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

AUTHORS

Sebastian Nick (EWI)

Benjamin Tischler (EWI)

EWI Working Paper, No 14/16

November 2014

Institute of Energy Economics at the University of Cologne (EWI)
www.ewi.uni-koeln.de

Institute of Energy Economics
at the University of Cologne (EWI)

Alte Wagenfabrik
Vogelsanger Straße 321
50827 Köln
Germany

Tel.: +49 (0)221 277 29-100
Fax: +49 (0)221 277 29-400
www.ewi.uni-koeln.de

CORRESPONDING AUTHOR

Benjamin Tischler
Institute of Energy Economics at the University of Cologne (EWI)
Tel: +49 (0)221 277 29-324
Fax: +49 (0)221 277 29-400
benjamin.tischler@uni-koeln.de

ISSN: 1862-3808

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

Sebastian Nick[a], Benjamin Tischler[a,*]

[a] *Institute of Energy Economics, University of Cologne, Vogelsanger Straße 321, 50827 Cologne, Germany.*

Abstract

The US and UK markets for natural gas are connected by arbitrage activity in the form of shifting trade volumes 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 accordance with the law of one price and explicitly accounts for transaction costs. Our empirical results reveal a high degree of market integration for the period 2000-2008. Although US and UK gas prices seemed to have decoupled between 2009 and 2012, we still find a certain degree of integration pointing towards significant regional price arbitrage. However, high threshold estimates in the latter period 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

JEL classification: Q40, Q41, G14, C51.

---

*Corresponding author

Email address: `Benjamin.Tischler@uni-koeln.de, +49 22127729324` (Benjamin Tischler)

1. Introduction

In the last decade, trade volumes of liquefied 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 since 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 while prices at the UK National Balancing Point (NBP) increased, resulting in high price spreads between the US and UK natural gas markets (see Figure 1). The law of one price (LOP) theory states that prices will adjust towards each other due to arbitrage activity once the price spread between two markets is larger than the transaction costs of spatial arbitrage. Thus, 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 forces of arbitrage even if persistent price spreads can be observed between these markets.

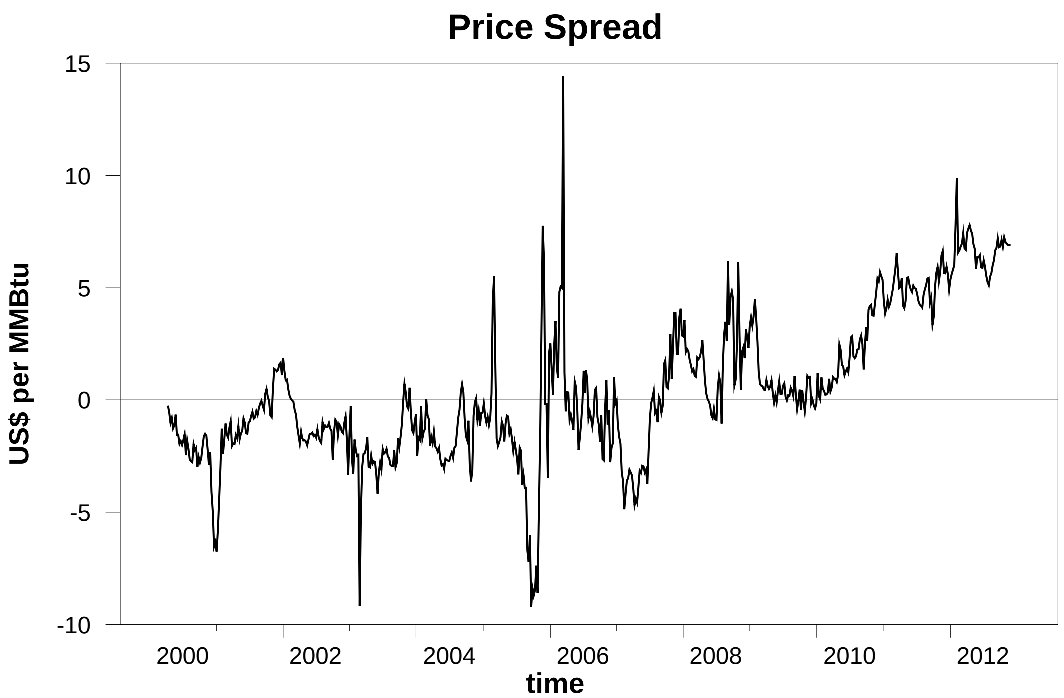

Figure 1: Price Difference between UK National Balancing Point and US Henry Hub

Up to now, the relationship between international gas prices has been mostly analyzed using linear cointegration analysis as done by 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 therefore conclude that there is a certain degree of integration between the US and UK gas markets that may be attributed to spatial arbitrage via LNG volumes.[1] Most recently, Li et al. (2014) use data from 1997 to 2011 and employ a test for market convergence that is not related to the notion of cointegration. A subsequent Kalman filter analysis of price convergence is based on a linear relationship between gas prices. The authors find several converging gas prices around the globe. Though, no convergence between the US gas market and other gas markets can be found.

However, linear (cointegration) models may not capture arbitrage dynamics in a spatial setting adequately since they do not account for transaction costs - including transportation costs - that can impede arbitrage activity. The inability to consider transaction costs may distort the validity of the cointegration analysis and hence the corresponding economic interpretation, i.e., the degree of market integration. To overcome this methodological caveat, we use a threshold cointegration approach to test for price convergence. We use a threshold cointegration framework since this enables the explicit consideration of transaction costs and thus fits well to the specifics of the LOP theory in a spatial setting.

The focus of this study is on the relationship between the natural gas spot prices in the US and the UK. First, we use both linear and threshold cointegration tests to test for price convergence between the US and the UK natural gas price. In other words, we test whether we can find empirical evidence of 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 to arbitrage activity such as capacity and contractual constraints. Second, in case we find evidence of threshold cointegration, we use a threshold vector error correction model (TVECM) in order to investigate the dynamics that restore the long-run equilibrium. The TVECM thereby provides additional insights regarding the speed and direction

[1] An exception is an early paper by Siliverstovs et al. (2005) who find no cointegration between the US and the European gas market from the early 1990s to 2004.

of adjustment of the individual price series during the arbitrage process. We hence obtain an indication as to the degree of transatlantic gas market integration and as to how quickly arbitrage is pushing price convergence.

We conduct the steps described above 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 previous research and thus enables the comparison with studies using linear cointegration approaches. The latter sub-sample corresponds to the period when the UK and US gas prices are often said to have decoupled. Linear and threshold cointegration tests both imply that natural gas markets are cointegrated in the full sample period 2000 to 2012. In addition, in the 2000 to 2008 sub-sample, there is empirical evidence of both linear and threshold cointegration of the UK and US price series. In the second sub-sample the linear cointegration test rejects the hypothesis of cointegration. However, using the threshold cointegration test that is more consistent with the LOP, there is empirical evidence of cointegration also in the second sub-sample.

The threshold estimates of our empirical approach provide an indication of the price differential that is necessary to trigger spatial arbitrage. While we find empirical evidence of arbitrage activity starting already at rather low price spreads in the first sub-sample, our results suggest that arbitrage is only triggered in the case of very high price spreads in the second sub-sample. Moreover, a comparison of our 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 suggest that between 2000 and 2008 both markets adjusted to restore the long-run equilibrium. In contrast, between 2009 and 2012, price convergence was exclusively achieved by the UK price of natural gas.

The contribution of our study is threefold. First, we improve the econometric framework for studying price convergence and spatial arbitrage in global natural gas markets by specifying an econometric model that is more consistent with LOP theory than previous approaches. Second, our empirical approach reveals that, at least for the 2009 to 2012 sub-sample, linear and threshold cointegration frameworks deliver different results regarding price convergence and thus arbitrage activity. Third, our empirical results provide evidence of the US gas price and the UK gas price being still pulled together by arbitrage as implied in the LOP, although both prices seem to have decoupled since 2009. The remainder of this paper is organized as follows: In Section 2, we show how the LOP can be represented by an econometric model explicitly accounting for transaction costs. Section 3 introduces the econometric procedures necessary to test for price convergence and arbitrage activity. We also present and discuss the empirical results in this Section. Section 4 concludes.

2. Theoretical Framework

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

Our study is grounded on LOP, stating that the price for the same good should be equal in different markets. The LOP theory is based on the assumption of a homogenous good that can be resold to different markets without restrictions. In such a setting, the LOP is expected to hold since any price divergence triggers arbitrage and thus is only of transitory nature. The arbitrage conditions for traders participating in two markets i and j subject to transaction costs τ, can be stated as

$$\begin{aligned} P_1 >& \quad P_2 + \tau \\ P_1 <& \quad P_2 - \tau. \end{aligned} \tag{1}$$

Thus, arbitrage activity may only be triggered if the implied gross profit of the trade covers transaction costs. In a frictionless world without transaction costs, τ equals zero and thus drops out of the equation.

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 this 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 spatial arbitrage in the natural gas market.

Since the price arbitrage that is of interest in this study 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 1 and 2. In addition, market 1 is assumed to be the more remote market for the exporter, resulting in increased transportation costs when this market is served instead of market 2. As long as the regional price differential $P_1 - P_2$ does not exceed the difference in transportation costs, $\Delta TC_{1,2}$, all spot volumes are shipped to market 2. In contrast, market 1 is exclusively served when the transportation cost differential is covered by the greater revenues that can be generated by selling the gas to market 1. Equation (2) states the indifference condition for the arbitrageur with regard to the potential destinations:

$$\Delta TC_{1,2} = P_1 - P_2 \tag{2}$$

with

$$\Delta TC_{1,2} = TC_1 - TC_2 \tag{3}$$

where TC_1 and TC_2 denote the transportation costs for the exporter to market 1 and market 2, respectively. The situation when switching from market 1 to market 2 is profitable for the arbitrage player in our simplified example is illustrated in Figure 2.

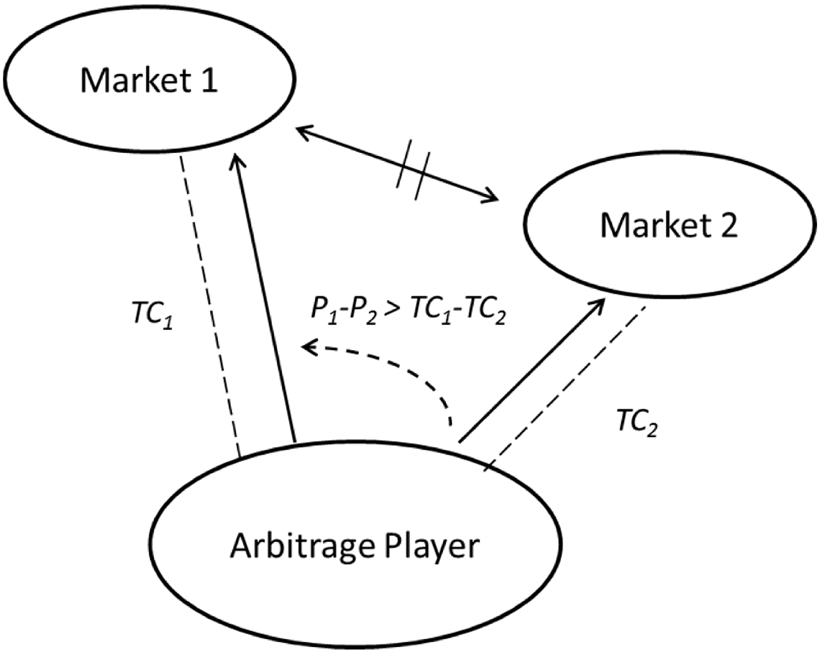

Figure 2: Regional Price Arbitrage in the Global Natural Gas Market

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 requires the stationary behavior of the price spread $s_t = P_1 - P_2$. 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:

$$s_t = (\varrho + 1)(s_{t-1}) + \epsilon_t \tag{4}$$

or equivalently

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

with $-1 < \varrho < 0$ to ensure stationarity of the process and ϵ_t as an error term with zero mean and finite variance.

The existence of transaction costs causes a "band of no arbitrage" between both markets as stated in Equation (1). 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 an adjustment of the prices towards a price spread of zero. However, the price spread never actually becomes zero as the adjustment towards the equilibrium stops when the price spread is equal to transaction costs and arbitrage is not profitable anymore. From this point on, the two prices move independently until a shock makes arbitrage profitable again. 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) than by an ordinary autoregressive process:

$$\Delta s_t = \begin{cases} \gamma_1(s_{t-1} - \tau) + \epsilon_t, & \text{if } s_{t-1} > \tau \\ \epsilon_t, & \text{if } |s_{t-1}| \leq \tau \\ \gamma_3(s_{t-1} + \tau) + \epsilon_t, & \text{if } s_{t-1} < -\tau \end{cases}, \tag{6}$$

where γ_1 and γ_3 are the adjustment coefficients and ϵ_t is an error term with zero mean and finite variance. The representation in Equation (6) 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 threshold τ. Balke and Fomby (1997) who first introduced this type of TAR-model call the corresponding stochastic process a band threshold autoregressive (BAND-TAR) process. In our empirical application, τ represents a time-invariant threshold since we are not aware of significant changes in LNG shipping costs over time. In addition, the computation of time-variant thresholds imposes high numerical complexity. We thus abstain from allowing the threshold to vary over time. However, we allow for different threshold values in our sub-samples.

In general, the model specified in Equation (6) accounts for asymmetric dynamics in the adjustment process. This means that the adjustment behavior may be different depending on whether the price spread is positive or negative. The specific case of symmetric adjustment, i.e., identical adjustment behavior regardless of the direction of the equilibrium deviation, is nested in Equation (6) by the coefficient restriction $\gamma_1 = \gamma_3$.

Accounting for transaction costs, the threshold vector error correction model (TVECM) seems thus well suited for the empirical investigation of arbitrage between two markets. We thus specify the following TVECM to investigate arbitrage dynamics between the two markets:

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

$$\Delta P_{t,2} = \begin{cases} \gamma_2^{(1)}(s_{t-1} - \tau) + \epsilon_{2t}, & \text{if } s_{t-1} > \tau \\ \epsilon_{2t}, & \text{if } |s_{t-1}| \leq \tau \\ \gamma_2^{(3)}(s_{t-1} + \tau) + \epsilon_{2t}, & \text{if } s_{t-1} < -\tau \end{cases}, \tag{8}$$

where the threshold τ equals the estimate of τ from the a univariate TAR model and ϵ_{1t} and ϵ_{2t} are error terms with zero mean and finite variance. In Equation (7) and Equation (8), prices stop to adjust towards the long-run equilibrium when the price spread drops below the transaction cost threshold. The TVECM outlined above accounts for asymmetric error correction, meaning that the adjustment of each individual price is allowed to differ with respect to the sign of the price spread. However, the specifications in Equation (7) and Equation (8) also nest the symmetric case via the coefficient restrictions $\gamma_1^{(1)} = \gamma_1^{(3)}$ 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.

3. Empirical Application

This section comprises four subsections and presents the econometric estimation and testing procedures as well as the corresponding empirical 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 and draw conclusions with regard to the degree of transatlantic gas market integration.

3.1. Data

We use weekly price data for the period April 2000 to November 2012. The Henry Hub (HH) spot price, 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 the sake of comparability, the UK price is converted to US dollars per MMBtu using appropriate physical conversion factors and the weekly exchange rate published by the Bank of England.

In order to investigate whether or not there is still price convergence after the "decoupling of gas prices", we perform all our empirical approaches 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 allows for an adequate number of observations in the second sub-sample.

In contrast to other studies of spatial arbitrage such as Lo and Zivot (2001), we do not use the logarithm of the natural gas prices but the price levels themselves. Using the logarithms is a frequent transformation in order to get the data more consistent with the assumptions needed for 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. [2] Thus,

[2] In addition, 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. In specific, their arbitrage conditions imply that the threshold, representing transaction costs and other frictions, is proportional to the revenues from arbitrage.

we argue that only a specification on actual price levels is in line with LOP theory. LOP theory implies that in the long run, prices should be equal and thus tied together by a linear relationship.

3.2. Threshold Estimation and Testing for (Threshold) Cointegration

First and foremost, it has to be determined whether UK and US natural gas prices share 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 if UK and US prices are cointegrated, error correction, price convergence and hence market integration will occur. For the purpose of comparison, 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 14th 2000 to November 30st 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 in order 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 previous studies and to provide a reference for the threshold cointegration tests. When testing for cointegration, we use the structural economic information that, according to LOP theory, the prices are expected to be equal in the long run. The corresponding prespecified cointegration vector is thus (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.[3] In our case, the null hypothesis that the price 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.

$$\Delta s_t = \varrho(s_{t-1}) + \sum_{i=1}^{M} \Delta s_{t-i} + \epsilon_t \tag{9}$$

with $-1 < \varrho < 0$ to ensure stationarity of the process.

If ϱ is not significantly different from zero, the price spread s_t will be exclusively driven by its current error term. In other words, s_t follows a 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, the null hypothesis of non-stationarity will be rejected and the process is stationary. Stationarity of the price spread means implies a stable a long-run equilibrium relationship of the two prices. According to the Engle and Granger (1987) representation theorem, cointegration requires a significant error correction process. In this context, error correction describes the behavior that whenever a shock drives the prices out of their long-run equilibrium, at least one of the prices adjusts in order to restore the equilibrium.

Table 2: Cointegration Test for the 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 14th 2000 to November 30st 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 sub-sample 2000

[3] We abstain from using Johansen and Juselius (1992) or Engle and Granger (1987) cointegration tests. These tests ignore that theory clearly states a cointegration vector of (1,-1) and instead estimate the parameters of the long-run relationship. Thereby, additional uncertainty is introduced that is reflected in critical test values that are too conservative. In our case, the testable long-run relationship (1,-1) can clearly be derived from LOP theory. Therefore, we directly test the known relationship for (non-)stationarity as suggested by Horvath and Watson (1995).

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

As already outlined, standard testing for cointegration with known cointegration vectors can be performed by testing the null hypothesis of a unit root against the alternative hypothesis of linear cointegration. In specific, linear in this context means that independent of the size of the deviation from the equilibrium, the respective 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 periods, there will be no arbitrage and hence 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 comprises a symmetric band around the long-run relationship that is confined by two symmetric thresholds representing transaction costs and other impediments to arbitrage. Only if the price spread is larger in absolute terms than the threshold value, there will be a reversion of the price spread towards the long-run relationship. Balke and Fomby (1997) and Enders and Granger (1998) argue 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 can strongly decrease the power of conventional linear cointegration tests. 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. The econometric representation of the BAND-TAR model is shown in Equation (10).

$$\Delta s_t = \gamma_1(s_{t-1} - \tau)[s_{t-1} > \tau] + \gamma_2(s_{t-1} + \tau)[s_{t-1} < -\tau] + \sum_{k}^{K} \Delta s_{t-k} + \epsilon_t \tag{10}$$

Equation (10) resembles the BAND-TAR of Equation (6). The changes in the 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 an autoregressive process $\gamma_1(s_{t-1} - \tau)$ if the lagged price spread s_{t-1} is above the threshold value τ, or an autoregressive process $\gamma_2(s_{t-1} + \tau)$ if s_{t-1} is smaller than $-\tau$, 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 avoid residual autocorrelation that would render the parameter estimation inconsistent.

The parameters of Equation (10) 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 (10) and a super-consistent estimate of the threshold parameter τ (Chan, 1993).

After estimating Equation (10), the presence of threshold cointegration can be tested. In general, testing for threshold cointegration is similar to testing for linear cointegration. In specific, Equation (10) 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, we will expect $\gamma_1 = \gamma_2 = 0$. 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 $\gamma_1 \neq 0$ and $\gamma_2 \neq 0$. The threshold cointegration test is performed using an F-Test for the joint restrictions implied by the null hypothesis. Unfortunately, no critical values for the general version of the test Equation (10) are available. However, approximate critical values are available when we use a more restricted version of 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 (10) by setting $\gamma_1 = \gamma_2 = \gamma_{arbitrage}$ and hence effectively create a two regime threshold cointegration test. [5] This

[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.

[5]$\rho_{arbitrage}$ is the autoregressive coefficient for the arbitrage regime and the inner, no arbitrage regime follows a random walk. 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 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.

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.

Further, if evidence of cointegration is found, we can test whether the corresponding error correction process has indeed threshold nonlinear character. Linear adjustment, as opposed to threshold nonlinear adjustment, means that the speed of adjustment in all regimes is equal. Thus, it has to be investigated whether the speed of the adjustment in the arbitrage regime is equal to the speed of adjustment in the no arbitrage regime. The speed of adjustment in the no arbitrage regime is zero as implied by the random walk. Accordingly, the null hypothesis of zero adjustment in the arbitrage regime has to be tested, 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, $\gamma_{arbitrage} = 0$, can be rejected this is regarded as evidence of threshold nonlinear error correction.

In the subsequent paragraphs, the threshold estimates and test results are presented. A comprehensive economic discussion of the results follows below in Section 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 (10) 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. Interestingly, the 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 by 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.

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 of cointegration in the full sample and in each of the sub-samples as the null hypothesis of a unit root can be rejected. The fourth and fifth row of Table 3 show the results for the threshold nonlinearity tests. The null hypothesis of a linear process can clearly be rejected at the 1 percent significance level in all sample

Table 3: Tests for Cointegration and Threshold Nonlinearity

		2000-2012	2000-2008	2009-2012
Threshold value		4.72	2.89	6.56
Threshold cointegration and non-linearity test	Test statistic	67.18	72.51	14.27
Threshold cointegration test	Significance level	1%	1%	1%
Nonlinearity test	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.

periods. This can be regarded as strong evidence of threshold nonlinearity and, hence, threshold cointegration of the US and UK natural gas prices.

3.3. TVECM Estimation - Adjustment of Individual Prices

Up to now, we found evidence of the UK and the US natural gas prices being cointegrated. In order 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 the individual price series adjusts when the UK and the US prices are not in the long-run equilibrium and arbitrage is profitable. According to the LOP accounting for transaction costs, there should only be arbitrage and hence statistically significant adjustment of at least one of the two price series if the absolute value of the price spread is greater than the threshold value representing transaction costs. The following system of equations represents the TVECM model applied.

$$
\begin{aligned}
\Delta p_{UK,t} &= \gamma_{UK,high}(s_{t-1} - \tau)[s_{t-1} > \tau] + \gamma_{UK,low}(s_{t-1} + \tau)[s_{t-1} < -\tau] + \sum_{k=1}^{K} \Delta p_{UK,t-k} \\
&\quad + \sum_{j=1}^{L} \Delta p_{US,t-j} + \epsilon_{UK,t} \\
\Delta p_{US,t} &= \gamma_{US,high}(s_{t-1} - \tau)[s_{t-1} > \tau] + \gamma_{US,low}(s_{t-1} + \tau)[s_{t-1} < -\tau] + \sum_{m=1}^{M} \Delta p_{US,t-m} \\
&\quad + \sum_{l=1}^{N} \Delta p_{UK,t-l} + \epsilon_{US,t}
\end{aligned} \tag{11}
$$

Equation (11) resembles the BAND-TVECM Equations (7) and (8). The changes in 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 as well as an asymmetric adjustment version of the BAND-TVECM described above since economic theory does not make a clear a priori case for one of the two model versions. The more general, asymmetric adjustment specification is represented by Equation (11). For the symmetric adjustment version, we restrict $\gamma_{l,high} = \gamma_{l,low}$ for $l = UK, US$. The set of lags of the dependent variable and the other explanatory variables is determined by the sequential elimination (SE) algorithm as outlined in Lütkepohl (2004).[6] 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 TVECM, the sequential elimination procedure is started 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 upon request. The final model is estimated by GLS.[7] The estimated adjustment coefficients for the full sample, and the two sub-samples for the final specification after the sequential elimination procedure are shown in Table 4.[8]

The estimation results for the full sample symmetric BAND model show that once the price

[6]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. 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.

[7]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.

[8]All estimated models were tested for residual autocorrelation with LM tests as proposed by Lütkepohl (2004). No evidence of 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.

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 the sense that there is adjustment in both prices. In addition, the asymmetric model provides us with more refined insights about the error correction process. In specific, adjustment in the UK price only takes place when the price spread is above the threshold. In contrast, there is no adjustment if there is a negative price spread, that is, the US price is higher than the UK price. 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 the asymmetric model is much stronger at 28.9 percent than in the symmetric specification.

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 prices adjust significantly. Again, the UK price with 46 percent shows much stronger error correction dynamics than the US price with only 9.4 percent. The results for the asymmetric BAND TVECM for 2000 to 2008 are qualitatively similar to 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 will be fully corrected after one week if the positive price spread is above the threshold value. In contrast, the US price adjusts only significantly 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. In this period, 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. 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 empirical results obtained from our econometric estimations. As outlined above, the LOP implies price convergence which is reflected in threshold error correction and cointegration in the econometric modeling. In contrast, linear cointegration tests ignore the potential threshold property of an adjustment process caused by transaction costs. This difference 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 sub-sample differ. In contrast to the linear cointegration test that finds no evidence of cointegration the threshold cointegration test strongly supports cointegration in the period 2009 to 2012. This finding provides empirical evidence against the notion of a "decoupling" of gas markets in recent years, at least if decoupling refers to the fact that the LOP does not hold anymore. Threshold nonlinearity tests further indicate that a threshold framework indeed improves previous linear cointegration approaches because it is a more appropriate model to capture adjustment dynamics of benchmark gas prices in different markets.

By and large, LNG trade is the only way of arbitrage between the US and the UK natural gas market. The typical transport cost differential of LNG transports from major exporting countries such as Qatar to US destinations compared to UK destinations is below 2 US dollar per MMBtu.[9]

[9]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.

During the last decade this LNG transport cost differential presumably has not changed substantially. For example, Maxwell and Zhu (2011) argue that LNG tanker costs change only gradually over time and that these costs affect LNG imports only in the long run. Therefore, comparing our threshold values between the two sub-samples provides an indication of the magnitude of non-transport cost impediments for arbitrage activity. Table 3 shows that the threshold estimates differ widely (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, respectively). This can be regarded as evidence of increasing impediments to arbitrage in the Atlantic gas market other than transport costs in the later period. Potential sources of these impediments are capacity constraints 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 may be increased Japanese LNG demand and prices after the Fukushima disaster in the year 2011. The spike of Asian gas prices may have created higher opportunity costs of delivering LNG quantities to the Atlantic basin. In addition, also contractual structures and other non-fundamental factors can be regarded as a potential explanation for the increase in the transatlantic price spread. Further, technical constraints as well as market power due to vertically integrated ownership in LNG shipping market may also play a role.

The results from the TVECM estimation presented in Table 4 allow for a more detailed look on the adjustment behavior 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. The adjustment of prices tends to be statistically significant and strongest when the disequilibrium is resulting from a market-specific positive price shock in the respective market. 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 as well as 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

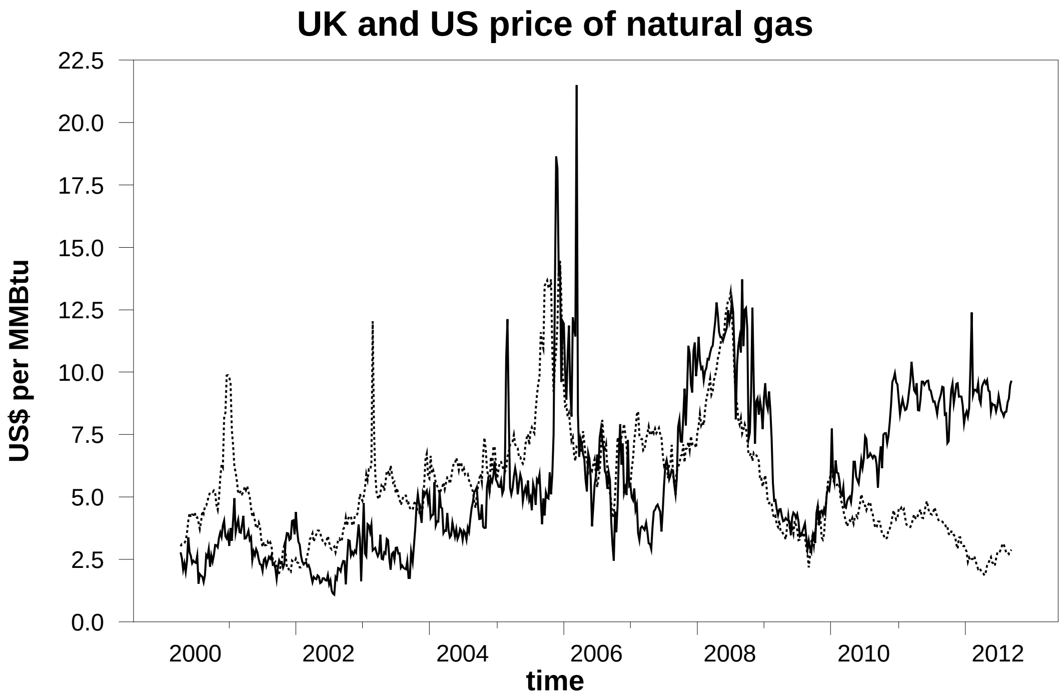

Figure 3: Prices for UK National Balancing Point (Solid Line) and US Henry Hub (Dashed Line)

2000 to 2008. In the period 2009 to 2012 the US price shows no significant adjustment which is in line with the fact that US LNG imports and US gas prices have dwindled to low levels in that period due to the shale gas boom. However, we observe significant downward adjustment of the UK price when the UK price is above the US price. This situation was particularly prevalent 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.

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 since the beginning of the year 2009. Given that transport costs have been far lower than these observed price spreads, this situation seems to contradict the LOP at first glance. In this study, we used a threshold cointegration framework to empirically investigate whether there is empirical evidence of the LOP still to hold between the US and UK natural gas market.

After we outlined the properties that made a threshold cointegration model more appropriate than linear cointegration to study the LOP in gas markets, we used a linear and a threshold cointegration model to test for cointegration as well as the presence of threshold nonlinearity. In contrast to the linear cointegration tests, we find strong evidence in favor of cointegration and price convergence as well as threshold nonlinearity in all our (sub-)samples using the threshold cointegration approach. Thus, although transatlantic natural gas prices seem to have become disconnected in recent years, they are still pulled together by arbitrage dynamics as implied by the LOP. Our threshold estimates constitute a measure for transaction costs and other impediments to arbitrage. Interestingly, the threshold in the period 2009 to 2012 is found to be much larger than the typical LNG transport cost differential between US and UK market. This indicates the emergence of very high non transport transaction costs and other arbitrage impediments such as capacity constraints or market power in LNG market. Hence, the decomposition of the threshold values into their different components is a very promising field for further research. The estimates of the threshold vector error correction models suggest that between 2000 and 2008, both US and UK prices adjusted significantly to restore an equilibrium. In contrast, 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, our econometric estimations provided evidence of the LOP to hold even in the period 2009 to 2012 when US and UK gas prices seemed to have decoupled. Moreover, our empirical 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.

References

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.

Li, R., Joyeux, R., and Ripple, R. D. (2014). International natural gas market integration. *The Energy Journal*, 35(4):159–179.

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.

Maxwell, D. and Zhu, Z. (2011). Natural gas prices, lng transport costs, and the dynamics of lng imports. *Energy Economics*, 33:217–226.

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

Siliverstovs, B., L'Hégaret, G., Neumann, A., and von Hirschhausen, C. (2005). International market integration for natural gas? a cointegration analysis of prices in europe, north america and japan. *Energy Economics*, 27(4):603 – 615.