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Cointegration and Volatility in the European Natural Gas Spot Markets

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Abstract

This thesis uses the historical daily spot price data of the four major European natural gas trading hubs NBP, Zeebrugge, TTF and Bunde in order to analyse their relationships. It applies the Engle-Granger two step approach and the Johansen procedure to test for cointegration between the four markets. In addition error correction models are estimated to analyse the spreads between the markets. An intervention analysis studies the impact of the Interconnector pipeline on the integration of the Continental and the UK gas markets. Moreover, this thesis estimates GARCH models and tests for Granger causality of volatility between the four markets. The results of the analysis indicate that the natural gas hubs in Europe are integrated, although the extent of this integration differs depending on each market pair. Finally the analysis shows that Zeebrugge and NBP are the leading natural gas markets in Europe with respect to the price setting as well as to the volatility transmission.

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1. Introduction

In the last decades there has been an impressive transformation of the European natural gas markets. Since the United Kingdom (UK) started the liberalization of the market at the end of the 1980s and Continental Europe followed this step around 10 years later, the European gas market changed from a vertically integrated state owned monopoly structure to a competitive market. An important element of this transformation is the development of natural gas trading hubs which are market places that enable companies to trade spot and forward deliveries of physical natural gas. Many European countries developed trading hubs in the last decade but the progress towards mature gas markets differs widely across the countries. This paper analyses the interrelationships between the hubs and investigates whether there is an integrated European market for natural gas.

For this econometric time series study the price histories of the four European hubs which have the longest trading history are analysed. The National Balancing Point (NBP) hub is located in the United Kingdom (UK) and the other three hubs Zeebrugge, Title Transfer Facility (TTF) and Bunde are situated in Continental Europe. The paper uses daily spot prices of the four markets over a three-year-period from March 2005 to May 2008 and it focuses on two points. Firstly, the integration of the four markets is analysed using the cointegration technique and secondly GARCH models are used to study the volatility of the gas markets.

The thesis starts by presenting the background for the econometric analysis. The second chapter analyses the development of the liberalized natural gas markets in Europe and the role of trading hubs in this new market setting. Moreover, the chapter describes the main trading hubs in Europe and highlights their physical connections in the European pipeline network. The subsequent chapter presents the dataset that is used for the econometric analysis. The econometric analysis itself consists of two main parts. The first part investigates the cointegrating relationships of the markets and it begins with an analysis of the unit root properties of the four price series. After concluding that the price series have a unit root, the cointegration of the four hubs is tested with the Engle-Granger two step approach and with the Johansen procedure. Assuming cointegration between the four markets bilateral error correction models are estimated in order to analyse the deviations from the long-run relationship between markets. This analysis is then extended by studying the bilateral price gaps between the hubs. In addition, an intervention analysis highlights the role of the Interconnector pipeline for the integration of the markets in the UK and Continental Europe. The second part of the econometric analysis focuses on the volatility of the four hubs. A GARCH model and a conditional volatility series are estimated for each market. The series are used to test for Granger causality of volatility between the hubs.

The results of the econometric analysis indicate that there is a cointegrating relationship between the four markets. The strongest relationship is found between the NBP and Zeebrugge which are connected through the Interconnector pipeline. Hence prices and the volatility in these two markets have similar patterns. However, the connection between the two markets breaks down when the Interconnector pipeline is shut down for maintenance. The other markets are less strongly integrated due to the restricted pipeline capacity between them which limits the potential arbitrage between the locations. Therefore the prices can deviate in the short-run but in the long-run they are tied together through arbitrage. The GARCH (1,1) models show that an interrelationship does not only exist for the prices but it also shows that the volatility in the four markets is related.

2. Liberalization of the European Natural Gas Markets

The following chapter briefly summarises the liberalization process of the European natural gas markets and it highlights the role that natural gas trading hubs are playing in this new market setting. Prior to liberalization most national markets were dominated by a vertical integrated monopoly supplier. The liberalization of the natural gas market started in the UK already in the mid 1980s giving the UK a considerable advance in creating a mature market compared to the European continent. On the continent the liberalization process was initiated in 1998 when the first gas market directive 98/20/EC was published. The aim of the directive was to establish common rules for an internal competitive market for natural gas and to enable consumers to freely choose their supplier. These reforms introduced gas-to-gas competition in the market in order to increase the efficiency of the natural gas industry and to decrease the costs for the final consumer. The competition in the market was introduced in stages firstly allowing power plants and big industrial natural gas users to choose their supplier and subsequently opening the market for the smaller consumers (IEA 2008, p. 24).

In order to allow competition in a network industry like natural gas which has a natural monopoly in the transmission and distribution infrastructure, there is a need for a regulatory framework. The EC directive of 1998 establishes Third Party Access (TPA) forcing the incumbent suppliers which are also network owners at the same time to open their pipelines for third parties. Furthermore, the directive establishes an unbundling provision of the network activities of the incumbents to ensure a transparent and non-discriminatory access for third parties to the existing pipeline capacity (Neumann, Siliverstovs and Hirschhausen 2006, p. 728).

In 2003 the first directive was replaced by a new directive 2003/55/EC. This directive was supposed to speed up the liberalization process since the progress on the reforms of the earlier years differed widely across the member states. While the first directive left it open to the EU countries whether or not to create a regulation authority for the TPA the second directive obliged the countries to establish an independent regulator. This regulator was responsible for the ex-ante approval of the pipeline tariffs for distribution and transmission. Important infrastructure projects could be exempted from this TPA in order to boost investment incentives. Moreover, the transmission system operator (TSO) had to be legally separated from the other activities of the vertical integrated incumbents. This provision was stronger than the formerly implemented unbundling of the accounts, but it did not go as far as to establish an ownership unbundling which would force the incumbents to sell their network entities (IEA 2008, p. 25).

In January 2007 the European Commission (EC) published its proposal for a third legislative package inter alia focusing on the issue of ownership unbundling. An alternative proposal was put forward by natural gas industry association proposing to hand over the management of the pipelines to a system operator and to leave the ownership of the assets in the hands of the vertical integrated supply companies. The negotiations on the third package have not been finished yet.

During the liberalization process of the European gas markets several natural gas trading hubs were created which are key elements of a liberalized market. In the following chapter the role of natural gas trading hubs in a liberalized gas market will be discussed. Based on that analysis the development of hubs in Europe will be studied.

2.1. The Role of Natural Gas Trading Hubs in Liberalized Markets

Trading hubs are points in a natural gas pipeline network where gas is exchanged between owners. A hub can be defined either as a physical hub which covers a single point in a network or as a virtual hub which covers a whole network area. A physical hub has the advantage that there is a local price signal for one region, but this decreases liquidity because the gas has to be delivered at a specific point in the network. Therefore the pipeline capacity to that specific point has to be purchased which makes trading more difficult and involves higher transaction costs. In order to circumvent these problems virtual trading hubs have been developed. These virtual hubs cover an area network with various entry and exit points that can be used for the delivery of the physical gas. Therefore sellers only have to make sure that the gas arrives at one of the entry points of the network and it does not matter at which exit point the gas bought at the hub is taken out of the network (IEA 2008, p. 53). Since the entry and exit charges are independent from the location where the gas is finally injected or withdrawn from the virtual hub all the gas in the market can be transferred to another party at a single price (Jackson and Harris 2007, p. 37).

Generally speaking two main functions of natural gas trading hubs can be distinguished. Firstly, hubs create a balance of supply and demand in order to find a price for the delivery of natural gas at a specific location for a specific date. Prices at the hubs can therefore serve as a pricing reference for various kinds of contracts which derive their value from the hub price. The second main function is that they serve as a provider for physical flexibility through this balancing of supply and demand. This allows market participants to constantly buy and sell deliveries of natural gas for a specific time period at the hubs. The following section will start by giving a brief overview how natural gas was priced in Europe prior to the liberalization of the market and how the development of the trading hubs will affect the pricing in the industry. Afterwards there will be a short summary of the flexibility services hubs are providing to the market participants. At the end of the chapter the actors who are trading at the hubs in Europe will be discussed.

Since the creation of the European natural gas industry in the middle of the 20^th^ century oil price indexed long-term supply contracts have played the determining role for the pricing of natural gas in Continental Europe. The raison d'être for this link can be found in the first natural gas discoveries in Continental Europe. When the Netherlands discovered the Groningen gas field in 1959 there was no market price available to sell the gas to the costumers. That is why the gas was sold to the international buyers using an oil-index. The idea was that the gas should be priced in relation to its substitutes as for example oil, so it had a competitive price. At the same time it should not offer a cheap alternative to the substitutes which were sold by the same companies. Therefore, today most long-term natural gas contracts from all exporting countries to Europe are indexed to crude oil, oil distillates or another substitute of gas as for example coal. The prices for the delivery of gas from these contracts are updated on a regular basis and the pricing index normally includes the lagged prices of the substitute over the last couple of months (IEA 2008, p.11).

Due to the development of liquid hubs in the liberalized markets there are alternative reference points which can be used for the pricing of long-term contracts. In the UK already 60 percent of the gas contracts are sold at the NBP price. There is also a trend in Continental Europe towards the use of hub indexed long-term contracts. One reason for this development is that many long-term contracts include flexible volume and hence these contacts can already be optimized using the hubs (IEA 2008, pp. 41-42). So the buyers of the gas can decrease the volume delivered under the contracts and buy the gas on the market instead or they can increase the volume when the price in the markets is high. Therefore, there is already a link of the hub prices and the oil-indexed long-term contracts in the current market situation. This does not necessarily mean that hub pricing will replace oil-indexed pricing, but it means that the two pricing schemes can coexist and are not mutually exclusive. As a result oil price changes as well as the price of other commodities that are used in the indexes affect the prices for gas at the hub. However, this effect is less strong for the day-ahead prices which are analysed in this paper and it is more pronounced for the forward/future contracts.

The spot prices at the hubs are mainly determined by the physical availability of gas and by the anticipated demand for it. The market therefore captures marginal supply and demand imbalances and as a result it is quite volatile. Thus price drivers in the spot market are factors affecting this supply and demand balance. The availability of supply is determined by storage capacities, transport capacities and the operational data of gas fields, pipelines and entry terminals. The demand is mainly influenced by the weather, the price of electricity, and the price of carbon emission certificates. Due to the substitution possibilities in the power production the prices of substitutes like coal and other fuels, as well as the amount of wind power production also affect the natural gas spot prices (Jackson and Harris 2007, p. 63).

Since the prices for natural gas at the trading hubs have already been playing a mayor role for the natural gas industry and they will gain even more importance in the coming decades, it is essential to investigate how these prices move and how the prices in the different market areas are related to each other. This thesis investigates the relationship between the prices and the volatility in the four main natural gas trading areas in Europe. On the one hand, this helps to understand how these hubs can be used as a pricing reference for long-term contracts or other derivatives in different countries in Europe. On the other hand, the findings are crucial for trading companies arbitraging between the market areas or taking speculative position in one of the markets.

However, natural gas hubs are not only important as a pricing reference for the gas but also as a pricing reference for flexibility services the hubs provide. Hubs allow market participants to buy physical flexibility in the markets by buying gas on a short-term basis. Traditionally this flexibility is included in the long-term contracts which in many cases allow a certain amount of so-called swing capacity. This enables importers to buy above or below the fixed contracted volume. The extent of this swing capacity depends on the terms of each contract. With the introduction of spot and forward trading and the maturing trading hubs, companies are able to buy additional gas or sell gas which they do not use in the markets. Therefore trading hubs provide a clear value mechanism for the flexibility included in the contracts (IEA 2008, pp. 42-43). Natural gas storage is another physical flexibility source which becomes a much clearer value through the trading hubs (Jackson and Harris 2007, pp. 19).

After having discussed the functions of the hubs in a liberalized market the market players will be presented in the following paragraph. The participants in the trading activity at the hubs can be broadly categorized into three groups according to their primarily usage of the market. Firstly, there are asset management traders owning physical assets like production fields, long-term contracts, storage facilities and pipeline capacity. These companies use the trading hubs to optimize their physical asset portfolio. In addition, companies may have contractual obligations to supply gas to consumers. This supply used to be delivered on long-term contracts, but forward/future markets are gaining increased importance for the delivery of gas to the consumers. Furthermore, spot markets are used to balance supply portfolios which consist of long-term contracts in the short-run. The second category of market participants are speculative traders doing directional bets on the gas prices in one region or arbitraging between locations and time periods. These can be either physical or financial positions. Thirdly, there are companies who use the hubs for risk management purposes. These companies are exposed to the fluctuations of the gas price and wish to lock in their prices and margins. These companies can be on the consumer or producer side of the market (Jackson and Harris 2007, pp. 27-28).

However, most of the companies in the markets cannot be put into only one of the three categories since they are trading for different purposes in the market. Although their industry background indicates the main focus of their trading activity, this is however expanding as many companies are becoming more experienced in natural gas trading. For instance there are utilities and gas production companies with a strong physical asset position in the market. Investment banks participate in the markets in order to do proprietary trading and to provide risk management services to clients. In addition, there are pure energy traders combining a variety of activities (Jackson and Harris 2007, pp. 70-85).

2.2. Development of the Natural Gas Trading Hubs in Europe

This section discusses how trading hubs developed during the liberalization process in Europe. This thesis analyses the historical prices of four hubs in Europe the National Balancing Point in the UK, the Title Transfer Facility (TTF) in the Netherlands, the Zeebrugge Hub in Belgium and the Bunde/Oude at the Dutch German border. The most developed and most liquid hub in Europe is the National Balancing Point (NBP) in the UK. It is a virtual hub covering the entire British transmission grid and its trading activities started in 1996. Most gas enters the NBP system through the five beach terminals in the North Sea but there are also two direct pipeline connections to Continental Europe (IEA 2008, pp. 47-48). The Title Transfer Facility (TTF) is a virtual hub covering the Dutch pipeline network. It is connected to the NBP through the BBL pipeline which is used to transport gas from Balgazand in the Netherlands to the Bacton terminal in the UK[1]. The BBL pipeline was opened in December 2006 which increased the linkages between the UK and Continental gas markets and brought the prices in

[1] For further information see http://www.bblcompany.com.

both markets closer together (Jackson and Harris 2007, p. 65). Moreover, the TTF market area has several pipeline interconnections to the neighbouring countries Belgium and Germany[2].

Zeebrugge is a physical trading point in Belgium. It includes a connection to the North Sea pipeline and a LNG terminal[3]. The Zeebrugge hub is connected to the Bacton terminal of the NBP market area through the Interconnector pipeline which started operations end of 1998[4]. The Interconnector was originally build to export gas from the UK to the Continent, but in contrast to the BBL pipeline the flow of the Interconnector can be reversed. Therefore the Interconnector can be also used in the same direction as the BBL to export gas from the Continent to the UK which is mostly the case in the winter months. The BBL and the Interconnector are the only direct links from Continental Europe to the UK. However, there is an additional indirect link between the two markets through the North Sea pipeline network, since many gas fields in that area can deliver gas to the Continent as well as to the UK. Therefore, there are several opportunities for traders to exploit the arbitrage potential between the two markets which limits the price differential between the locations. Yet this arbitrage is limited by the pipeline capacities and by the fact that BBL can only export gas to the NBP (IEA 2008, p. 48).

The fourth hub analysed in this paper is the physical Bunde/Oude hub on the border between the Netherlands and Germany which also offers access to the North Sea pipelines at Emden. It used to be active between 2002 and 2006 and it was the main trading point for Germany. However, the creation of the virtual TTF in the Netherlands and the virtual BEB and the EGT hubs in Germany drew a lot of liquidity away from Bunde (see also Neumann et al. 2006, p. 728). Hence it finished operation in 2006 (Jackson and Harris 2007, p. 37). For the period after 2006 this paper uses the prices of the BEB virtual hub which includes the former Bunde/Oude border point and which is now one of the two hubs in the German network.

There are several other recently created hubs on the European Continent which will probably play an important role in the upcoming decades for the European gas markets. These hubs have not been used in this paper because their price histories are still too short. Most notably there is the E.ON Gastransport (EGT) virtual hub in Germany. The liquidity on the EGT hub increased considerably in 2007/2008 and it has the potential to become the main Continental pricing point (IEA 2008, p. 49). In addition there is the Point d'Echange Gaz (PEG) in France which started operating in 2004, but trading is still difficult due to the existing five different trading zones which make entry and exit capacity booking rather complicated. The Punto di Scambio Virtuale (PSV) in Italy is especially

[2] For details about the European gas transmission network see http://www.gie.eu.com.
[3] For further information see http://www.huberator.com.
[4] For further information see http://www.interconnector.com.

interesting because of the large share of gas fired power production in the Italian power market. However, trading at the hub is still not very active since most pipeline capacities in the market area are blocked by the market incumbents (IEA 2008, p. 49). The Central European Gas Hub (CEGH) at Baumgarten in Austria has a great importance as a transit point for Russian gas. In future it might serve as a distribution point for Russian gas to Italy, Germany and Central Europe, but until now it is not very clear how a market with only one significant supplier will operate in the long-run. Finally, there is an internal Russian auction market (EPT) which was started by Gazprom in November 2006 (IEA 2008, pp. 50-51).

Different trading platforms are used to initiate trades at the hubs and broadly speaking two different types of platforms can be distinguished: the Over-The-Counter market (OTC) and the exchanges. In the OTC market trades can be either executed through a broker or through a bilateral agreement without broker. GFI, ICAP, Spectron and Tullet Prebon are the main brokers in the natural gas trading in Europe and the majority of the volume exchanged at the hubs is traded with their platforms. The data of the trades executed through the brokers is used to build daily price indices which are used for the analysis in this paper. The construction of the indices will be discussed in the next chapter (IEA 2008, pp. 58-59). In addition, some natural gas contracts are listed at exchanges. These have the advantage that the exchange is the counterparty in all deals and therefore there is no need for trading agreements and credit lines with all market participants. But transaction costs charged on the exchange are higher and the volume exchanged is still low compared to the OTC market. The day-ahead contracts for the TTF and NBP are traded at the APX exchange and for the German markets BEB and EGT at the European Energy Exchange (EEX). Future contracts for these markets are traded either at the Intercontinental Exchange, the ENDEX or the EEX. Since there are market participants that are trading on the OTC market as well as at the exchange the day-ahead prices in the two platforms tend to follow each other very closely. When exchange future and OTC forward prices are compared the difference in the cost of financing has to be taken into account (IEA 2008, pp. 58-60).

3. The Descriptive Statistics of the Data

The dataset used in this paper contains daily spot prices for the four most liquid natural gas spot hubs in Europe. It includes the National Balancing Point (NBP), the Title Transfer Facility (TTF), the Bunde hub (Bunde) and the Zeebrugge Hub (Zeebrugge). The data covers the period from March 9, 2005 until May 30, 2008 and it includes 824 observations for each series. Missing observations on non-trading days varied in each country because of national holidays. There are between 12 and 15 missing observations for each price series and these gaps were filled by repeating the last observation (Alexander 2001, p. 439).

The data sources are Bloomberg L.P. for NBP, TTF and Zeebrugge and Reuters Ltd. for Bunde[5]. The daily spot prices reported by Reuters and Bloomberg are either obtained from Over-The-Counter (OTC) trading platforms which were mentioned earlier (for example SpOT operated by Spectron Group Limited[6]) or they are reported by companies covering the OTC trades through daily telephone surveys. There are two ways how the quoted price is obtained. Firstly, it can be an index which reflects the volume weighted average price of all transactions for delivery on the next working day either executed through the trading platform or obtained from a phone survey. Secondly, it can be a price assessment of the market at a specific time of the day. The paper uses day-ahead prices for the analysis. Alternatively, future/forward or with-in day prices could have been used. However, these instruments are not available in all markets, they are not traded as frequently and their price history is not as long as for the standard day-ahead contract.

Prices at Zeebrugge and NBP are reported in pence sterling per therm whereas prices at Bunde and TTF are reported in Euro per megawatt hour (MWh). For the following analysis in this paper all prices are converted in Euro per megawatt hour (Eur/MWh). A conversion factor of 29.3071 kilowatt hours per term is used[7]. The currency conversion is made by using the exchange rates from the European Central Bank[8].

Day-ahead contracts have the whole next gas day as delivery period. The gas day begins at 6 a.m. and lasts 24 hours. The contract volume for most of the trades ranges between 10 MW/h and 120 MW/h at Bunde and TTF and this volume has to be delivered during each hour of the gas day. Hence the total daily volume which has to be delivered for a 30 MW/h contract is 720 MWh. So a day-ahead contract with a price of 20 Euro/MWh has a total value of 14400 Euros. For Zeebrugge and NBP the trades are quoted in therms per day. Therefore a standard trade at the NBP of 100 000 therms/d is equal to around 122 MW/h. The trading of daily and hourly quantities is due to the different balancing regimes used at the hubs.

This paper uses OTC trades instead of exchanged traded data for three reasons. Firstly, since the volume traded on the European Energy Exchange (EEX) and the APX Group is still relatively low, there are periods with no trades and therefore no price movements in the exchange data. Secondly, since

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[5] Ticker symbols in Bloomberg: NBPGDAHD for NBP, TTFGDAHD for TTF, ZEEBDAHD for Zeebrugge; Ticker symbol in Reuters: GA1BU-D for Bunde/BEB.

[6] For further information see http://www.spectrongroup.com.

[7] According to APX Group http://www.apxgroup.com.

[8] Statistical Data Warehouse of the European Central Bank at http://www.ecb.eu.

natural gas contracts are only recently traded on exchanges, the price history is even shorter than for the OTC markets. Thirdly, as explained above the exchange traded data and the OTC data have unsurprisingly a very high correlation and thus conclusion drawn from the OTC data is applicable as well to the exchanges.

Table 1 provides the summary of the descriptive statistics for the prices of the four hubs which are analysed in this study. Comparing the standard statistics of all time series provides a first evidence of the market activity at the four hubs.

Table 1. Descriptive Statistics for daily spot prices in Eur/MWh

	Bunde	NBP	TTF	Zeebrugge
Mean	17.55	19.45	18.00	19.67
Maximum	59.90	91.96	48.31	91.59
Minimum	1.80	3.04	2.88	3.54
Standard deviation	5.47	9.69	5.31	9.39
Skewness	1.02	2.60	0.53	2.63
Kurtosis	7.73	14.04	4.44	14.47
Jarque-Bera	911.30	5113.95	110.05	5464.08
Nr. of observations	824	824	824	824

Notes: The 1% critical value for a rejection of normality is 9.21 $\chi^2(2)$ (Alexander 2001, p. 287).

The mean price over the period between 2005 and 2008 is 19.45 Eur/MWh at NBP and 19.67 Eur/MWh at Zeebrugge. This is considerably higher than the mean price of 17.55 Eur/MWh at Bunde and 18 Eur/MWh at TTF. Also standard deviations of Zeebrugge and NBP are remarkably similar. The same holds for the pair Bunde and TTF where the standard deviations are much lower. The maximum price during that period was around 91 Eur/MWh for Zeebrugge and NBP and 59.9 Eur/MWh and 48.31 Eur/MWh for Bunde and TTF. Also the minimum prices for the sample period differ. The different minimum and maximum values point out that there is at least temporally no integration between the pair NBP and Zeebrugge and the other two Continental European markets. Therefore prices in these markets can deviate from each other at least in the short-run.

As reported in Table 1 the time series for all hubs display skewness and excess kurtosis. The Jarque-Bera test clearly rejects normality for all four series. This thesis will follow the approach of Wang and Cuddington (2006) using the log transformation of the price series in the econometric models in the following chapters. This transformation reduces the skewness and excess kurtosis of the series (see also Lütkepohl and Krätzig 2004, p. 19). The values for the transformed log prices are reported in Table 2. They are closer to the normal distribution than the level values, but a Jarque-Bera test still rejects the normality hypothesis for the four series at the 1% significance level.

Table 2. Descriptive Statistics for daily log prices

	Bunde	NBP	TTF	Zeebrugge
Mean	2.82	2.87	2.84	2.89
Maximum	4.09	4.52	3.88	4.52
Minimum	0.59	1.11	1.06	1.26
Std. Dev.	0.32	0.42	0.31	0.40
Skewness	-0.63	0.38	-0.52	0.43
Kurtosis	5.84	4.35	3.88	4.25
Jarque-Bera	332.24	82.40	63.11	78.64

Notes: The 1% critical value for a rejection of normality is 9.21 $\chi^2(2)$ (Alexander 2001, p. 287).

Figure 1 plots the daily spot prices for the four natural gas hubs for the period between March 2005 and May 2008. The figure confirms the above evidence of the standard statistics that the price patterns at NBP and Zeebrugge as well as at TTF and Bunde are very similar.

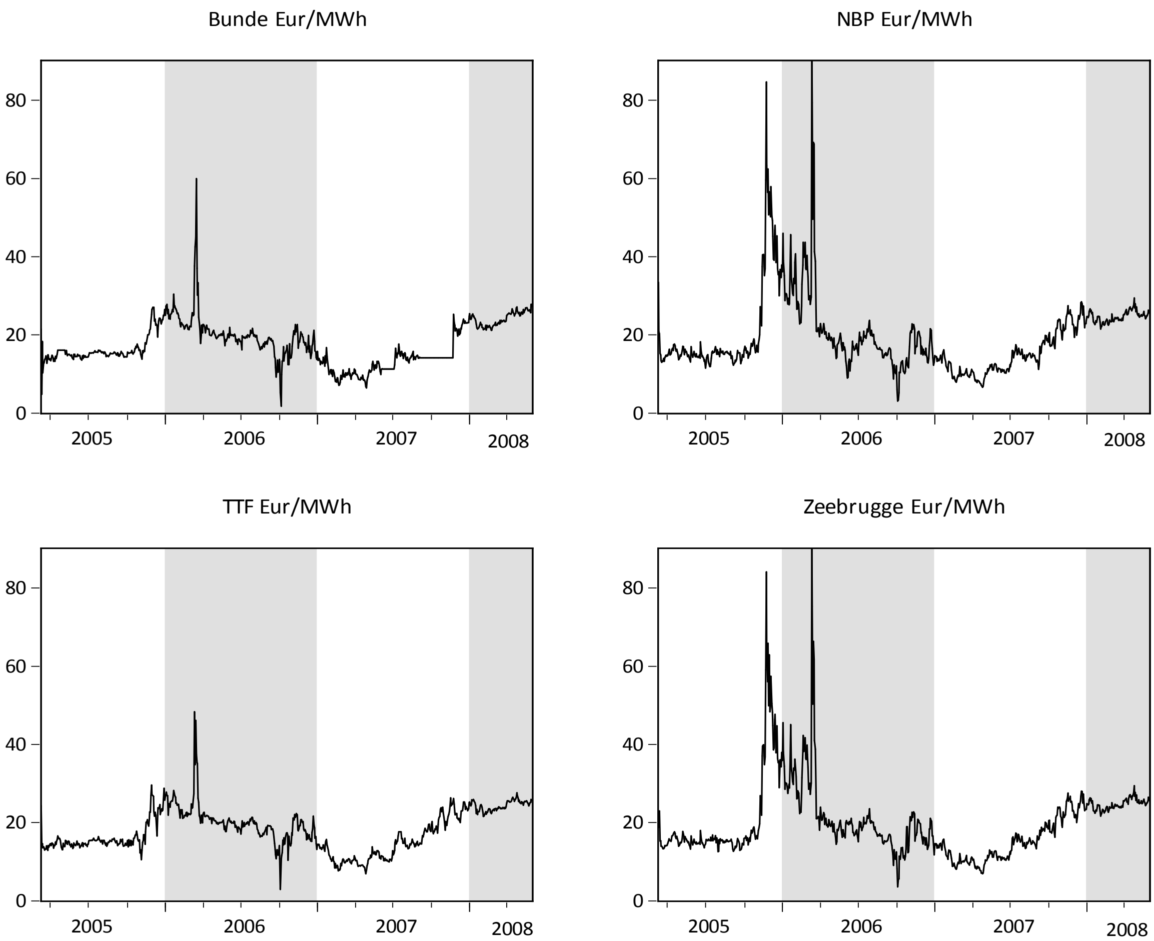


Figure 1. Daily Natural Gas Spot Prices of four European Trading Hubs

There is a stark visual difference between the series in the winter 2005/06. The price series of Zeebrugge and NBP show a characteristic pattern of high volatility and high prices during that period.

These high prices were due to a tight supply situation in the UK market in that winter. Since the BBL pipeline was not yet opened gas could only flow from the Continent to the UK market through the Interconnector pipeline. There is one spike in these months in the series of TTF and Bunde but the series stay relatively calm compared to Zeebrugge and NBP. The visual inspection therefore seems to confirm the evidence that the four hubs were temporally not very well integrated. For the years 2007 /08 all four series have a rather similar pattern of increasing prices and relatively low volatility. One distinctive feature of the Bunde price series is a period where prices remained unchanged from September to November 2007 because there was no reported trading activity at the hub.

4. Cointegration Tests

The econometric analysis developed in this thesis starts by applying two cointegrating techniques to the four price series. Since Engle and Granger (1987) introduced their two step approach to test for an equilibrium relationship between two time series when the data is non-stationary there has been a wide application to use this technique to test for market integration. After the deregulation of the North American natural gas markets in the mid 1980s a considerable amount of work has been done applying this methodology to this market and testing for cointegration of the numerous trading hubs in this area. De Vany and Walls (1993) apply the Engle-Granger two-step approach to test for cointegrating relationships in daily spot prices of 190 natural gas market pairs and they use sub samples in order to identify time changes in this relationship (see also Doane and Spulber (1994); Walls (1994a)). Marmer and Shapiro (2007) expand this analysis and use impulse response technique to analyze how shocks spread across the network. Walls (1994b) uses the Johansen procedure to test for cointegration in the U.S. natural gas spot markets.

King and Cuc (1996) and Serletis (1997) use monthly price series to study the gas spot price integration in the North American market. King and Cuc (1996) report that the Eastern as well as the Western market area are cointegrated. However, they do not find a common stochastic trend between these two areas and conclude therefore that there is a split between the Western and Eastern North American natural gas market. Serletis (1997) challenge these results by using the Johansen's multivariate approach to test for a cointegrating relationship between the market regions.

For the European natural gas markets only little research is done applying cointegration techniques. Asche, Osmundsen and Tveteras (2002) investigate whether the German natural gas market is integrated by analyzing long-term contracts for imports to Germany from the Netherlands, Norway and Russia. There is also only a small amount of literature investigating the cointegration relationship of the European trading hubs which came into existence after the restructuring in the late 1990s. Neumann et al. (2006) use daily price data of Bunde, NBP and Zeebrugge hub and estimate time varying cointegration coefficients by using a Kalman filter. They find a rather strong integration between the NBP and Zeebrugge. However, they do not observe a cointegration between the continental hubs Bunde and Zeebrugge in the period under investigation until early 2005. The part about cointegration of this thesis extents the research done by Neumann et al. (2006) by including the Dutch TTF hub in the analysis and by applying the Johansen procedure.

4.1. Engle-Granger Two-Step Approach

4.1.1. Methodology

Analysing the relationship between natural gas prices at different points in a network is fundamental to assess the degree of market integration and to evaluate how well a market performs. The *Law of one Price* (LOOP) states that prices at different locations in one market should be equal when taking into the transaction costs. Cointegration theory can be used to evaluate these linkages when the price data is non-stationary. If there is a stationary series which is obtained from a linear combination of two non-stationary series they are cointegrated and share a common stochastic trend. In this case deviations from long-run equilibrium between these two series are stationary even if each of the series is non-stationary (De Vany and Walls 1993, pp. 1-6).

Cointegration of price series from two locations indicates that the two locations are integrated in one market and there is evidence that there are market actors who are able to perform arbitrage between the two market areas. However, if the analysis fails to show cointegration the markets at the two locations are separated and they can show diverging price patterns over longer periods of time. In a physical market, like natural gas, a lack of cointegration can be explained for example by bottlenecks in the networks due to capacity constraints (Marmer and Shapiro 2007, pp. 14-17).

This paper will use the two step approach to test for cointegration which was first used by Engle and Granger (1987). The idea behind the approach can be formally illustrated by looking at the price series $P_{i,j}$ of two markets in the locations i and j. A necessary condition for using cointegration is that both time series have a unit root and hence they are non-stationary. Series are weakly stationary when they have a constant mean as well as a constant variance over time and the autocovariances do only depend upon the gap between the two periods (Walls 1994a, p. 41). If one of these conditions is not satisfied the series is non-stationary. A stationary series is denoted as I(0) and it is said to be integrated of order zero. A non-stationary series which becomes stationary by taking the first differences is said to be integrated of order one or I(1).

A unit root leads to non-stationarity and for an autoregressive process of order one AR(1) this requires that the condition $\theta = 1$ holds in the following equation:

$$P_t = \theta P_{t-1} + e_t \tag{1}$$

where e_t is random error term with zero mean and a finite variance. As shown by Dickey and Fuller (1979) the test of the hypothesis that $\theta = 1$ does not have a Student's t-distribution. Therefore the Dickey-Fuller test has to be used which also may include a constant in the above testing equation. In this paper the Augmented-Dickey-Fuller (ADF) is used which also applies to higher order autoregressive processes (see De Vany and Walls 1993, pp. 6-8). The number of lags included in the ADF testing equation is set according to different lag length criteria which will be discussed more in detail in the next chapter. In addition the residuals in the test equation are checked for serial correlation. For each test an ADF test equation of the following form is estimated (Enders 2004, p.225):

$$\Delta P_t = \alpha + \gamma P_{t-j} + \sum_{j=1}^{p} \beta_j \Delta P_{t-j} + e_t \tag{2}$$

The equation contains a constant α and an error term e_t. The test for a unit root in the series is a test of the null hypothesis that $\gamma = 0$. If the hypothesis cannot be rejected the series is assumed to be non-stationary.

After testing both time series for a unit root the first step of the Engle and Granger (1987) approach estimates with Ordinary Least Squares (OLS) the following linear combination of the two price series where $\alpha_{ij,t}$ is a constant:

$$P_{i,t} = \alpha_{ij,t} + \beta_{ij} P_{j,t} + e_t \tag{3}$$

This equation is referred to as cointegrating equation. In the second step of the Engle-Granger approach the error term e_t is analysed. Both series are cointegrated if the error term e_t in this cointegrating regression of equation (3) is stationary. This condition is tested using the ADF test but different critical values have to be employed (see also Verbeek 2004, pp. 315-316). If the condition holds the two series are cointegrated and there is a long-run equilibrium relationship between the two series.

When analysing market integration the cointegrating vector β measures the degree to which the two markets are integrated. The LOOP states that the prices $P_{j,t}$ and $P_{i,t}$ should be equal in the long-run when taking into account transaction and arbitrage costs ($\alpha_{ij,t}$). Therefore LOOP implies that that $\beta_{ij} = 1$ at any time t, if $\beta_{ij} \neq 1$ there are deviations from the LOOP (King and Cuc 1996, p. 19). However, the coefficients of the Engle and Granger procedure for the cointegrating vector only have a t-distribution in special circumstances and hence the above restriction cannot be tested directly when using this approach.

4.1.1. Empirical Results Unit Root Test

The ADF test to test for a unit root is performed for the log price series of the four hubs. The test is done using a constant in the testing equation (2) to account for a drift in the series. A time trend is not included in the equation since there it is not significant in any test equation. Ng and Perron (1995; 2001) show that the lag length choice for an ADF test is important when constructing a test with good size and power properties. An ADF testing equation with too few lags can have large size distortions but an over-parameterized model leads to a low power of the test. The differences in the power across tests with different lags become smaller when the sample grows but size distortions are independent of the sample size. Generally speaking a method which chooses more rather than less lags is preferred for this reason because it has less size distortions and therefore decreases the probability of an over-rejection of the unit root hypothesis (Ng and Perron 1995, p. 277).

In this paper the test will be performed using several criteria for the length selection. In a first step the number of lags is chosen to minimize the Akaike Information Criterion (AIC). In a second and third step the ADF tests are performed using the AIC + 2 rule (Serletis, p. 51), and the General-to-Specific method for lag length selection (Ng and Perron 1995, p. 272). After each test the sample residuals are checked for autocorrelation using a correlogram. For all three lag length selection criteria no autocorrelation was found in the residuals. The marginal significance levels and the chosen lag length for the tests are reported in Table 3. A low value indicates that there is strong evidence that the null hypothesis of a unit root can be rejected and the series can assumed to be stationary.

At first the test is performed using the standard Akaike Information Criterion (AIC) for lag length selection. The tests cannot reject the presence of a unit root at a 10% significance level for Bunde, TTF and Zeebrugge. However, the null hypothesis of a unit root in the log price series of NBP can be rejected even at a 5% level. Nevertheless, further tests show that the results for NBP are not robust since they are very sensible to the number of lags included in the ADF test equation.

As Ng and Perron (2001; 1995) point out the use of the AIC for the lag length selection in unit root tests may lead to an insufficient number of lags in the ADF equation. This will have the effect that in some circumstances the unit root hypothesis is rejected too often. Therefore the ADF tests are repeated following the approach of Serletis (1997) which uses an AIC + 2 rule for the lag length determination. Increasing the lag length by two lags leads to a non-rejection of the unit root hypothesis for NBP at the 5% significance level. The unit root hypothesis for all other price series cannot be rejected at a 10% level.

In a third sequence of tests the General-to-Specific approach is used which is described by Ng and Perron (1995). The strategy uses the t-statistics of the coefficient for the lags in the ADF testing equations (Ng and Perron 1995, p. 272). First a model with 20 lags is estimated and the last lag is excluded if the coefficient for the lag is not significantly different from zero at the 10% level. Afterwards a model with one lag less is estimated and this procedure is subsequently repeated until the last lag coefficient is significant at a 10% level which will be the selected lag length for the test. The marginal significance levels as well as the chosen lag length of these ADF tests are reported in Table 3. Compared to the AIC the selected lag length increases for NBP and the test cannot reject the unit root hypothesis for any of the four series at a 10% significance level. For the other three series the chosen lag length does not change compared to the AIC and that is why the test results are identical.

Table 3. Marginal significance levels and lag length of ADF unit root tests

	Bunde	Lags	NBP	Lags	TTF	Lags	Zeebrugge	Lags
	Lag selection criterion			*AIC*				
Log Prices								
Significance level	0.320	14	0.043	5	0.264	13	0.164	8
First differences of log prices								
Significance level	0.000	13	0.000	7	0.000	12	0.000	7
	Lag selection criterion			*AIC + 2*				
Log Prices								
Significance level	0.360	16	0.078	7	0.336	15	0.159	10
	Lag selection criterion			*General-to-Specific*				
Log Prices								
Significance level	0.313	14	0.116	8	0.264	*13*	0.164	8

Notes: Values of the significance level below 0.05 indicate that the null hypothesis of a unit root can be rejected at the 5% significance level.

Cuddington and Wang (2006) use the Modified Akaike Information Criterion (MAIC) to test for a unit root in the log prices of the North American natural gas hubs. Using the MAIC for the four series analysed in this paper the chosen lag lengths are identical to the General-to-Specific approach. Hence the results are not reported here (see also Ng and Perron 2001).

Given the mixed results and taking into account the findings of Ng and Perron (1995; 2001) that a unit root test with more lags has better properties the unit root hypothesis for the four hubs under observation cannot be rejected. Therefore an additional ADF is performed to test for a second root in the price series. As shown in Table 3 the hypothesis of a unit root in the first log differences for all four hubs can be rejected. Only the results for the AIC lag length selection are reported since the results are not sensitive to the number of lags included in the testing equation. Thus, combining these two results there is evidence that the log prices of the four European natural gas spot price series analysed in this paper are a non-stationary process which is integrated of order one I(1). This is a common finding in the literature about the natural gas markets (see above mentioned articles).

4.1.2. Empirical Results Engle-Granger Cointegration Test

Based on the results from previous chapter it is assumed that all four log price series are non-stationary. The analysis therefore continues to test whether the four series are cointegrated. As explained above the Engle-Granger (1987) two step approach is used to test for cointegration in each market pair. First the cointegrating regression is estimated and in the second step the error terms of the cointegration equation are tested for stationarity. The ADF test is used to test for a unit root in the error term. The test can be interpreted as a test for no-cointegration and two outcomes can be distinguished. First, if the null hypothesis of a unit root in the error term cannot be rejected, the series is assumed to be non-stationary and the two series are not cointegrated. Second, if the test can reject the null of a unit root at a reasonable significance level, the series are assumed to be cointegrated. The t-statistics for the ADF test for each market pair and the number of lags included in the testing equation are reported in Table 4. The series listed horizontally are endogenous in the cointegrating equation. A high t-statistic for a market indicates that the no-cointegration hypothesis can be rejected. When interpreting the results of the test it has to be considered that the normal critical values for the ADF test are not valid. That is because the test is not applied to an observed series but rather to the OLS residuals. So the adjusted critical values reported by Davidson and MacKinnon (1993) have to be used (as quoted in Verbeek 2004, p. 316).

The ADF tests for cointegration are run for three lag selection criteria. First, the AIC is used and these results are compared to the AIC + 2 rule and the general-to-specific lag length selection procedure. The ADF test statistics for a rejection of the null hypothesis of no-cointegration are reported in Table 4.

Table 4. T-statistics for Engle and Granger Co-Integration tests

	Lag length selection			*AIC*				
	Bunde	Lags	NBP	Lags	TTF	Lags	Zeebrugge	Lags
Bunde			-4.269***	7	-3.168*	12	-3.543**	16
NBP	-3.024	12			-2.744	16	-5.626***	13
TTF	-3.181*	12	-3.143*	16			-3.329*	15
Zeebrugge	-3.820**	7	-5.776***	13	-2.934	15		
	Lag length selection			*AIC + 2*				
	Bunde	Lags	NBP	Lags	TTF	Lags	Zeebrugge	Lags
Bunde			-3.956***	9	-2.997	14	-3.468**	18
NBP	-2.936	14			-2.603	18	-5.474***	15
TTF	-3.072*	14	-3.055*	18			-3.320*	17
Zeebrugge	-3.736**	9	-5.606***	15	-2.927	17		
	Lag length selection			*General-to-specific*				
	Bunde	Lags	NBP	Lags	TTF	Lags	Zeebrugge	Lags
Bunde			-3.251*	12	-3.168*	12	-3.543**	16
NBP	-3.024	12			-2.970	15	-5.626***	13
TTF	-3.181*	12	-3.143*	16			-3.329*	15
Zeebrugge	-4.240***	4	-5.776***	13	-2.934	15		

Note: Series listed horizontally are endogenous variables in the cointegrating equation. Significance of rejection of the null hypothesis of no-cointegration at the 1%, 5% and 10% level is denoted with ***,**, and * using asymptotic critical values -3.90 for 1%, -3.34 for 5% and -3.04 for 10 % (see Verbeek 2004, p. 316).

However, the results indicate that the conclusions of the test are not independent of the choice of the exogenous variable in the cointegrating equation (3). The no-cointegration hypothesis can be rejected at the 10% significance level for all market pairs for at least one choice of the exogenous variable. There are considerably fewer market pairs for which cointegration is found in both directions. For the market pairs Bunde-TTF, Bunde-Zeebrugge, NBP-Zeebrugge the null hypothesis can be rejected independent of choice of the exogenous variable at the 10% significance level. Therefore three out of six market pairs show robust evidence of cointegration. The strongest rejection of the no-cointegration hypothesis is found for the market pair NBP-Zeebrugge. The null is rejected at the 1% significance level independent of the exogenous variable. In addition, the test statistics are the highest of the sample for both cases. This observation supports the results of Neumann et al. (2006) who find that NBP and Zeebrugge are very well integrated (p. 730). Moreover, the analysis of Neumann et al. shows that Zeebrugge and Bunde are poorly integrated between the years 2000 and 2005 (pp. 730-731). For the period analysed in this thesis between 2005 and 2008 there is no evidence for this conclusion and the Engle-Granger approach finds a rather strong cointegrating relationship between these two hubs.

Table 4 also compares the results of the cointegration test using different lag length selection procedure. These tests lead to the same conclusions as the test using the AIC. However, in two cases (Bunde-Zeebrugge, NBP-Bunde) the significance level of the rejections weakens or becomes stronger depending on the lag length.

The results of the Engle-Grange two-step approach give only tenuous evidence for a long-run cointegrating relationship between all four natural gas hubs analysed in this study. Therefore one might conclude that there are binding pipeline capacity constraints or other barriers to trade between the market areas, which lead to breakdown of the arbitrage pricing equality and hence there is no long-term relationship between some of the hubs. However, as Enders (2003) points out the Engle-Granger approach is easily implemented but it does have some important shortcomings. First, the decision to which variable from a market pair is endogenous in the cointegrating equation influences the results when the sample size is limited. As the results from the ADF tests above show the Engle-Granger methodology indicates a cointegrating relationship in one direction but rejects this relationship when reversing the order. Moreover, the ADF test lacks power and therefore the results are very sensitive to the lags included in the testing equation. In addition, the Engle-Granger approach does not allow hypothesis testing on the cointegrating parameters because they tend to have a non-normal distribution (Verbeek 2004, pp. 317-329). Therefore in the following the Johansen procedure will be used to test for cointegration and to analyse whether the Law one Price holds.

4.2. Johansen Cointegration Procedure

4.2.1. Methodology

In order to confirm the results of the Engle and Granger approach this paper uses the Johansen (1988) procedure to test for a cointegrating relationship which is a multivariate generalization of the Dickey-Fuller test (Enders 2004, p. 348). In addition, this procedure allows for hypothesis testing on the cointegrating vector and therefore it can be used to directly test the validity of the LOOP. The Johansen test is based on a Vector Error Correction Model (VECM) which is a combination of a Vector Autoregressive model with p lags and an error correction term. The VECM takes the following form:

$$\Delta P_t = \delta + \sum_{i=1}^{p-1} \Gamma_i \Delta P_{t-i} + \Pi P_{t-1} + e_t \qquad (4)$$

where δ is a constant term and P_t is a k-dimensional vector which contains k price series which are *I*(1) and which are to be tested for a cointegrating relationship. Hence the first differences ΔP_t are stationary. The error term e_t is stationary *I*(0) by assumption and so the error correction term ΠP_{t-1} must be stationary in order to balance the equation. Therefore according to Verbeek (2004) three different cases of the model can be distinguished (p. 326). First, if there is no cointegrating relationship between the variables and there is no linear combination of the price series ΠP_{t-1} that is stationary, it must be that $\Pi = 0$. Second, if the matrix Π, which has the dimension $k \, x \, k$, is of full rank, all variables in P_t must be stationary in levels, which is excluded by the assumptions. Third, if the matrix Π is of rank r ($0 < r < k$) there are r stationary linear combinations in ΠP_{t-1} and there are

r cointegrating vectors. In this case the error correction term ΠP_{t-1} can be written as a combination of α and β which are both $k\ x\ r$ matrices:

$$\Pi P_{t-1} = \alpha\beta' P_{t-1} \tag{5}$$

The coefficients in β are the cointegrating vectors and the coeffecients in α are the adjustment parameters of the error correction model. Consequently, by analyzing the rank of the matrix Π, it can be tested whether the prices series in P_t form a long-run cointegrating relationship like in the previous chapter in equation (3). The Johansen procedure determines the rank of the matrix by estimating the number of non-zero eigenvalues of the matrix. In this paper the bivariate Johansen procedure will be used to test at first for cointegration in each market pair and second these results are compared to the multivariate version of the Johansen procedure.

In the bivariate case each market pair is tested separately for cointegration. If the two price series form a cointegrating relationship the rank of the matrix $\Pi = \alpha\beta'$ should be equal to $\mathrm{r} = 1$ which means that there is one cointegrating vector. In this case α and β' are both $2\ x\ 1$ vectors. If the rank of the matrix turns out to be $\mathrm{r} = 0$, there is no cointegration between the series. The Johansen approach also allows testing restrictions on the cointegrating vector and the adjustment parameters by applying maximum likelihood ratio tests. Therefore the analysis can be extended to test whether the LOOP holds. It can be evaluated by testing the restrictions on the cointegrating vector β' in equation (5). If the LOOP holds the vector is $(1, -1)$ (Asche et. al 1999, p. 572). This means, if this condition holds the prices at both hubs are equal in the long run. A constant is included in the cointegrating equation to account for transaction and transportation costs.

Afterwards the Johansen procedure is used to test for cointegration in a multivariate setting. All price series are cointegrated if there is only common stochastic trend in the system. In a system with k variables and r cointegrating vectors there are $k - r$ common stochastic trend. Therefore in a system with k series there must be $k - 1$ cointegrating vectors if all variables are cointegrated. As explained above this condition can be tested using the Johansen approach. In general the multivariate procedure should confirm the results of the bivariate approach. If all price series are integrated in pairs, there is only one common stochastic trend in the system which should be confirmed when testing for cointegration in the multivariate setting (Asche et. al 1999, p. 572).

4.2.2. Empirical Results

In this second part of the empirical results of the cointegration tests the Johansen procedure is used to test for a cointegrating relationship between the four markets. The results are compared with the above results of the Engle-Granger two-step approach in order to test their robustness. In addition, restrictions on the cointegrating vector are tested to investigate whether the LOOP holds. Moreover, the Johansen procedure is used to test for market integration in a multivariate setting.

The results of the bivariate Johansen tests are reported in Table 5. The hypothesis of no-cointegration is tested for all market pairs. The basis for the test is, as noted earlier, a Vector Error Correction model. The lags in the model have been chosen in order to minimize the AIC. The chosen lag length for all models is between 7 and 9 lags. There was no evidence of serial correlation in the residuals of each model. As explained above, if there is no cointegration between the markets, the matrix of the cointegration vectors must have rank $r = 0$. This hypothesis is tested against the alternative that the rank of the matrix is $r = 1$. Furthermore Table 5 reports the p-values of a rejection of the hypothesis using the trace test. Since the maximum eigenvalue tests for the determination of the rank of the matrix leads to the same results, these are not reported here. The results of the Johansen procedure indicate that the hypothesis of no-cointegration can be rejected at the 10% significance level for all market pairs. For NBP-TTF and TTF-Zeebrugge the Johansen test cannot reject no-cointegration at the 5% significance level. Other model specifications for these two market pairs with fewer lags can reject no-cointegration at the 5% significance level. So there is evidence that the first results are not very robust. The degree of integration of the market pairs will be further discussed in the next chapter when the adjustment parameter of the error correction term is analysed. Considering only the results of the bivariate Johansen procedure there is evidence that all six market pairs are cointegrated.

Table 5. Bivariate Johansen test for Cointegration

	Bunde			NBP			TTF		
	r=0 p-value	β=(1,-1) p-value	Lags	r=0 p-value	β=(1,-1) p-value	Lags	r=0 p-value	β=(1,-1) p-value	Lags
Bunde									
NBP	0.030	0.266	8						
TTF	0.039	0.793	9	0.061	0.225	8			
Zeebrugge	0.028	0.232	8	0.000	0.184	7	0.091	0.210	8

Notes: Low p-values indicate rejection of the hypothesis. P-values for cointegration rank test (trace) based on MacKinnon-Haug-Michelis (1999) (as reported by EViews). The number of lags was chosen to minimize the AIC. The likelihood ratio test statistic for the cointegration vector β=(1,-1) follows a $\chi 2$ distribution with one degree of freedom.

The results of the Johansen procedure confirm the evidence of the Engle-Granger approach that there is a long-run cointegrating relationship between the natural gas hubs in Europe. However, using the Engle-Granger approach, the rejection of no-cointegration depends on the choice of the exogenous variable for some market pairs. The evidence for a cointegrating relationship between the prices of the four hubs is stronger when using the Johansen procedure. One explanation of the diverging results is that, as noted earlier, the ADF test often lacks power. Therefore the test does not reject the null of no-cointegration even if it is false. The Johansen procedure is more powerful and therefore leads to more appropriate results.

Furthermore it was tested whether the LOOP holds by using the likelihood ratio statistic. The results of these tests are reported in Table 5. The hypothesis that the cointegrating vector is $\beta = (1, -1)$, cannot be rejected for any market pair at a reasonable significance level. Therefore it can be concluded that the LOOP holds for all natural gas market pairs analysed in this study. The results indicate that the natural gas spot markets were well integrated during the period under investigation from March 2005 until May 2008.

As explained in the methodology section one advantage of the Johansen procedure is that it allows a multivariate test of cointegration. Asche, Bremnes and Wessells (1999) note that when testing for the cointegration of k markets there should be $k-1$ cointegrating vectors. If this is the case all markets are pairwise integrated. Furthermore it is analysed whether the LOOP holds by testing a restriction on the cointegrating matrix which is similar to the bivariate case. Each column of the matrix represents a cointegration vector for a market pair and according to Asche et al. (1999) it can be represented in the following form (p. 572):

$$\beta = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ -1 & -1 & -1 \end{bmatrix}$$

The results of the multivariate Johansen procedure are reported in Table 6. The chosen lag length for the VECM of the four price series is six. If there is a cointegrating relationship between all markets there should be three cointegrating vectors (see also Asche et al. 1999, p. 575).

Table 6. Multivariate Johansen Procedure to Test for Cointegration

Number of cointegrating vectors	p-value
None	0.000
At most 1	0.030
At most 2	0.094
At most 3	0.115

Notes: P-values for cointegration rank test (trace) based on MacKinnon-Haug-Michelis (1999) (as reported by EViews). The number of lags was chosen to minimize the AIC.

The test does not reject that hypothesis at the 10% significance level. However, when the 5% level is chosen as cut off level, the test does not reject the hypothesis that there are not more than two cointegrating vectors. Therefore, the evidence for only one common stochastic trend in the price series of the four hubs in the multivariate setting is similar to the bivariate case. However, the assumption of one common stochastic trend seems to be the most reasonable interpretation of these results (for similar problems see Asche et. al 2006, p. 37). The test does not reject the hypothesis that are at most three cointegrating vector in the system at the 10%.

The likelihood ratio test of the cointegrating matrix for the LOOP estimates a p-value of 0.598. Therefore the test cannot reject on a reasonable significance level that the LOOP holds when three cointegrating vectors are assumed. These results confirm the evidence of the bivariate case.

5. Error correction model

Based on the above evidence that there is a cointegrating relationship between the four price series analysed in this thesis, the following chapter will further study the bilateral error correction model. The paper will estimate an error correction model for each market pair, in order to study the long- and short-run relationship between the markets. The model describes the dynamics of the price variables in the European gas markets and analyses how the variables respond to deviations from the long-run equilibrium relationship. In addition, the series are tested for Granger causality. There are some applications of error correction models to the energy markets in the literature. Asche, Osmundsen and Sandsmark (2006) use a VECM to analyse the UK energy market and come to the conclusion that crude oil is weakly exogenous. Serletis and Herbert (2007) use an error correction model to study the dynamics in the North American energy markets.

5.1. Methodology

The Granger representation theorem states that when a Vector Autoregressive Model (VAR) of cointegrated *I*(1) variables is estimated without including the error correction the model will be misspecified. Taking into account the results above that the price series for the European natural gas hubs are cointegrated, the paper will continue the analysis by estimating an error correction model (ECM). The vector representation of the ECM was already presented in a previous chapter in equation (4). For each market pair of the price series the vector ECM consists of two equations (Alexander 2001, p. 362). The following two equations illustrate the ECM for the log price series of the hubs NBP and Zeebrugge p_t^{NBP} and p_t^{ZEE}:

$$\Delta p_t^{NBP} = \sum_{i=1}^{p-1} \theta_i^{NBP} \Delta p_{t-i}^{NBP} + \sum_{i=1}^{p-1} \gamma_t^{NBP} \Delta p_{t-i}^{ZEE} + \alpha^{NBP}(\beta_1 p_{t-1}^{ZEE} - \beta_2 p_{t-1}^{NBP} - \delta) + e_t^{NBP} \quad (6)$$

$$\Delta p_t^{ZEE} = \sum_{i=1}^{p-1} \theta_i^{ZEE} \Delta p_{t-i}^{ZEE} + \sum_{i=1}^{p-1} \gamma_t^{ZEE} \Delta p_{t-i}^{NBP} + \alpha^{ZEE}(\beta_1 p_{t-1}^{ZEE} - \beta_2 p_{t-1}^{NBP} - \delta) + e_t^{ZEE} \quad (7)$$

where Δp_t denotes the first difference operator and hence the log return of each price series. As in the usual VAR model each first difference is regressed on its own lagged values and the lagged values of another series. The first differences are used in the model, since the price series are *I*(1). The number of lags p is chosen to minimize the AIC. In contrast to the standard VAR, the ECM takes into account the cointegrating relationship between the two markets and includes an error correction term $(\beta_1 p_{t-1}^{ZEE} - \beta_2 p_{t-1}^{NBP} - \delta)$ in the regression where β_1 and β_2 are the coefficients of the cointegrating vector. The δ is a constant which accounts for transaction and transportation costs in the cointegrating relationship. Moreover, a normally distributed error-term e_t is integrated in the equations. This ECM representation enables to analyse how the prices series respond to stochastic shocks and to deviations from the long-run equilibrium relationship between the two variables (Alexander 2001, p. 362). This long-run structural relationship in the case of market integration is the LOOP, which was tested in the previous chapter and could not be rejected.

The following analysis will focus on two key model parameters in equations (6) and (7). First, the adjustment parameter α will be studied. This parameter determines how fast the series returns to the long-run equilibrium after disequilibrium occurred in the cointegrating relation. A larger α parameter leads to greater response of the series to deviations from long-run equilibrium and the price gap between the series will be very stable. A small α parameter means that the series is relatively unresponsive to an equilibrium error and hence it will reach the long-run equilibrium only relatively slowly (Serletis and Herbert 2007, p. 166).

Furthermore, the parameter α is used to determine if a price series is weakly exogenous. This is the case when the adjustment parameter in a cointegrated system is not significantly different from zero. When this condition holds the price series is not influenced by a discrepancy from the cointegrating long-run relationship. Since the price series in the error correction term are non-stationary the distribution of the test $\alpha = 0$ is non-normal (Enders 2004, p. 368). Therefore a likelihood ratio test is used to test the restriction. This test provides evidence whether one market drives the prices of the other market in the long-run and the market is the price leader in the bilateral relationship (Asche et al. 1999, pp. 576-577). The test can be also interpreted as an additional test for cointegration because at least one parameter α for each market pair has to be non-zero if the variables are cointegrated (Verbeek 2004, p. 319).

The adjustment parameter refers to the long-run relationship between the price movements in the two markets. The short-run effects can be analysed by applying the concept of Granger causality to the ECM. Granger causality refers to a lead-lag relationship between two variables and exists when the lagged values in one variable help to forecast the current value of another variable (Alexander

2001, p. 344). In equations (6) and (7) the parameters γ_i determine how the return in one market responds to the lagged returns of the other market. However, when the concept of Granger causality is applied to an ECM, the adjustment parameter has also to be considered since effects can also occur through the error correction channel. Therefore if the adjustment parameter and the coefficients γ_i in one of the equations (6) and (7) are significantly different from zero, the return of the other market Granger causes the return in the analysed market (Lütkepohl and Krätzig 2004, p. 146; Serletis and Herbert 2007, p. 166). The test can be performed by using a block exogeneity F-test since all lagged variables are expressed in first differences and therefore they are stationary (Enders 2004, p. 287). The test does not include a test on the adjustment parameter α**,** since it is tested in the prior section. In addition, this two-step approach has the advantage that it allows distinguishing between the short-run and long-run effects (Asche et al. 1999, pp. 578-579).

5.1. Empirical results

The analysis of the ECM will proceed in two steps. First, the model is estimated and in a second step the restrictions on the parameter are tested. The results of the tests are reported in Table 7. The price series on left-hand side of the ECM equation are listed horizontally in the table. The values and the signs for the adjustment parameter α in equation (6) and (7), as well as the p-value of a likelihood ratio test for the null hypothesis $\alpha = 0$ are reported. In addition, Table 7 lists the p-values of a chi-square test statistic for the exclusion of all lags of the second market which is a test for Granger causality. For all but one case the adjustment parameter for the error correction part has the right sign. The parameter for TTF-Bunde should have been positive and therefore is denoted in parenthesis. Moreover, the parameter is not significant and therefore it is excluded from the discussion.

The adjustment parameters which are significantly different from zero at the 10% significance level range from 0.045 for NBP-Bunde to 0.180 for NBP-Zeebrugge[9]. The parameter of NBP responding to changes in an NBP-Zeebrugge error is almost double the size of the second fastest adjustment parameter of Bunde-TTF. This indicates that the NBP and Zeebrugge are very well integrated which confirms the results of the cointegration tests. Therefore, deviations from the long-run relationship between the two hubs do not persist over long periods and the price gap between the two series returns fast to the equilibrium. For example, if the error correction term in equation (6) in period $t-1$ is positive, the Zeebrugge price is relatively high compared to the NBP-Price and there is

[9] The following notation is used when referring to the parameters of the ECM: For example, when analysing the adjustment parameter for NBP-Zeebrugge, the first mentioned hub refers to left variable in left-hand side the equation (6) or (7) and the second mentioned hub refers to the exogenous hub in the equation.

disequilibrium. Therefore in the next period t, the NBP price is likely to increase substantially which leads to a high log return at NBP due to a high α^{NBP}. Due to this reaction the two series will return the long-run equilibrium.

Table 7. Error Correction Model of the European Natural Gas Spot Markets

	Bunde			NBP		
	α coefficient	α=0 p-value	Granger p-value	α coefficient	α=0 p-value	Granger p-value
Bunde				0.016	0.548	0.005
NBP	-0.066	0.006	0.000			
TTF	-0.098	0.002	0.000	0.036	0.269	0.001
Zeebrugge	-0.080	0.003	0.000	0.180	0.008	0.227

	TTF			Zeebrugge		
	α coefficient	α=0 p-value	Granger p-value	α coefficient	α=0 p-value	Granger p-value
Bunde	(-0.015)	0.711	0.041	0.003	0.931	0.000
NBP	-0.045	0.091	0.000	-0.050	0.437	0.000
TTF				0.010	0.801	0.000
Zeebrugge	-0.062	0.059	0.000			

Notes: The likelihood ratio test statistic for the adjustment parameter follows a $\chi 2$ distribution with one degree of freedom. A low p-value indicates a rejection of the null hypothesis that the adjustment parameter is not significant. The Granger column reports the p-value for chi-square test that all lagged values of the exogenous market are insignificant.

These movements can be an important indicator for trading companies when designing a successful trading strategy in the two markets (Serletis and Herbert 2007, 168). Furthermore, the results indicate that the NBP is the endogenous variable which adjusts when disequilibrium occurs. The adjustment parameter for Zeebrugge is not significant at any reasonable significance level indicating that Zeebrugge is weakly exogenous. This result is especially interesting because most practitioners in the markets would argue that the NBP determines the prices at Zeebrugge and not the other way round. Therefore, the relationship between these two markets still offers room for further research.

When analyzing the other adjustment parameters for Zeebrugge it can be noticed that none of them is significant at the 10% level. Hence it can be concluded that the Zeebrugge hub is weakly exogenous in all three bilateral market pairs. However, it cannot be concluded that this leads to a rejection of the cointegrating hypothesis. In the reverse direction all adjustment parameters are significant at the 10% level and Bunde-Zeebrugge and NBP-Zeebrugge are even significant at the 1% level. This means that other hubs respond to disequilibrium with the Zeebrugge hub and hence there is evidence for a long-run cointegrating relationship between these hubs.

At the NBP a pattern similar to the one at Zeebrugge can be observed. Only the adjustment parameter NBP-Zeebrugge is significantly different from zero. NBP-Bunde and NBP-TTF are not significantly different from zero at the 10% significance level. This is evidence that NBP is weakly exogenous to the latter ones. It can be concluded that NBP only responds to disequilibrium in the NBP-Zeebrugge long-run relationship. The observed adjustment parameters lead to the conclusion that Zeebrugge and NBP are the price leaders in the European natural gas spot markets and TTF and Bunde are following the price movements of NBP and Zeebrugge.

There is some evidence in the data which leads to the rejection of cointegration for the market pair NBP-TTF. The bivariate Johansen test in the previous chapter could reject no-cointegration only at the 10% level. The tests of both adjustment parameters show that both parameters of the market pair are not significant at the 5% level and that the one for NBP-TTF is not even significant at the 10% level. Combining these two results the evidence for a cointegrating relationship between the two hubs is the weakest one which is found in this analysis.

When analysing the short-run relationship between the four markets the focus is on the lagged returns of the non-left-hand side price series in equations (6) and (7). The p-values for the chi-square test that the coefficients for these lagged returns are jointly insignificant are reported in Table 7 in the column Granger. The null hypothesis that the coefficients of these lagged returns are not significant to determine today's returns in the analyzed market is only not rejected for NBP-Zeebrugge at the 10% significance level (p-value: 0.227). Since this is the market pair where the adjustment process of the long-run relationship takes place very rapidly there is evidence that the short-run relationship is already captured by the error correction term in model. Since the adjustment parameter is non-zero it still can be rejected that Zeebrugge prices do not Granger cause NBP prices. As explained above this requires not only the γ coefficients to be insignificant, but also adjustment parameter to be zero. The latter condition is not fulfilled for the NBP-Zeebrugge market pair.

The chi-square statistic of the coefficients of the lagged values of Bunde in the TTF equation is not significant at the 1% level. Since the adjustment parameter TTF-Bunde is also not significant, the two tests do not reject that Bunde does not Granger cause TTF at the 1% significance level. But the tests reject non-causality at the 5% level. Therefore, the hypothesis of no Granger causality can be rejected for any market constellation at the 5% significance level.

6. Price Gaps

In the following part the deviations from the long-run cointegrating relationship that are estimated in the previous chapter are further analysed (see also McAvoy 2007). Furthermore, the role of the Interconnector connecting the UK and Continental Europe is investigated. As explained above the

Interconnector connects Zeebrugge to the NBP. The analysis focuses on the deviations from the LOOP which is referred to as a price gap or spread between two hubs. It is defined as the difference between the two price series. This difference is equal to transportation and transaction costs and it implies that the cointegrating vector is $\beta = (1, -1)$. The results of the previous chapter show that this hypothesis cannot be rejected for all market pairs.

The adjustment parameters in the ECMs indicate how fast the market pair returns to its long-run relationship after deviations took place. As shown above this adjustment speed differs substantially between the various market pairs. This analysis focuses on three characteristic market pairs. Two market pairs include the NBP and therefore they represent a relation of the United Kingdom to the Continental European natural gas price. Furthermore, the price gap between Bunde and TTF which represents a relationship of two continental hubs is also investigated. In addition, the ECM shows in all three market pairs that one hubs is exogenous which is evidence that only one hub in each pair is likely to adjust to deviations from the long-run equilibrium.

First, the Zeebrugge and NBP gap will be analysed for which the above error correction analysis shows that the adjustment between the two price series NBP and Zeebrugge takes place relatively fast; the adjustment parameter α is 0.180. This indicates that the two hubs are very well integrated and that there is sufficient pipeline capacity available to arbitrage between the two markets. Therefore, arbitrage opportunities are exploited fast and do not persist over longer time periods. Second, the TTF and NBP market pair where the series converge rather slowly to equilibrium ($\alpha = 0.045$) is analysed and as discussed above the evidence for cointegration is less strong. The slow adjustment and the weak cointegrating relationship can be caused by two factors: First, pipeline capacity between the two hubs is not always available in a sufficient amount. Therefore deviations from the equilibrium can continue for longer periods since market participants are unable to perform arbitrage. Reasons for this might be that the BBL pipeline which directly connects the NBP and TTF only opened in the second part of the sample. In addition, the BBL only offers physical flow from the Continent to the UK. Secondly, one of the hubs might not be liquid and hence arbitrage might not be possible because counter parties for trades are not available. But an illiquid hub may also be caused by insufficient pipeline capacity and bottlenecks in the transmission net. The third analysed price gap is Bunde-TTF for which the ECM estimates a rather fast adjustment parameter ($\alpha = 0.098$) indicating that the two hubs are well integrated.

The descriptive statistics of the price gap series for all six market pairs are reported in Table 8. As mentioned above, the analysis will focus on three characteristic market pairs which are reported in the upper part of Table 8. All series are stationary[10] and have a mean slightly different from zero. The statistics show that the TTF-NBP gap is more volatile and has a higher maximum and a lower minimum than the Zeebrugge-NBP price gap. The Bunde – TTF gap is a slightly more volatile than the Zeebrugge-NBP price gap. The very low minimum is due to two outliers. The descriptive statistics of the price gaps confirm the results of the error correction model that the adjustment between NBP and Zeebrugge is faster than in the other two markets pairs and it indicates a better integrated market.

Table 8. Descriptive Statistics of the Price Gap Series

	Gap Zeebrugge - NBP	Gap TTF - NBP	Gap Bunde - TTF
Mean	0.02	-0.03	-0.03
Standard deviation	0.08	0.22	0.13
Maximum	0.79	1.17	0.59
Minimum	-0.39	-1.40	-1.77
	Gap Bunde - Zeebrugge	Gap TTF - Zeebrugge	Gap Bunde - NBP
Mean	-0.08	-0.05	-0.06
Standard deviation	0.21	0.19	0.23
Maximum	0.57	0.72	0.80
Minimum	-1.41	-1.39	-1.47

Notes: The price gap series are defined as the difference between two log price series.

In Figure 2 the three price gap series for Zeebrugge- NBP, TTF- NBP and Bunde - TTF are plotted. The plot of Zeebrugge – NBP confirms the earlier results. The gap series is relatively calm and fluctuates around its slightly positive mean most of the time. There are three large spikes in the series. Moreover, in autumn 2006 there is a time period with some considerable deviations from the long-run relationship. The plot of the TTF-NBP price gap looks remarkable different. There are longer periods with large deviations in both directions from equilibrium and the price gap is more volatile during the whole sample period. The plot for Bunde-TTF is more volatile than the Zeebrugge-NBP, but the deviations from the long-run relationship do not persist for long periods as it is the case for the price gap TTF-NBP. As explained earlier, at the end of 2007 there is a two week period without trades at the Bunde hub. During that time span the prices could deviate from the LOOP. The plots and the descriptive statistics indicate that the TTF and NBP are relatively weakly integrated compared to the Zeebrugge-NBP and TTF-Bunde. This confirms the earlier results from error correction model.

[10] An ADF unit root test rejects the null of a unit root at the 5% significance level for all lag lengths.

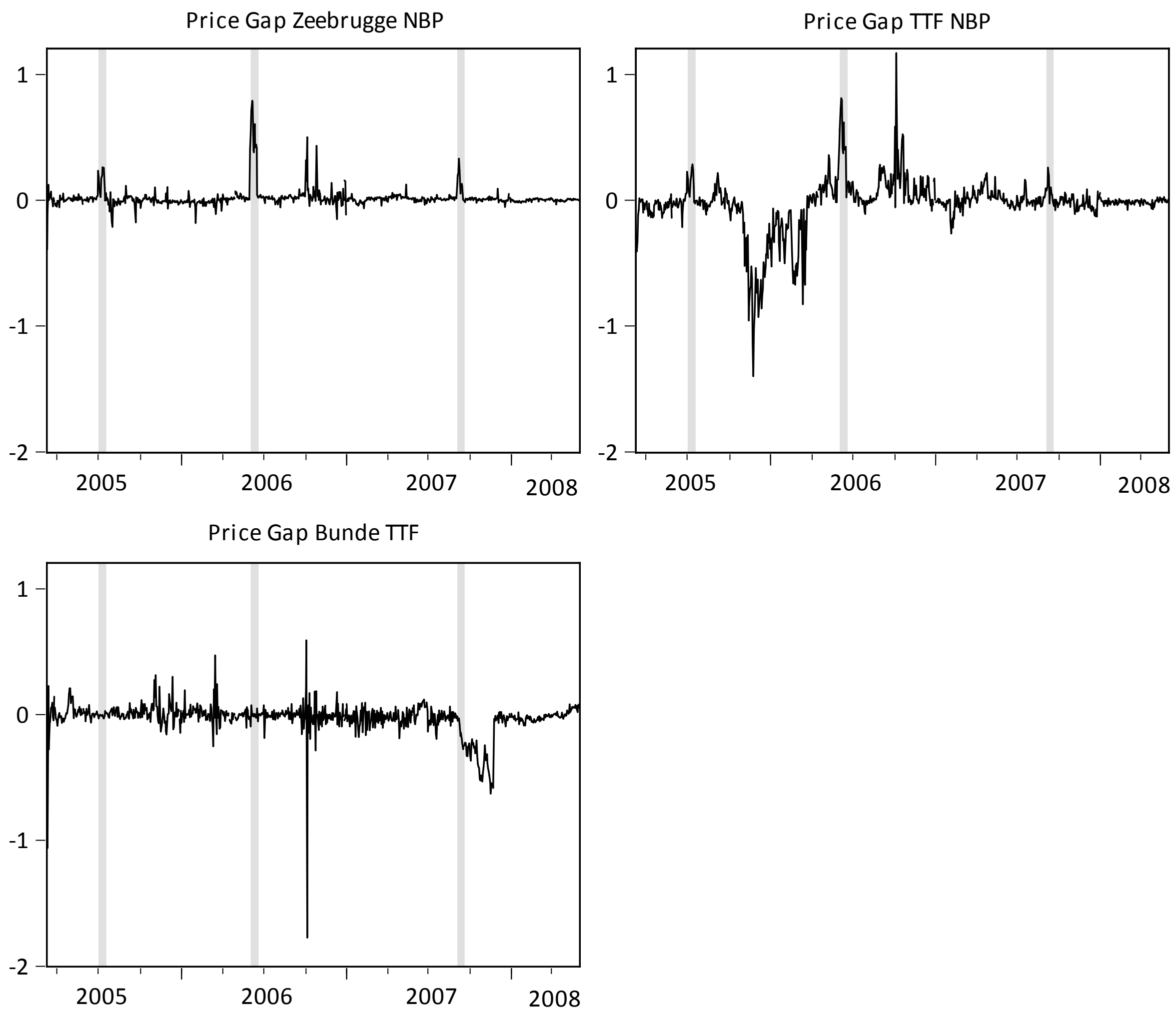


Figure 2. Price gaps between between log prices of Zeebrugge-NBP, TTF-NBP and Bunde-TTF

The following analysis will focus on how the Interconnector between the United Kingdom and Continental Europe influences the deviation from the long-run relationship. The shaded areas in Figure 2 highlight the periods when the Interconnector between the UK and Continental Europe was shut down for a maintenance period. The Interconnector is closed for maintenance once a year for a period of two weeks. The large spikes in the Zeebrugge-NBP occurred during the maintenance phases when the Interconnector was closed. During these periods the prices could deviate from the long-run equilibrium and the price at Zeebrugge was higher than in the United Kingdom. Furthermore, this pattern indicates that during normal operation periods of the Interconnector the pipeline capacity is sufficient and the two markets are liquid. The historical flow data of the Interconnector confirm these results[11]. The capacity of the pipeline was fully booked only for some days in February 2006 and hence there was enough space for arbitrage trading during the rest of the sample period.

The spikes during the maintenance periods of the Interconnector can also be observed for the TTF-NBP price gap. However, the deviations during the maintenance period are small compared to other deviations in the rest of the sample period. This indicates that the Interconnector plays only a minor role for the integration of the two markets and that other reasons are likely to cause deviations from the long-run relationship. The large deviations between the two markets occurred before the BBL pipeline began operating in December 2006. Hence, insufficient pipeline capacity between Zeebrugge where the Interconnector begins and the TTF may have caused the deviations in the winter 05/06. For the period after the opening of the BBL the TTF and the NBP seem to be better integrated.

Finally, when looking at the price gap Bunde and TTF the maintenance periods do not indicate periods in which the LOOP does not hold. This result is not surprising since the Interconnector pipeline does not connect the two markets and therefore the shutdown should not affect the relationship of the two markets.

6.1. Intervention Analysis of the Interconnector Shutdown

The effect of the Interconnector shutdown is estimated by using the intervention analysis model of Enders (2001, pp. 240-246). This model allows to test whether the mean in the gap changes significantly when the Interconnector is unavailable due to maintenance for two weeks in the summer. The gap series GAP_t is modelled with an ARMA model and a dummy series INT_t for the interconnector shutdown. In order to estimate the impact of the Interconnector shutdown on the gap series the following equation is estimated:

$$GAP_t = c + \sum_{i=1}^{p} \beta_i \, GAP_{t-i} + \sum_{i=i}^{q} \alpha_i \varepsilon_{t-1} + \lambda INT + \varepsilon_t \qquad (8)$$

The lags are chosen to minimize the AIC. Further, the Ljung-Box Q-statistics are evaluated in order to make the residuals look like white noise. The dummy represents a pulse function which accounts for a temporary intervention during the maintenance periods. The dummy is equal to 1 when the Interconnector is shut down and it is equal to 0 on all other days. The statistical significance of the dummy coefficient λ can be tested using a standard t-test. The size of the coefficient determines how much the price gap between the series increases when the Interconnector is shutdown. The long-run mean of the series is equal to $\frac{c}{1-\sum_{i=1}^{p}\beta_i}$ (Enders 2001, p 241).

[11] The data can be found on http://www.interconnector.com/onlineservices/historicflows.htm.

The model is estimated for the three representative price gaps analysed in the previous section. The estimates are reported in Table 9. The AIC indicates an ARMA(3,0) for the Zeebrugge-NBP gap, an ARMA(5,1) for the TTF-NBP gap and an ARMA(4,2) for the Bunde-TTF price gap. The results were robust to other model specifications. The ARMA(3,0) for the Zeebrugge-NBP price gap is the only one of the models where the constant term was significant. That is why in contrast to the other price gaps the long-run mean is different from zero. The λ coefficient for this series is positive and highly significant at the 1% level. This indicates that during the maintenance period the mean of the series increases by 0.13. Hence the price level at Zeebrugge increases significantly relative to the NBP price during the maintenance period.

Table 9. Intervention Analysis of the Interconnector Maintenance Periods

	Gap Zeebrugge-NBP	Gap TTF-NBP	Gap Bunde-TTF
Model	ARMA(3,0)	ARMA(5,1)	ARMA (4,2)
Long-run mean	0.05	0.00	0.00
λ-coefficient	0.13	0.08	-0.01
P-value	0.00	0.02	0.84

Notes: The p-value indicates the significance of the rejection of the null hypothesis λ=0.

The hypothesis that the Interconnector shut does not affect the TTF-NBP price gap can also be rejected. The coefficient of the dummy is significant at the 5% level. This size of the coefficient is 0.08. So the effect of an Interconnector shutdown is slightly less large for the TTF-NBP price gap than for the Zeebrugge-NBP price gap. As already mentioned earlier, other factors may overshadow the effects of the Interconnector shutdown for the TTF-NBP price gap. As expected the Interconnector shutdown does not affect the price gap between Bunde and TTF. The coefficient for the dummy is small and not insignificant. Therefore, the results of the intervention analysis confirm the evidence from the plots of the price gaps.

6.2. Impulse Response Functions

In the following the impulse response function of the three price gaps will be analysed. Cuddington and Wang (2006) use the impulse response functions to determine the degree of integration in the North American natural gas spot markets. The impulse response functions are based on the ARMA models estimated in the previous section. A standardized one unit shock is introduced in the three models and it is then observed over 25 periods. The estimated functions are plotted in Figure 3.

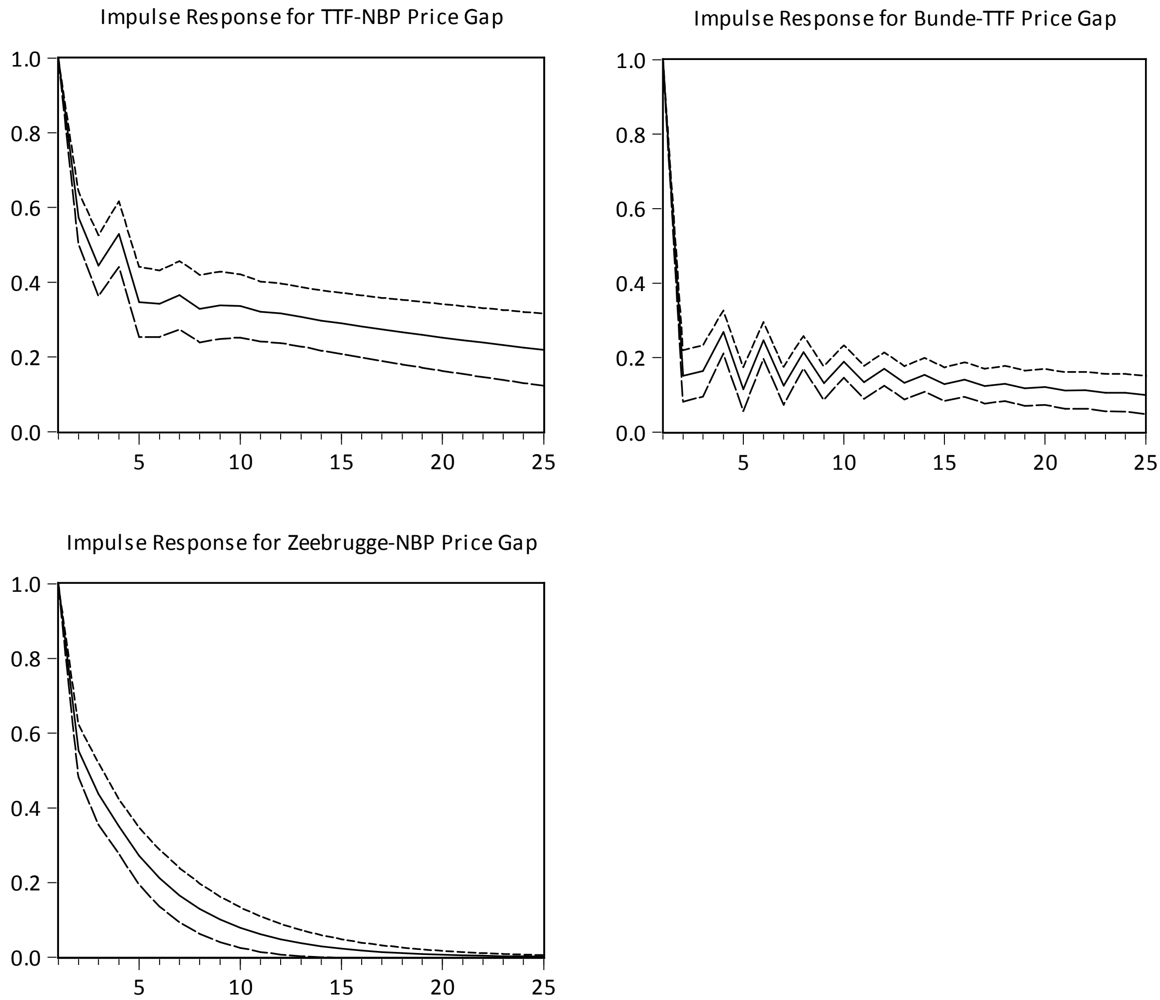


Figure 3. Impuls Response Functions for three characteristic price gaps with 95% confidence band

The functions confirm the earlier results about the degree of integration of the three analysed market pairs. The effects of the one unit shocks die out relatively quickly in the Bunde-TTF and in the Zeebrugge-NBP price gap series. This confirms that the two market pairs are relatively well integrated and that deviations from LOOP persist only for short time periods. In contrast to this the effect of the one unit shock introduced in the TTF-NBP price gap model falls initially, but afterwards decreases at a slower rate. This is evidence that the two markets are more loosely integrated. The impulse response function for this market pair therefore confirms the results of the error correction model where the least strong cointegrating relationship is found for this market pair. However, it can be noted that the effect of the introduced shock does not fail to converge to zero (periods after 25 not shown in figure). So the impulse response function does not indicate that the price gap is non-stationary and the series are not cointegrated (see also Cuddington and Wang 2006, pp. 205-206).

7. Volatility Model

This chapter moves the focus of the analysis away from the cointegrating relationships to the volatility in the four markets. For participants of financial markets it is essential to understand the volatility of the market. Due to several characteristics of the market, this is even more true for participants in a physical market, like natural gas. First, volatility changes affect the risk exposures of consumers which have generally a short position in the market and producers which have generally a long position. Second, physical and financial claims based on natural gas are influenced by the volatility in the market. For the valuation of financial derivatives, as well as physical infrastructure which depends on the price at the gas hubs, it is important to know the volatility process in the market. That is why the volatility in the market will influence the decision of market actors to invest in storage, transportation, exploration and other physical infrastructure. Third, as explained in the second chapter of this thesis, the natural gas trading hubs in Europe are gaining importance as a reference for the pricing of long-term supply contracts. In addition, options and other derivatives are created with a natural gas contracts as the underlying. Therefore understanding the volatility in these markets is becoming more and more essential for actors on all sides of the market.

Financial markets, as well as energy markets, often exhibit volatility clustering and therefore the volatility in these market is not constant (Tsay 2005, p. 99). One way to deal with this characteristic is the use of Generalized Autoregressive Conditional Heteroscedasticity models (GARCH). These models are widely applied in the financial econometrics literature to account for volatility clustering in financial time series (Kirchgässner and Wolters 2006, pp. 232-234). However, there is only a relatively limited amount of academic research about the application of these models to the natural gas markets. Eydeland and Wolyniec (2003) estimate various GARCH models for gas prices at several locations in North America and find that these estimated models generally fit the data well (p. 173). Pindyck (2004) uses weekly and daily log price changes of natural gas and oil futures in order to estimate GARCH models. He finds a positive trend in natural gas volatility in the sample period and he is able to reject the hypothesis that volatility increased during the Enron collapse in 2001. Moreover, he investigates the interrelationship between natural gas and oil volatility by using Granger causality tests. He finds evidence that oil price volatility Granger causes natural gas volatility. Serletis and Shamoradi (2007a) use a GARCH model to identify conditional heteroscedasticity in the NYMEX Henry Hub natural gas futures contracts. They use log price changes to model the volatility and estimate the impact of seasonal effects and open interest on volatility. Serletis and Shamoradi (2007b) estimate a vector autoregressive moving average GARCH-in mean model to investigate the relationship between electricity and natural gas spot prices. They find bidirectional predictability between electricity and natural gas prices, as well as volatilities. Mu (2007) uses a GARCH model to estimate the effects of weather surprises, Monday effects and storage announcements on the conditional volatility of log price changes of natural gas future contracts. He finds that these three factors are statistically significant, but they cannot explain a large fraction of the volatility.

7.1. Methodology

Most econometric time models assume that the variance of the error term is constant. However, this assumption is inappropriate for many price series of financial assets. These series exhibit periods of tranquillity, followed by periods of high volatility. This phenomenon of volatility clustering is called heteroscedasticity (Enders 2004, p. 112) and is also found in energy markets. In 1982 Engle introduced an Autoregressive Conditional Heteroscedasticity (ARCH) model which estimates simultaneously the mean and the variance of a time series. Based on Engle's work Bollerslev developed the Generalized ARCH (GARCH) model in 1986 which will be used in the following analysis (Tsay 2005, p. 98).

The GARCH model for the return series analysed in this paper is based on two equations: the conditional mean and the conditional variance equation. The conditional mean is often described by a constant and an error term which accounts for deviations from the average return over the data period. Since the returns of the gas hubs analysed in this thesis show significant autocorrelation a time-varying conditional mean equation is used. Therefore, in equation (9) ARMA terms are included in the mean equation to account for the autocorrelation:

$$r_t = c + \sum_{i=1}^{p} \beta_i r_{t-i} + \sum_{i=i}^{q} \alpha_i \varepsilon_{t-1} + \varepsilon_t \tag{9}$$

The number of lags is chosen to remove the autocorrelation in the error term. The second equation of a GARCH model describes the conditional variance of the return series (Alexander 2001, p.70). The variance equation (10) includes GARCH terms representing the forecasted variance from previous periods and the ARCH terms representing the squared error term of the mean equation from previous periods. These GARCH terms are denoted as σ_{t-i}^2 and ARCH terms are denoted as ε_{t-i}^2. Moreover, a constant c which is the long-run average of the variance is included in the following variance equation:

$$\sigma_t^2 = c + \sum_{i=1}^{p} \beta_i \sigma_{t-i}^2 + \sum_{i=i}^{q} \alpha_i \varepsilon_{t-i}^2 \tag{10}$$

The order p,q of the GARCH(p,q) model is selected to minimize the Schwartz Information Criterion (SIC). Monte Carlo studies show that this criterion usually finds the correct order of a GARCH model and thus it may be preferred to the other selection criteria like the AIC (Taylor 2005, p. 256).

In this paper the GARCH coefficients are estimated using the maximum likelihood procedure included in EViews. The maximum likelihood function is estimated assuming that the errors are normally distributed. However, alternative distributions can be imposed, but imposing a wrong distribution on the errors is not serious since these Quasi-Maximum Likelihood estimators for the means of the coefficients and the conditional variance are still consistent (Taylor 2005, p. 217; Enders 2004, p. 155). The appropriateness of the normality assumption can be tested by plotting a Quantile-Quantile plot of the standardized residuals. These standardized residuals are obtained by dividing the residual from the mean equation by the conditional standard deviation estimated in the GARCH model. If the plot indicates a non-normal distribution of the residuals, there are two solutions in order to estimate a consistent covariance matrix. First, the Maximum Likelihood Estimator can impose another underlying distribution on the residuals. Second, a robust covariance matrix estimator proposed by Bollerslev and Wooldridge can be used (Campbell, Lo and MacKinlay 1997, p. 489). This thesis will use the second approach.

The adequacy of the model is checked by analysing the standardized residuals. After standardising there should be no autocorrelation in the residuals and squared residuals if the model is well specified. This diagnostic check is performed by analysing the Q-statistics of the series (Taylor 2005, p. 257).

7.2. Empirical Results

7.2.1. Descriptive Statistics of the Returns

The daily log returns for the four natural gas hubs analysed in this chapter are plotted in Figure 4. The returns for NBP and Zeebrugge look remarkably similar and are more volatile than the returns for Bunde and TTF. All four hubs exhibit a period of high returns in winter 2006/07 and for the hubs NBP, TTF and Zeebrugge a period of high returns and volatility can be also found throughout the winter 2005/06. In the first quarter of 2006 the prices at NBP and Zeebrugge were very volatile. As already discussed earlier in chapter three, this was due to cold weather and a tight supply balance. In March 2006 this situation was even worsened when a fire at the Rough storage broke out, which is the principal storage facility for the UK market (Jackson and Harris 2007, p. 64). During that period daily returns at NBP increased to up to 113%. The figures provide some evidence for volatility clustering in the four series. Calm periods with relatively steady low returns are followed by periods where there are high returns and volatility. The following section will first analyse formally whether there are Autoregressive Conditional Heteroscedasticity (ARCH) effects in the data before continuing with estimating a GARCH model.

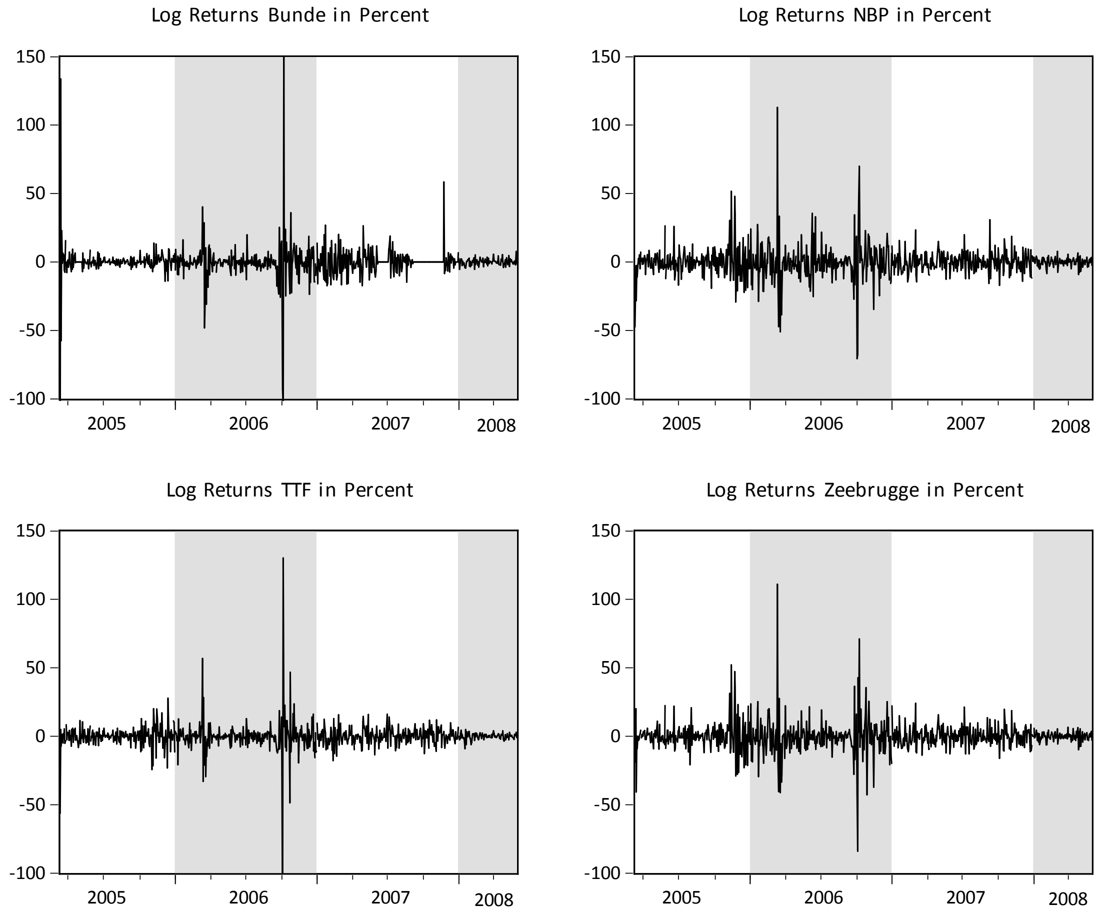


Figure 4. Log Returns for Bunde, NBP, TTF and Zeebrugge

Table 10 provides the summary statistics for the daily log returns of the four natural gas hubs for the sample period between March 2005 and May 2008. The mean for all returns is only marginal different from zero percent. The returns for TTF are the least volatile. The return series has a standard deviation of 9.6%, compared to 12.8% for the Bunde hubs, which has the most volatile returns. The high volatility at Bunde is however due to some outliers. When removing four observations from the sample the standard deviation decreases to 9.4%. All return series show significant evidence of skewness and excess kurtosis. Therefore, all series fail to satisfy the null hypothesis of the Jarque-Bera test for normality.

Table 10. Summary Statistics and Autocorrelation of the Return Series

	Bunde	NBP	TTF	Zeebrugge
Mean (in %)	0.029	-0.033	0.007	0.015
Daily Volatility (in %)	12.800	10.989	9.556	10.641
Annualized Volatility (in %)	202.393	173.754	151.095	168.243
Skewness	1.158	1.124	-0.141	1.214
Kurtosis	86.916	24.363	91.438	26.820
Jarque-Bera	241663.400	15823.540	268206.200	19658.710
Q(4)	0.000	0.000	0.000	0.000
Q(12)	0.000	0.000	0.000	0.002
$Q^2(4)$	0.000	0.000	0.000	0.000
$Q^2(12)$	0.000	0.000	0.000	0.000

Notes: The Q-statistic tests the null hypothesis of no autocorrelation up the analysed lag. The critical values are χ^2 distributed with degrees of freedom equal to the number of analysed lags (Enders 2004, p. 68).

Table 10 also provides the Ljung-Box Q-test p-values for the returns and for the squared returns. The Q-test p-value is reported for lag 4 and 12 and it shows the significance of a rejection of the null hypothesis that there is no autocorrelation up to the tested lag. The tests can reject the null hypothesis of no-serial correlation for the all returns and the squared returns of the four series at the 1% significance level. So this test for serial correlation in the squared returns provides strong evidence of volatility clustering and it is therefore concluded that conditional heteroscedasticity is in the data (Serletis and Shamoradi 2007a, p. 208). The statistics also suggests that the returns are not serially independent (Tsay 2005, p. 104).

In order to further investigate the changing volatility in the markets, a 30-day rolling volatility window for the daily log returns is created. The rolling windows volatilities are annualized and plotted in Figure 5. The figures show that volatility was the highest during the year 2006 in all four markets. In the years 2007 and 2008 the markets experienced a period of decreasing volatility. This trend was only interrupted by a period of high volatility at Bunde at the end of 2007 which occurred after a period of no trades at that hub in September and November 2007. All four series exhibit volatility spikes. During these periods the annualized volatility reaches 400-700 %. The volatility spikes for Zeebrugge and NBP occur with one exception in the summer 2006 during the same periods. The same is true for Bunde and TTF. This is some evidence that the volatility in the markets is correlated. This hypothesis will be tested in the next section by analysing whether there is Granger causality of volatility between the markets.

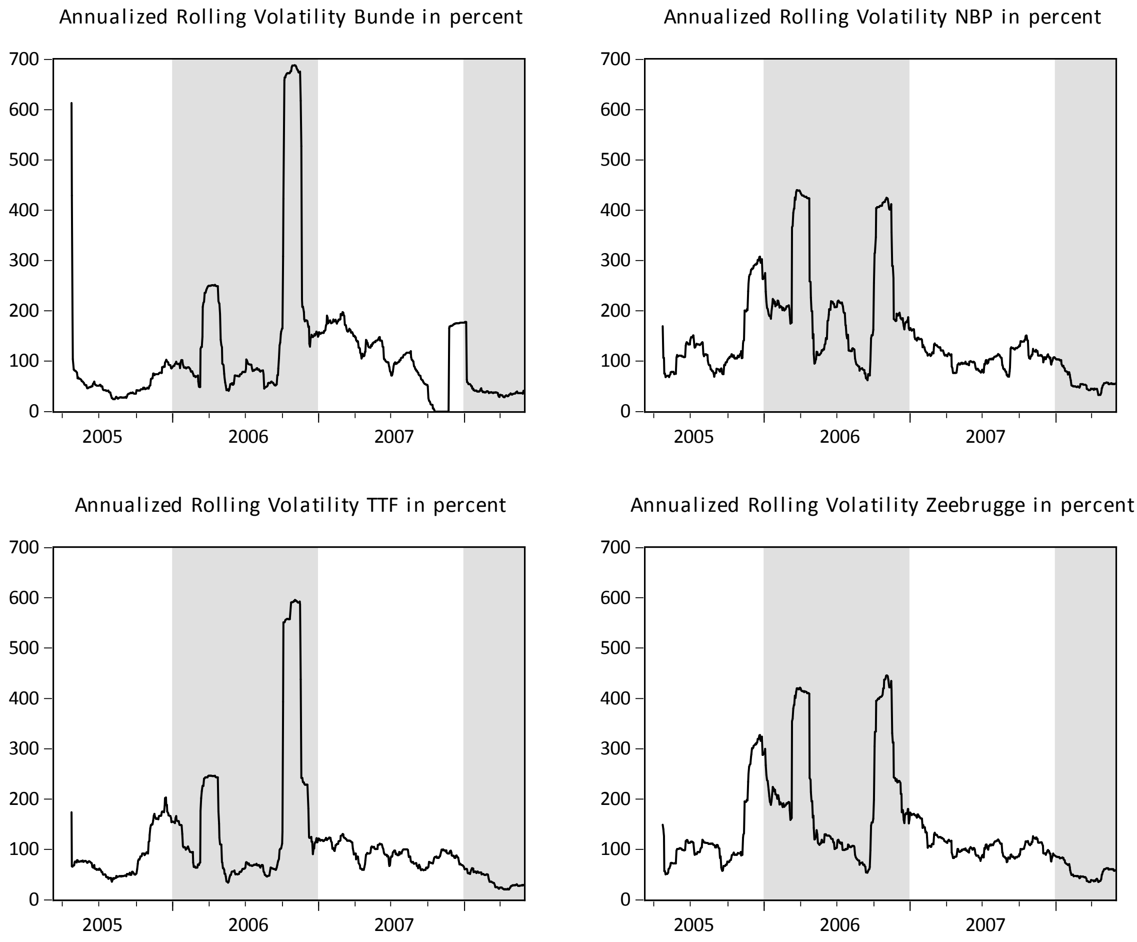


Figure 5. Annualized Spot Price Volatility in Percent (30-Days Moving Window)

7.2.2. GARCH-Models

This section will present the estimation results for the GARCH models for the four natural gas hubs. The SIC indicates the GARCH(1,1) specification for three return series. But for the TTF return series the SIC is minimized when a second ARCH lag is included in the model. But the GARCH(2,1) for TTF estimates a large negative coefficient for the second ARCH term which makes the fitted conditional variance considerably more volatile. Since the squared residuals of the model do not indicate a better fit of the GARCH(2,1) model, the more parsimonious GARCH(1,1) is chosen.

The Quantile-Quantile plots are shown in Figure 6. In the figure the quantiles of the distribution of the standardized residuals are plotted against the quantiles of a normal distribution (Tsay 2005, p. 109). If the residuals are normally distributed the dots should fall approximately on the dashed line. For all four hubs the residuals have an s-shaped distribution which is evidence that the standardized residuals are not normally distributed. For this reason the Quasi-Maximum Likelihood estimator is used and robust errors and covariance matrixes are estimated using the approach of Bollerslev and Wooldridge (Campbell et al. 1997, p. 489). This hypothesis is confirmed by the Jarque-Bera test which rejects normality for all four standardized residual series at the 1% significance level.

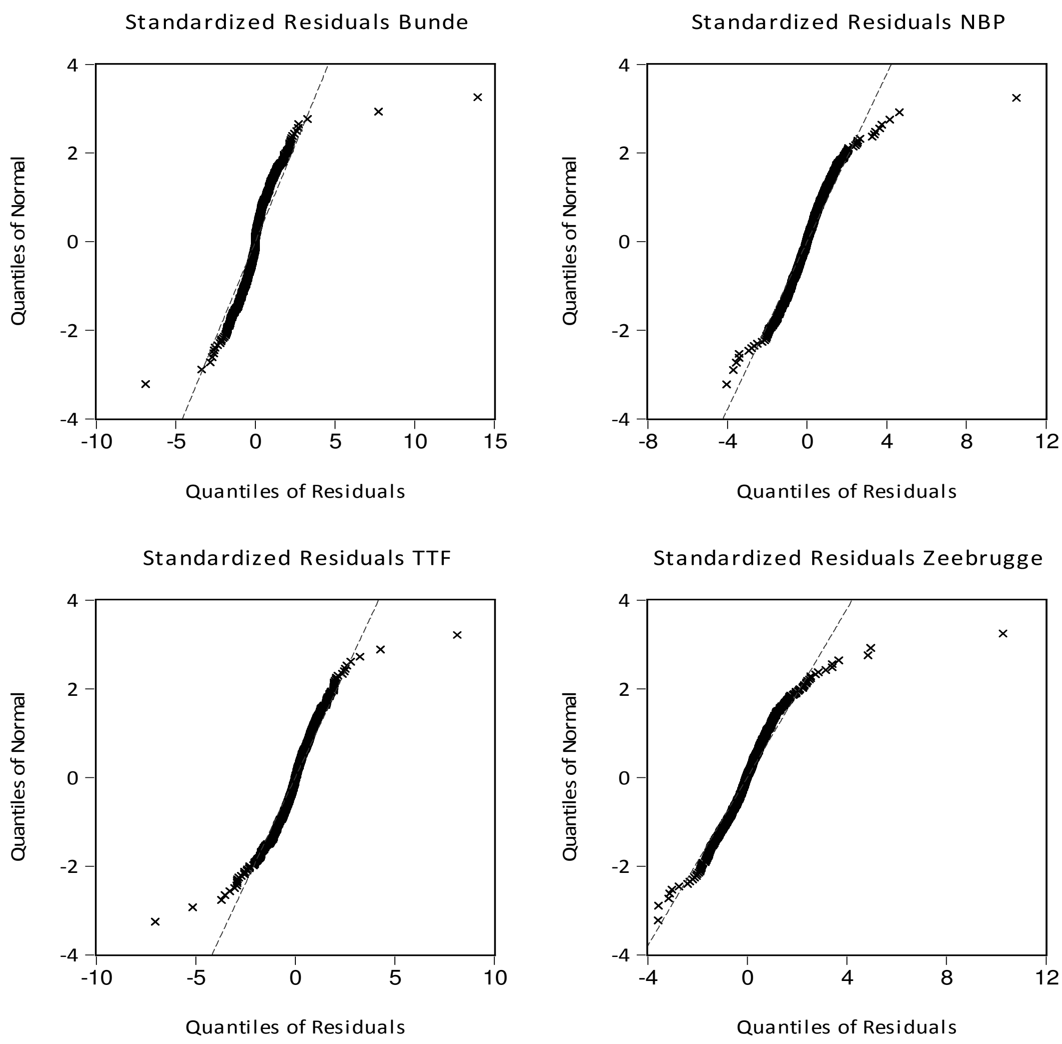


Figure 6. Quantile-Quantile Plots for Standardized Residuals of GARCH (1,1) models

The estimates of the GARCH coefficients reported in Table 11 indicate that the sum of the ARCH and GARCH coefficients is near unity for all hubs. Eydeland and Wolyniec (2003) conclude that this is a common finding for energy markets. If the sum of the ARCH and GARCH terms is unity, the volatility in the model is persistent and hence there is no long-term volatility to which the process reverts (Eydeland and Wolyniec 2003, p. 178). In this case today's volatility affects forecasts of volatility into the indefinite future. When $\alpha + \beta = 1$ holds in the variance equation (10) of a GARCH model, the model is called integrated GARCH (IGARCH) (Campbell et al. 1997, p. 484). Lumsdaine (1995) shows that the hypothesis $\beta + \alpha = 1$ can be tested by using a Wald test when the robust covariance estimator is used. The p-values of a rejection of this hypothesis are reported in Table 11.

Table 11. Estimation Results of GARCH(1,1) Models

	Bunde	NBP	TTF	Zeebrugge
Mean equation				
AR(1)	-0.568		-0.100	
Std. error	*0.057*		*0.052*	
p-value	*(0.000)*		*(0.0573)*	
AR(2)		0.382		0.507
Std. error		*0.049*		*0.116*
p-value		*(0.000)*		*(0.000)*
MA(1)	0.408			-0.117
Std. error	*0.071*			*0.035*
p-value	*(0.000)*			*(0.000)*
MA(2)		-0.518		-0.627
Std. error		*0.057*		*0.107*
p-value		*(0.000)*		*(0.001)*
	Bunde	NBP	TTF	Zeebrugge
Variance equation				
ARCH(-1)	0.276	0.170	0.364	0.336
Std. error	*0.104*	*0.039*	*0.162*	*0.090*
p-value	*(0.008)*	*(0.000)*	*(0.024)*	*(0.000)*
GARCH(-1)	0.635	0.863	0.729	0.747
Std. error	*0.070*	*0.029*	*0.068*	*0.032*
p-value	*(0.000)*	*(0.000)*	*(0.000)*	*(0.000)*
Constant	0.001	0.000	0.000	0.000
Std. error	*0.001*	*0.000*	*0.000*	*0.000*
p-value	*(0.218)*	*(0.384)*	*(0.015)*	*(0.161)*
ARCH+GARCH	0.911	1.033	1.093	1.082
p-value Wald test	0.512	0.360	0.353	0.314

Notes: P-values of the Wald test indicate the significance of a rejection of the null hypothesis that the GARCH model is not integrated.

The Wald test cannot reject the null hypothesis for none of the four series that the coefficients in the model sum up to one. Hence, it can be concluded that an IGARCH model is an appropriate representation for the volatility series of the four natural gas hubs. For this reason the volatility in the price series is persistent and there is no long-term volatility to which the process reverts (Eydeland and Wolyniec 2003, p.173).

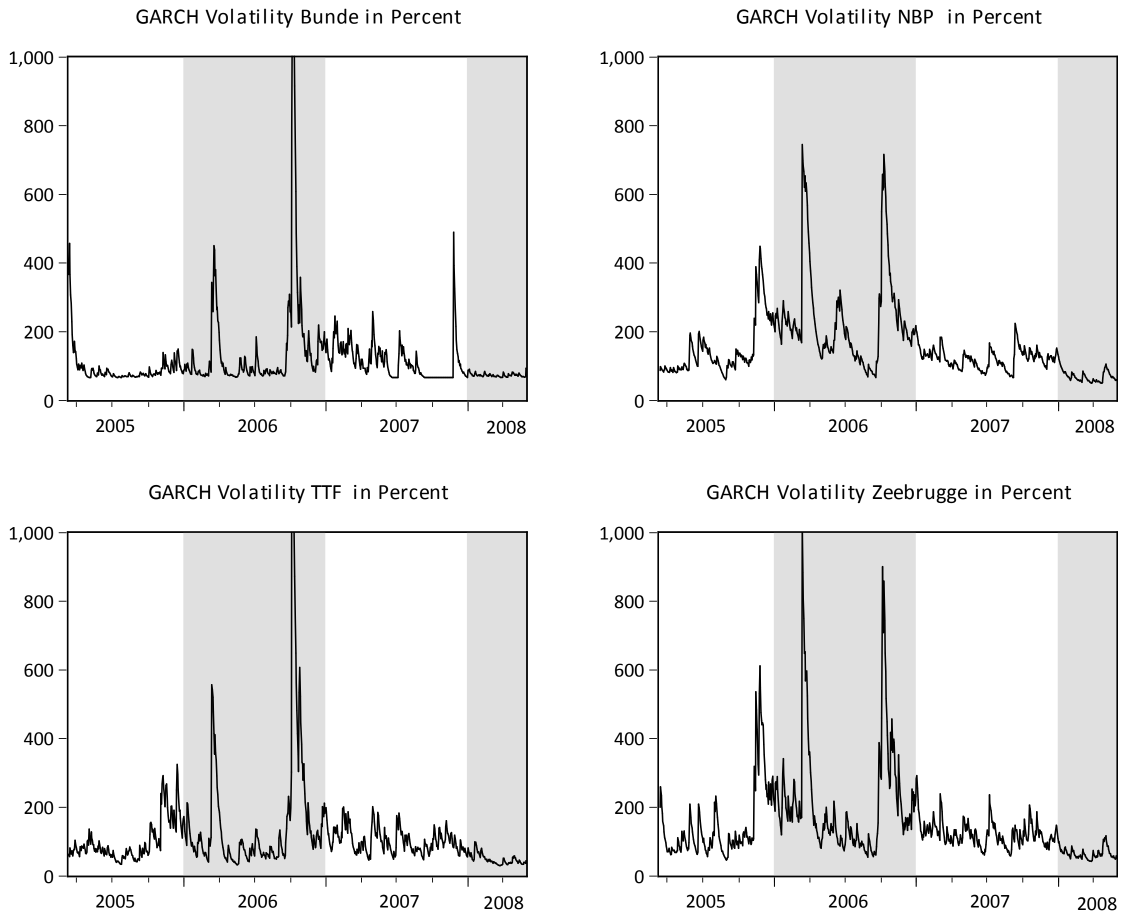
The GARCH(1,1) models for all hubs are checked for adequacy by performing diagnostic tests on the standardized residuals. These are obtained by dividing the residuals of the mean equation by the conditional standard deviation estimated in the model (Enders 2004, p. 147; Tsay 2003, p.109). First, the series are tested for remaining autocorrelation. For this purpose the Ljung-Box Q-statistics are evaluated at the lags 4,8,12 and 16. The second test investigates whether there are remaining GARCH effects in the series. The test is done by analysing the Q-statistics for the squared standardized residuals. If the test can reject serial correlation and GARCH effects in the standardized residuals, the model is considered appropriate. The results of the tests are reported in Table 12. They indicate that the GARCH models seem to capture well the conditional volatility of the series. At the 5% significance level the hypothesis of no serial correlation can be rejected only for the Q(4) statistics of the Bunde series. For all the other lags and for the squared residuals the Q-statistics cannot reject no autocorrelation at the 10% significance level. There are other Q-statistics rejecting the no autocorrelation hypothesis at the 10% significance level for the other hubs. However, the overall picture is clear and indicates a rather good fit of the estimated GARCH (1,1) models.

Table 12. GARCH(1,1) Model Adequacy – P-values of the Ljung-Box statistics

	Bunde	NBP	TTF	Zeebrugge
Q(4)	0.033	0.510	0.765	0.022
Q(8)	0.166	0.077	0.354	0.180
Q(12)	0.488	0.075	0.392	0.460
Q(16)	0.543	0.139	0.145	0.565
$Q^2(4)$	0.990	0.934	0.629	0.406
$Q^2(8)$	1.000	0.995	0.093	0.966
$Q^2(12)$	1.000	0.999	0.335	0.997
$Q^2(16)$	1.000	1.000	0.574	1.000

Notes: The Q-statistic tests the null hypothesis of no autocorrelation up the analysed lag. The critical values are χ^2 distributed with degrees of freedom equal to the number of analysed lags (Enders 2004, p. 68).

Figure 7 plots the conditional standard deviations implied by the GARCH (1,1) for all hubs. The estimated series are remarkably similar for Zeebrugge and NBP. This finding supports the results of the earlier chapters that the two markets are well integrated. To a lesser extent there are also similarities in the volatility estimates for Bunde and TTF.



Notes: Four observations for Bunde and TTF between 4th and 10th of October 2006 are not shown in the figure. The estimated annualized volatility during that period is up to 1626% for Bunde and up to 1578% for TTF.

Figure 7. Estimated Annulized GARCH Volatility in Percent.

7.2.3. Granger Causality of Volatility

Following the procedure of Pindyck (2004) this chapter tests whether Granger causality between the fitted conditional volatility estimates can be found. The annualized standard deviation estimates of the GARCH (1,1) models of the previous section are used for this analysis. Testing whether volatility in one market can help to predict volatility in another market increases the understanding of the interrelationship between the four markets. In order to test for Granger causality equation 11 is estimated for each market pair.

$$\sigma_t^{ZEE} = c + \sum_{i=1}^{p} \beta_i \, \sigma_{t-i}^{NBP} + \sum_{i=i}^{q} \alpha_i \, \sigma_{t-i}^{ZEE} \qquad (11)$$

For the example NBP and Zeebrugge it is tested whether the coefficients of the lagged values of the NBP σ_{t-i}^{NBP} are significant when predicting the current volatility σ_t^{ZEE} at Zeebrugge. These tests are F-tests of the exclusion restrictions $\beta_i = 0$. The tests are repeated for each market pair and for different lag lengths following the approach of Pindyck (2004). In this paper the equation (11) is estimated for the lag lengths 4, 8, 12 and 16. The p-value of the F-test for all market pairs and lag lengths are reported in Table 13. A high p-value indicates that the null hypothesis of no Granger causation cannot be rejected at a reasonable significance level. The results for the market pairs TTF/NBP and TTF/Zeebrugge are dependent on the chosen lag length. However, for all other market pairs the rejection or non-rejection of the null hypothesis at the 5% significance level is independent from the number of lags included in the equation.

Table 13. P-Values of F-Test for Granger Causality in GARCH Volatility Estimates

Null hypothesis	P-values depending on lag length			
	4	8	12	16
Volatility at **NBP** does not Granger cause volatility at **Bunde**	0.000	0.000	0.000	0.000
Volatility at **Bunde** does not Granger cause volatility at **NBP**	0.134	0.408	0.633	0.818
Volatility at **TTF** does not Granger cause volatility at **Bunde**	0.000	0.000	0.000	0.000
Volatility at **Bunde** does not Granger cause volatility at **TTF**	0.442	0.654	0.058	0.290
Volatility at **Zeebrugge** does not Granger cause volatility at **Bunde**	0.000	0.000	0.000	0.000
Volatility at **Bunde** does not Granger cause volatility at **Zeebrugge**	0.418	0.399	0.317	0.169
Volatility at **TTF** does not Granger cause volatility at **NBP**	0.056	0.003	0.015	0.034
Volatility at **NBP** does not Granger cause volatility at **Bunde**	0.000	0.000	0.000	0.000
Volatility at **Zeebrugge** does not Granger cause volatility at **NBP**	0.298	0.390	0.693	0.850
Volatility at **NBP** does not Granger cause volatility at **Zeebrugge**	0.000	0.000	0.002	0.006
Volatility at **Zeebrugge** does not Granger cause volatility at **TTF**	0.024	0.030	0.019	0.027
Volatility at **TTF** does not Granger cause volatility at **Zeebrugge**	0.047	0.013	0.036	0.054

Notes: The p-value indicates significance level of an F-test that all coefficients β in equation 11 are equal to zero. The F-test is repeated for 4, 8, 12 and 16 lags (Pindyck 2004).

According to Table 13 the three hypotheses that Bunde volatility does not Granger cause volatility at one of the other hubs cannot be rejected at the 5% significance level. For all but one lag length the tests do not even reject the hypotheses of no causation at the 10% level. In addition, all of the hypotheses that one of the other three hubs do not help to predict volatility at Bunde can be rejected at the 1% significance level. This confirms the results of the previous chapter that Bunde is not a price setter in the European natural gas market and that Bunde follows the movements of the other European gas hubs. In contrast, the three hypotheses that NBP does not cause volatility in any of the other markets can be rejected for all lag length at the 1% significance level. This is more evidence for the earlier result which shows the important role the NBP also plays for the Continental European natural gas market. However, in contrast to the error correction model the volatility transmission indicates a more important role for NBP than Zeebrugge. The hypothesis that Zeebrugge volatility does not help to predict volatility at NBP cannot be rejected at the 10% significance level. The results for the TTF are more mixed. For TTF volatility the Zeebrugge volatility is significant at the 5% level. The two hypotheses that TTF volatility does not Granger cause NBP or Zeebrugge volatility can be rejected for 3 out of 4 lag lengths at the 5% level.

8. Outlook on the European Natural Gas Hub Trading

This thesis estimates quantitative models in order to analyse the degree of integration and the volatility of the European natural gas markets. Based on the results of these models this chapter points out the main challenges towards an integrated European market and it takes a look into the future to figure out how the market might look in the coming decade. The above econometric analysis presents evidence that the prices and volatilities of the four European trading hubs NBP, Zeebrugge, TTF and Bunde are linked and that they are following a long-term relationship. Since trading companies are performing continuously arbitrage between these markets, the prices cannot deviate more than the transport and transaction costs in the long-run. Consequently, the econometric evidence presented in this paper leads to the conclusion that the markets are integrated.

However, the degree of integration differs between each market pair. NBP and Zeebrugge seem to be rather well integrated, whereas TTF and NBP are rather loosely integrated. The most important reason for these differences is the physical constraints to the arbitrage due to limited pipeline capacity and in particular pipeline capacity that is not booked for long-term contracts. This leads to a breakdown of the link between the markets during tight market situations. The Interconnector between the NBP and Zeebrugge provides sufficient and easy bookable capacity between the two markets which can also be seen in the above analysis. In contrast, the situation at the Dutch-Belgian border is considerably tighter and therefore TTF and NBP/Zeebrugge show only weaker signs of integration. Since the opening of the BBL pipeline in December 2006 more capacity is available to connect these markets.

Therefore, the development of the interconnection pipelines between the market areas will be key for the further integration of the European gas markets. Integration will only be successful when there is excess capacity in the pipeline network which allows for additional gas flows to the already booked capacity used for long-term contracts. Another key issue is to determine how the capacity is allocated to the market participants (see also Neumann et al. 2006, p. 731). Non-discriminatory access of new market participants, transparency of the allocation and the trading capacity of unused capacity are some of the key policy areas which need close supervision by the regulators.

Besides physical available capacities the simplicity of the market access is important for the integration of the markets. The NBP is an example how this simplicity can be achieved. In Continental Europe trading is considerably more complicated since entry and exit capacities for several market areas have to be booked for the transmission of gas over more than one border. In addition, there are countries like France or Germany with several market areas which increase the complexity of trades and decreases liquidity in each part of the market. The reduction of the number of trading zones in Europe is already one of the priorities for the regulatory bodies, but there is still a lot of room for improvement. So another important factor for the integration of the European gas market is an effective regulation with a focus on creating a unified liquid European market. Achieving this goal will require a close cooperation of the national regulators.

This paper focused on the most liquid hubs in Europe and the Bunde hub which used to be viewed as the potential price setting for the Continent during its operations between 2002 and 2006. As already described earlier, there are other trading hubs in Europe where the traded gas volume might increase rapidly in the upcoming years. The EGT hubs on the E.ON gas transmission network saw already a rapidly increasing in the second half of 2007 and the first half of 2008. It has already become the most liquid hub in Germany and in a second step it has the potential to become the price setting market for the Continent. In addition, Italy, France and Austria are the most the likely candidates where mature hubs can develop in the next years. A growing number of hubs in Europe will create similar challenges as discussed above. It will increase the need for cross border pipeline capacities and a market oriented regulatory oversight. However, it will also give the opportunity to create an integrated pan-European market for natural gas which will cover most parts of the Continent.

One factor which will become more central in the coming decade is Liquid Natural Gas (LNG). There are already shipping terminals in many European countries which can receive LNG cargos and in some cases it is also possible to use these terminals for exporting cargos. Except for the Iberian Peninsula, LNG does not yet contribute an important amount of gas for the European supply. But the number of LNG terminals is expected to increase significantly in the coming decade on the Continent as well as in the UK. This will also increase the importance of LNG for the European supply and it will bring new influences to the European gas prices. LNG cargos can already be used for arbitrage between the natural gas markets in the whole world. A growing importance of LNG for the European supplies will lead to a stronger link between the worldwide natural gas markets. Therefore, in the middle-term there will be not only an integration of the European markets, but also an integration of the worldwide natural gas markets (IEA 2008, p. 8).

9. Summary and Conclusions

Trading hubs are an important component of the liberalized European natural gas market by providing physical flexibility and by serving as a pricing reference for market participants. This thesis presents an econometric analysis of how the prices and volatilities of the different hubs in Europe are interrelated. The analysis focuses on the historical daily price data for the four mayor trading hubs on the European Continent and in the United Kingdom. There are signs of new hubs becoming mature market places in Germany, France, Italy and Austria which provide ample opportunities for further empirical as well as theoretical research in this area in the coming years and decades.

The ADF unit root tests indicate that all four log price series are non-stationary. For that reason this thesis uses the Engle-Granger two step approach and the Johansen procedure to test for cointegration between the four gas hubs. This paper finds evidence of a cointegrated relationship between 2005 and 2008 for all four markets. The strongest connection is found between the NBP and Zeebrugge and price spreads between these markets disappear quickly. This is due to the Interconnector pipeline which is directly connecting both markets. Therefore, the intervention analysis finds that this spread widens significantly when the Interconnector is shut down for maintenance every year in summer. These findings underline the importance of sufficient pipeline capacity for the integration of the markets. The least strong integration is found between TTF and NBP. This relationship will be interesting to monitor in the next years when there is longer price history for the period after the opening of the BBL pipeline connecting these two markets.

The error correction model indicates that the Zeebrugge hub and the NBP are exogenous in the European natural gas market. Therefore, these two markets are the price leaders for the European gas market and TTF and Bunde are following the price movement of the former. In addition, the GARCH model indicates that the volatility is also Granger caused in this direction. It will be important to study how this relation develops in the upcoming years when the German and the Dutch market are becoming more mature and the trading volume in these markets increases. These developments will most probably increase the importance of the Continental gas markets for the NBP prices.

The analysis of the volatility showed that volatility clustering can be found in the markets. Based on this GARCH models are estimated and it is shown that a GARCH (1,1) is well suited to model the conditional volatility present in the data of all four markets. In addition, the hypotheses that the models are integrated and the volatility is persistent in the series cannot be rejected. These GARCH models can build the basis for the pricing of options and other derivatives based on the price of the European gas hubs.

The rapid development of trading hubs in Europe in the last years increased the need for regulators, policy makers and market participants to understand how the markets move and how the prices and volatilities in the different market areas are interrelated. This thesis provides some quantitative empirical insights into these issues which can serve as a starting point for further research in that area.

10. Abbreviations

AIC – Akaike Information Criterion

ARCH - Autoregressive Conditional Heteroskedasticity

BBL – Pipeline from Balgazand in the Netherlands to the Bacton terminal in the UK

ECM – Error Correction Model

GARCH - Generalized Autoregressive Conditional Heteroscedasticity

IGARCH – Integrated Generalized Autoregressive Conditional Heteroscedasticity

LNG – Liquid Natural Gas

LOOP – Law Of One Price

MAIC – Modified Akaike Information Criterion

MWh – Megawatt Hour

NBP – National Balancing Point (Natural gas trading hub in the United Kingdom)

OTC – Over-The-Counter

SIC – Schwartz Information Criterion

TTF – Title Transfer Facility (Natural gas trading hub in the Netherlands)

VECM – Vector Error Correction Model

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Eigenständigkeitserklärung

"Ich erkläre hiermit,

- dass ich die vorliegende Arbeit ohne fremde Hilfe und ohne Verwendung anderer als der angegebenen Hilfsmittel verfasst habe,
- dass ich sämtliche verwendeten Quellen erwähnt und gemäss gängigen wissenschaftlichen Zitierregeln nach bestem Wissen und Gewissen korrekt zitiert habe."

Hildesheim, September 2008 Kilian Leykam