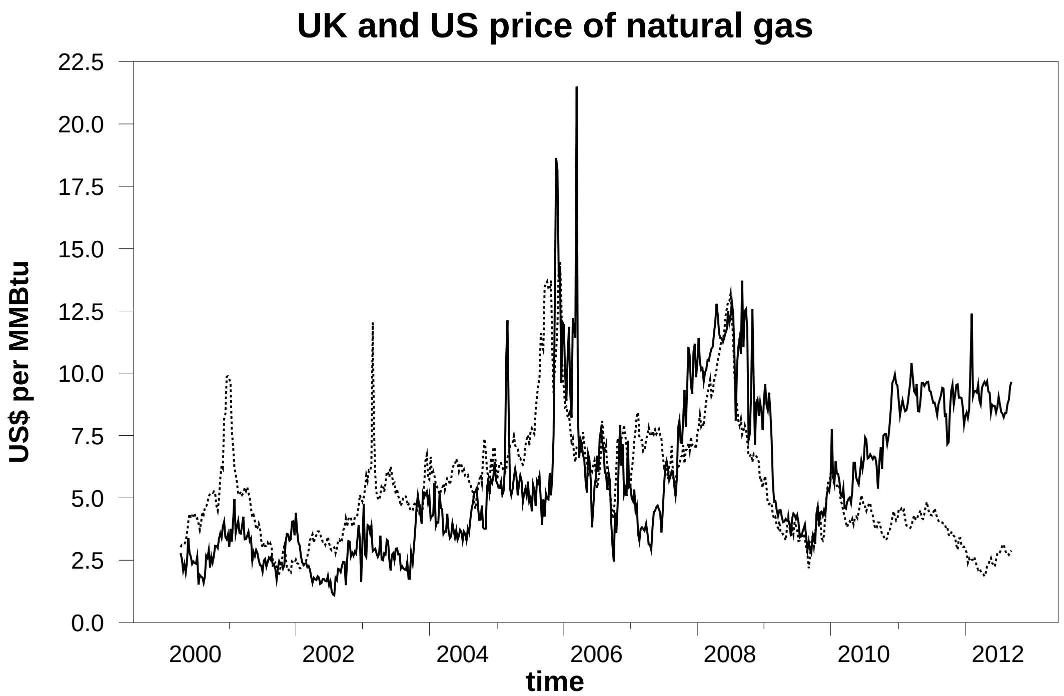

Figure 3: Prices for UK National Balancing Point (solid line) and US Henry Hub (dashed line)

The results from the TVECM estimation presented in Table (4) allow for a more detailed look at the adjustment of individual prices. In the symmetric model versions in all (sub)samples the UK price is adjusting stronger than the US price. Further, the results for the asymmetric adjustment models reveal an interesting pattern. Hence, adjustment in a price tends to be statistically significant and quantitatively strongest when disequilibrium is resulting from a market specific positive price shock in that respective market. Accordingly, arbitrage can be considered to play a role for restoring the spatial equilibrium mostly after a negative supply shock or a positive demand shock has induced a rise in prices in one of the markets. As shown in Figure (3) positive price shocks can be frequently observed in both the US and the UK natural gas markets. Most of these price spikes result from increased demand resulting for instance from unexpected cold spells or economic upswings or from perilous events on the supply side such as the US hurricane season in the year 2005. In line with the results from the symmetric model the asymmetric adjustment in the UK price is substantially stronger for the UK price than for the US price in the full sample and the sub-sample 2000 to 2008. In the period 2009 to 2012 the US price shows no significant adjustment which is in line with the fact that LNG imports to the US have dwindled to very low levels in that period. However, we observe significant downward adjustment of the UK price when the UK price is above the US price and arbitrage is profitable. The latter was the situation particularly in the late year 2011 and during the year 2012 when UK gas prices and UK LNG imports were both high. Thus, in the 2009 to 2012 period price convergence in accordance with the LOP is mainly induced by downward pressure on the UK price bringing it closer to the independently moving US prices.

4. Conclusion

The term "decoupling of gas markets" has been frequently used to describe the observation that benchmark natural gas prices such as the US and the UK price have diverged roughly since the beginning of the year 2009 and persisted at largely different levels from there on. Given that transport costs have been far lower than these observed price spreads this finding seemingly contradicts the fundamental economic law of one price. We use a threshold cointegration framework to empirically investigate whether there is empirical evidence for the law of one price to hold between the US and UK natural gas market.

First, we have outlined why a threshold cointegration model is more appropriate than linear cointegration approaches to study the LOP in gas markets. Second, we have used a linear and a threshold cointegration model to test for cointegration as well as the presence of threshold non-linearity. In contrast to the linear cointegration tests, when using the threshold model we find strong evidence in favor of cointegration and price convergence as well as threshold non-linearity in all our (sub)samples. Hence, even if Atlantic natural gas price seem disconnected in recent years they are still pulled together by the forces of arbitrage as implied by the law of one price. Third, our threshold estimates which constitute a measure for transaction costs and other impediments to arbitrage are found to be much larger than the typical LNG transport cost differential between US and UK market in the period 2009 to 2012. This implies the emergence of very high non transport transaction costs and other arbitrage impediments such as capacity constraints in LNG trade or market power. Hence, the decomposition of the threshold values into their constituents opens opportunities for further research. Fourth, our estimates of threshold vector error correction models indicate that between 2000 and 2008 both US and UK prices adjusted significantly to restore an arbitrage free situation with the UK price playing a stronger role in that regard. Between 2009 and 2012, when UK prices were mostly far above US prices we find downward pressure on the UK price, but no adjustment in the US price.

Taken together, we have provided evidence for the law of one price to hold - even in the period 2009 to 2012 when US and UK gas prices seemed to have decoupled. Moreover, our results indicate the presence of high non-transport transaction costs and other impediments to arbitrage in recent years that substantially decrease the speed of price convergence compared to the period 2000 to 2008.

Balke, N. S. and Fomby, T. B. (1997). Threshold cointegration. *International Economic Review*, 38(3):627–645.

Brown, S. P. A. and Yücel, M. K. (2009). Market arbitrage: European and north american natural gas prices. *The Energy Journal*, Special Issue:167–185.

Chan, K. (1993). Consistency and limiting distribution of the least squares estimator of a threshold autoregressive model. *The Annals of Statistics*, 21(1):520–533.

Enders, W. (2001). Improved critical values for the enders-granger unit-root test. *Applied Economics Letters*, 8:257–261.

Enders, W. (2008). *Applied econometric time series.* John Wiley & Sons.

Enders, W. and Granger, C. W. J. (1998). Unit-root tests and asymmetric adjustment with an example using the term structure of interest rates. *Journal of Business & Economic Statistics*, 16(3):304–311.

Engle, R. F. and Granger, C. W. J. (1987). Co-integration and error correction: Representation, estimation, and testing. *Econometrica*, 55(2):251–76.

Horvath, M. T. K. and Watson, M. W. (1995). Testing for cointegration when some of the cointegrating vectors are prespecified. *Econometric Theory*, 11(5):984–1014.

Johansen, S. and Juselius, K. (1992). Testing structural hypotheses in a multivariate cointegration analysis of the ppp and uip of uk. *Journal of Econometrics*, 53:211–244.

Kao, C.-W. and Wan, J.-Y. (2009). Information transmission and market interactions across the atlantic an empirical study on the natural gas market. *Energy Economics*, 31:152–161.

Lo, M. C. and Zivot, E. (2001). Threshold cointegration and nonlinear adjustment to the law of one price. *Macroeconomic Dynamics*, 5:533–576.

Lütkepohl, H. (2004). *Vector Autoregressive and Vector Error Correction Models*, chapter 3, pages 86–158. Cambridge University Press.

Neumann, A. (2009). Linking natural gas markets - is lng doing its job? *The Energy Journal*, Special Issue:187–200.