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The Relationship Between Day-Ahead Electricity and Forward Natural Gas/Coal Prices

A cointegration analyses of Dutch and German price series

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PREFACE AND ACKNOWLEDGEMENTS

Finding an interesting topic was not easy and getting started with this paper was harder than expected. I knew it would cost a lot of energy getting it done, but I was determined to do so.

I want to thank my family and friends for being supportive through my whole thesis writing period. Especially my mother, Ayşe Demir, who supported me through my knee surgery in December and pushed me to finish my thesis.

Special thanks to Mehtap Kılıç, who provided very good guidance and shared her knowledge and ideas of 'Cointegration'.

ABSTRACT

This paper examines the long-run relation and short-run dynamics within and between day-ahead electricity prices and two fossil fuel prices – coal and natural gas – for the period 10/10/2008 – 7/12/2011. The results show the following: (1) The existence of long-run relations between electricity, coal and natural gas within Germany and the Netherlands. Inter-country tests for both countries show the existence of long-run relations between base; peak and off-peak prices. Before the shutdown of nuclear reactors, long-run relations between electricity-coal and electricity-natural gas are found. After the shutdown only peak electricity-coal and peak electricity-natural gas are connected in the long-run. (2) The existence of short-run causality from base electricity to coal prices and from peak electricity to coal prices in Germany. Short-run causality from Dutch electricity to German electricity prices and short-run causality from electricity to coal prices before the shutdown of nuclear reactors. (3) Bidirectional causality between Dutch electricity and coal. Also bidirectional causality between off-peak prices and natural gas in Germany and the Netherlands.

Keywords:

[Energy prices, Cointegration, Causality, Stationarity, Error-correction.]

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1 Introduction

During the past five decades electricity prices have moved substantially in real and nominal terms. The 1960s were stable, following substantial nominal price increases in the 1970s. Between the 1980s and 1990s prices again were stable, and from upon 2000 prices increased. Similar long term movements have occurred in other energy prices (coal, natural gas and crude oil). Especially similar findings between electricity and coal prices as well as in crude oil and natural gas prices have been found (Mohammadi, 2009). The price movements during the last 10 years in the energy sector can possibly be explained by the global deregulation process. One of the main goals of deregulation is allowing markets to react to supply and demand. This implies a more competitive and interrelated market environment. This environment is especially found in the electricity and natural gas markets, where prices are determined more by market participants rather than by regulators (Park et al. 2006, 2008). Since electricity generation is dependent of its input fuel source(s) (e.g. natural gas or coal), increasing the competitiveness in electricity markets implies that spot market prices may immediately respond to price changes in input fuel source markets. Also the other way around, where changes in electricity prices cause movements in fuel source prices (Asche et al., 2006).

Economic theory suggests that, in a static framework, there should exist a relationship between input and output prices. To illustrate this, think of a single product which is produced by a single factor of production (input). In a static supply and demand framework, an increase in the marginal cost of input will lead to an increase in the product price, ceteris paribus. Assuming supply is fixed, an increase in demand for the product, will lead to a higher product price. Economic theory does not explain how such relationships will react in a dynamic framework with constantly changing prices and therefore a non-ceteris paribus environment. In reality there is more than one factor influencing the production and price setting process. Considering electricity production, this can be generated at different locations, using different input factors and also different proportions of input factors. Some power producers can be more efficient than others and there can be differences between substitutability and complementarity. Therefore the level of price transferring from input to output can vary, due to the differences in cost share of the involved input factor.

The dynamic nature of electricity markets provides the possibility of testing and understanding the relationship between input and output prices in a non- static environment. This relationship will be examined using *cointegration* analysis.

For many years in cointegration studies especially natural gas and crude oil prices were discussed, from upon the late 90’s electricity was introduced to cointegration analyses. However these analyses were mainly concentrated on spot prices. The motivation for this paper is to find whether there is a linkage between day-ahead electricity prices and gas/coal forward prices in and between the Dutch and German markets. Forward prices are mostly used by investors who are expecting delivery of the product to take place, by using forward contracts they can hedge their position and eliminate the volatility of the asset's price. The Dutch market is chosen because of the fact that almost 60% of its electricity supply is gas-fired and German electricity generation is for a large part, 42%, generated by coal . The Dutch one month forward natural gas prices, TTF, and the Dutch one month forward coal prices, ICE Rotterdam, will be combined with the Dutch day-ahead electricity prices. The same will be done for Germany, the NCG one month forward gas prices and the ARA one month forward coal prices will be combined with the German day-ahead electricity prices. The main goal of this study is to answer the following questions: (1) Is there a long-run relationship between natural gas/ coal prices and electricity prices, and what is the explanation for this relationship? (2) Are there causal relationships between electricity prices and gas/coal prices and in what direction? (3) Are the responses to deviations from the equilibrium symmetric or asymmetric?

The paper is organized as follows. Section 2 gives an overview of the main results in cointegration literature. Section 3 provides the data set and some descriptive statistics of energy commodity prices. Section 4 describes the methodology and section 5 follows with the empirical results. In section 6 the paper is concluded and sections 8 and 9 provide references and the Appendix.

2 Literature review

The most striking paper on cointegration was written by Engle and Granger (1987). Their work formed the basis of many researches and papers. Cointegration became a powerful technique for investigating common trends in multivariate time series, and captures both long-run and short-run dynamics in a system. Most research applies cointegration on the price dynamics of single commodities in single markets. For example Carol Alexander (1999) who focuses on the WTI crude oil spot and near futures prices and the NYMEX sweet crude prices; also the NYMEX natural gas market and the Kansas City 'Western' natural gas contract. She finds that it is the spot price that predicts future prices.

Gjölberg and Johnsen (1988) investigated how deviations from a statistical long-run equilibrium can provide predictions for price changes in the short-run. They research long-run spot price co-movements among crude oil and different products of crude oil (gasoline, naphtha, jet fuel, gas oil, light/heavy fuel oil) on monthly basis for the period 1992-1998. Besides heavy fuel oil, they find that all prices are cointegrated with the crude oil price.

For the period 1990-1997 Asche, Osmundsen and Tveterås (2000) researched border prices of natural gas delivered from Russia, Norway and the Netherlands to France. Cointegration analyses have shown that prices of gas to France differ from each other, but they move proportionally over time, which means that the Law of One Price holds. Furthermore the connection between France, Germany and Belgium is tested, the findings imply that national markets are strongly integrated.

In 2002 Asche, Osmundsen and Tveterås examined gas export prices from Norway, the Netherlands and Russia to Germany in the period 1990- 1998. They find these prices to be primarily different from each other, but still these prices seem to move proportionally over time, indicating an integrated gas market.

Silverstore, Neumann and Hirschhausen (2005) analyze the dynamics of gas prices within and between different continents, particularly the European, Japanese and North American markets. Cointegration tests provide evidence of co-movements within the European/

Japanese and North American markets, furthermore the two groups of markets are not integrated. This is consistent with the orthodox way of thinking that gas markets were not integrated across continents, and especially not between Europe and North America during the 1990s.

Panagiotidis and Rutledge (2007) investigate the relationship between UK wholesale gas prices and the Brent oil price over the period 1996-2003. Their goal is to find whether liberalization of the gas markets will cause 'decoupling' of oil and gas prices. The results imply that there is cointegration between UK gas and oil prices over the whole sample period, which indicates that there is no effect of 'decoupling' due to the opening of the Interconnector and the highly liberalized nature of the UK gas market.

A relatively long period, 1989-through-2005, is analyzed by Villar and Joutz (2006) to investigate the WTI crude oil prices and the Henry Hub natural gas prices. The paper presents two key findings. The first is statistical evidence of a long-run cointegration relationship between the WTI oil and Henry Hub gas prices, despite periods where they may have appeared to decouple. They find that the direction of causality is from the WTI oil prices to Henry Hub gas prices. The second key finding is the existence of a statistically significant trend term, which suggests that natural gas prices are growing at a slightly faster rate than crude oil prices.

Bachmeir and Griffin (2006) test for cointegration within and between different crude oil, coal and natural gas markets. Various crude oils from global markets seem to be highly cointegrated and a cointegration relationship in the long-run between oil and natural gas is found, but in contrast a weak cointegration relationship in the U.S. coal market is the case.

An interesting research is done by Brown and Yücel (2007). Using weekly WTI crude oil prices and Henry Hub natural gas prices, they find evidence of a cointegration relationship over the period January 1994- July 2006. Tests for the shorter period of June 1997- July 2006 give evidence of *no* cointegration. Based on the longer period cointegration relationship they come up with interesting results. Short-run deviations from the estimated long-run relationship could be explained by weather, seasonality, gas storage levels and production delays in the Gulf of Mexico due to hurricanes. Weather and storage levels are both found to have significant effects on natural gas prices, they have influence on the long-run relationship and move the natural gas prices away from crude oil prices. Like Villar and Joutz, they find that oil prices may influence gas prices, but there is no causal effect the other way around.

Similar findings are pointed out by Hartley, Medlock and Rosthal (2007), they find that changes in weather and inventories, or hurricanes and other seasonal factors affect the short-run dynamic adjustment of prices. Furthermore many authors had in their opinion a ‘different’ view when researching crude oil prices and natural gas prices. Hartley et al. believe there is an indirect relationship between these prices, while in most literature it was seen as a direct relationship. It is indirect, because crude oil is in fact having no influence, the residual fuel oil prices that competes with natural gas is the directly related variable. The results further suggest that U.S. natural gas and residual fuel oil prices follow the movements of the international crude oil market, but the opposite is not true. Finally the importance of technology is pointed out. The used power generation system is of major concern, since crude oil and natural gas prices can be priced significantly different if production becomes more efficient. Future innovations will influence the long-run relationship of crude oil and natural gas in a way that simple time trends cannot recognize. So to have a clear picture of the short-run and especially the long-run relationship between natural gas and crude oil, one has to involve technological changes.

Bekiros and Diks (2008) investigate the linear and nonlinear causal linkages between daily spot and futures prices for one, two and four months of WTI crude oil using cointegration methods. They find that causality in their dataset can change over time. Although theory suggest that futures markets play a bigger role in price discovery, the spot market can also be the one that takes this role.

2.1 Introduction of Electricity

So far in cointegration studies, especially crude oil and natural gas prices are tested for long and short-run relationships. In 1999 De Vany and Walls add electricity prices to this topic. They use daily spot- peak- and off-peak electricity prices to find market integration in the

Western Systems Coordinating Council (WSCC). The sample period is from December 1994 to April 1996. They find all off-peak market pairs are cointegrated and 87% of the peak market pairs are cointegrated. Two thirds of the off-peak market pairs are strongly integrated and half are perfectly integrated. One-third of the peak market pairs are strongly integrated and a few are perfectly integrated.

Serletis and Herbert (1999) study energy prices in North-America. They use daily data from October 1996 to November 1997 to analyze the behavior of Henry Hub/ Transco Zone 6 natural gas prices, New York Harbor fuel oil prices and PJM electricity prices. They find that natural gas and fuel oil prices are cointegrated. The electricity spot market is stationary and therefore bivariate cointegration would be spurious.

In 2001 Gjölberg examines the movements of electricity prices relative to natural gas and crude oil prices in Europe for the period 1993-1999. The author expects a medium and long term correlation between electricity and fuel oil, because they are to a degree substitutes. However technological, storage and transportation restrictions could limit substitutability. The result is a cointegration relationship between natural gas, crude oil and electricity prices. A second finding is that between 1995 and 1998, after the deregulation of the U.S. gas market, natural gas and electricity prices follow the movements of crude oil prices.

Emery and Liu (2002), make use of daily data from March 29, 1996 to March 31, 2000 and find a cointegration relationship between futures prices of electricity and natural gas. They examine California Oregon Border and Palo Verde electricity prices, both are equally sensitive to changes in natural gas prices. This can be explained by the fact that natural gas is frequently used as input for peak power generating.

A market integration analyses between natural gas, electricity and crude oil prices in the UK is done by Asche, Osmundsen and Sandmark (2006). The sample period is chosen in such way that the natural gas market was deregulated and was not connected to the continental European gas market (January 1995 to June 1998). They find evidence of cointegration among these commodities and also an exogenous and therefore leading role of crude oil.

This leading role is explained by the fact that there is a global market for oil while this is not the case for electricity and natural gas. To find out if the opening of the Interconnector had an influence on cointegration, the same test were performed for the period July 1998 December 2002, cointegration was not found in this sample period.

Papers that focus on electricity separately are for example: Bosco et al. (2006) They were the first to examine electricity price interdependencies in four major European markets (Germany, France, Austria and the Netherlands). When comparing electricity , gas and oil prices, their believe is that electricity should have a constant mean ratio with gas prices and gas in turn should have a stable ratio with oil prices. Using a multivariate dynamic analyses they find the presence of strong integration and a common trend between the four electricity markets. They find this common trend to be cointegrated with the oil price.

Furthermore making use of daily price of Henry Hub natural gas, Brent ICE crude oil and EEX electricity prices over the period 2000-2007, Cristina Bencivenga et al (2008) find a long-run relationship between natural gas- crude oil prices, natural gas-electricity prices and oil-electricity prices. They find cointegration between these markets and the results imply that the introduction of competitive wholesale electricity markets did not change the leading role of crude oil prices on electricity prices.

In 2009 Mjelde and Bessler studied dynamic price relationships between US peak and off-peak electricity wholesale spot prices from the PJM and Mid-Columbia (Mid-C) for the period 2001-2008. These prices were linked to four major fuel sources; natural gas, crude oil, coal and uranium. They study eight price series and find all eight to be cointegrated with all series included in the long-run relationships, keeping the price-movements together. However they find less than n-1 cointegrating vectors, which means the markets are not fully integrated and there is no single common trend. Electricity prices influence natural gas prices in contemporaneous time and natural gas prices influence oil prices. In the long-run, fuel source prices have a leading role on electricity prices. The fuel prices (except uranium) are stable when disequilibrium finds place. Uranium and electricity are the variables that change in order to restore equilibrium.

Mohammadi (2009) researched the long-run and short-run dynamics between electricity prices and three fossil fuels (coal, natural gas and crude oil) in the U.S. making use of yearly data for 1960 – 2007. He finds only evidence of significant long-run relations between electricity and coal. Crude oil prices have no significant influence on electricity prices and the relationship between natural gas and electricity prices is statistically weak. In the short-run a one way causal relationship is detected from coal and natural gas prices to electricity prices.

Bencivenga and Sargenti (2010) investigate the short and long-run relationship between crude oil, natural gas and electricity prices in the US and European commodity markets. They use daily prices over the period 2001- 2009 and use a correlation approach to test the short-run dynamics. The short-run tests give no decisive outcomes. The long-run dynamics are tested by cointegration tests and cointegration relationships are found between each pair of commodities.

An important paper for the Dutch market regarding cointegration between power and gas markets is written by de Jong and Schneider (2009). They show how cointegration can be applied to capture the joint dynamics of multiple energy spot prices. They combine the UK (NBP, natural gas market), Belgian (Zeebrugge gas spot market, or ZEE) and the Dutch (TTF) natural gas markets with the Dutch power market APX. Clear evidence of cointegration is detected between the gas spot prices of TTF, Zeebrugge and NBP markets. The results show that the gas markets are connected strongly in a specific pattern, which is from TTF to Zeebrugge to NBP, or vice versa. Both gas spot markets are cointegrated with the APX spot market, but this is only in the 'forward time scale'.

For many years cointegration researches were mainly concentrated on spot prices. The motivation for this paper is to find whether there is a linkage between day-ahead electricity prices and *forward* natural gas and coal prices in and between the Dutch and German markets. The goal is to get a better understanding of Dutch and German power markets and provide useful information for interested market practitioners.

3 Data

This paper analyses daily electricity, natural gas and coal prices starting from 10-10-2008 and ending in 12-07-2011. This research is limited to this sample period because of the unavailability of time-series data on especially coal prices but also German natural gas prices. In order to match the three different variables, Electricity; natural gas and coal, this certain sample period is chosen.

The choice for forward natural gas and coal prices in combination with day-ahead electricity prices can be justified by their linkage. Forward prices can, if the underlying asset is tradable, be estimated through spot prices and are usually the market's closest guess of future spot prices. Regarding energy prices, it is very important to take mean-reversion into account. Suppose that electricity prices instantly rise from € 10,- per MWh to € 100,- per MWh due to an extreme event, e.g. extreme cold weather. This price change would normally be expected to disappear and return to its average level when the cause of the extreme event disappears. Therefore cointegration methods, which assumes prices will revert to equilibrium in the long-run, are appropriate for energy price testing.

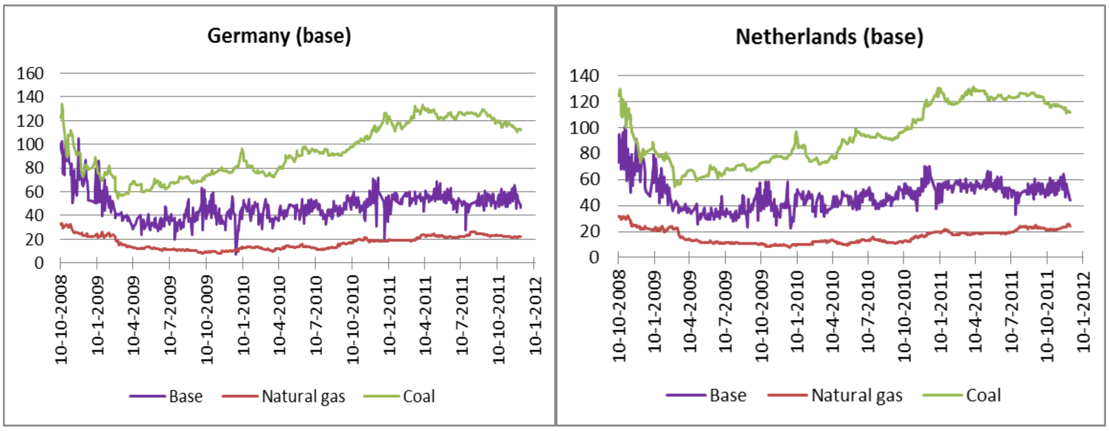
Base electricity prices are obtained by the average of hourly spot prices, the average of 24 hours during one day. Peak prices are obtained by taking the average of prices starting at 08.00 o'clock and ending at 19.00 o'clock. Off-peak prices are obtained by taking the average of prices between 20.00 o'clock and 07.00 o'clock. Electricity and natural gas prices are expressed in Euro per MWh and coal prices are expressed in Euro per metric tons. All time-series are obtained from the Bloomberg database.

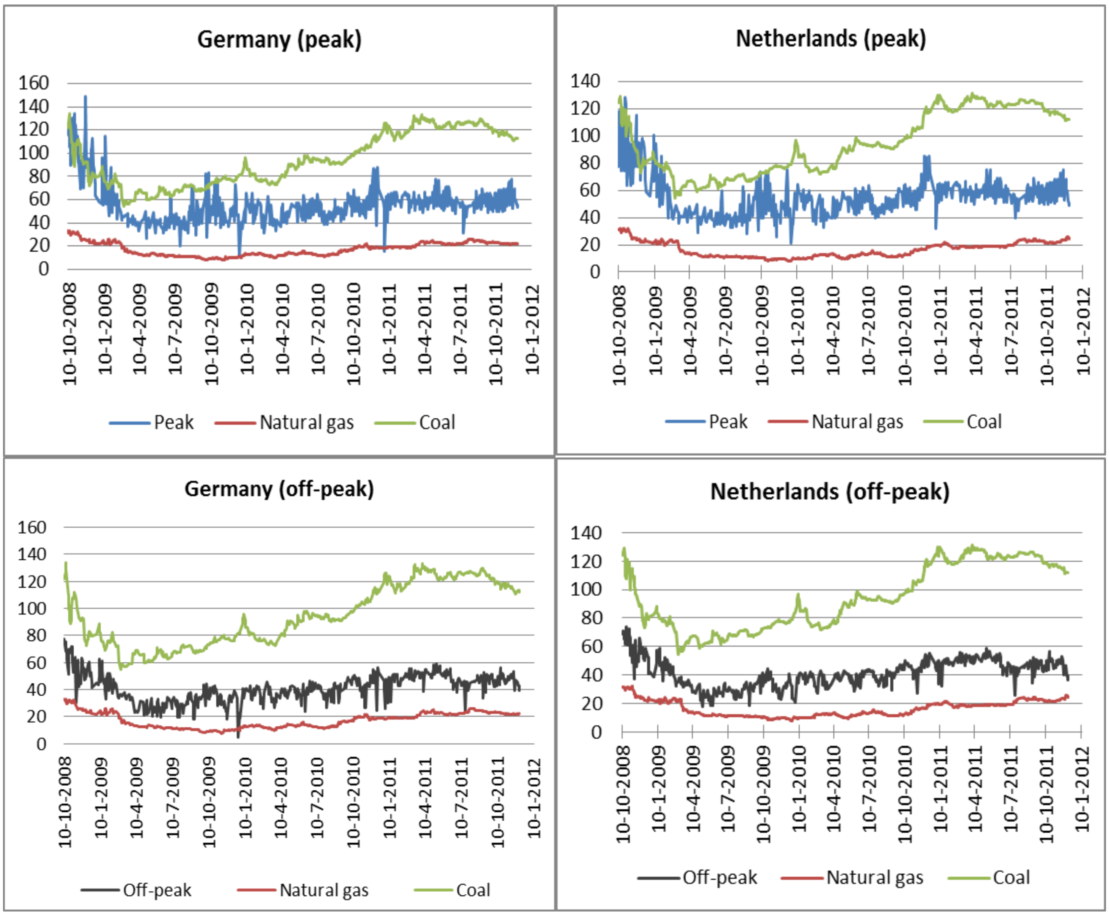
3.1 *Trends*

Fig. 1 plots the energy prices. The figure shows that until mid-February 2009 all price series seem to be decreasing in both Germany and the Netherlands. From upon mid-February 2009 the coal prices in both countries are showing an increasing trend, while the electricity and natural gas prices are still decreasing. In the Netherlands the natural gas prices follow an increasing trend starting at the end of December 2009, it shows some drops around April and August 2010, but overall there is an increasing trend. Natural gas prices in Germany show a decreasing trend until November 2009 and starts an increasing trend after, even though it decreases a few times over time. Although it is not stable, Dutch electricity prices seem to show a slowly increasing trend from upon August 2009. In Germany electricity prices start increasing around April 2009.

The graphs indicate two interesting findings: First, the same commodity prices in both countries seem to show similar overall movements. Second, electricity prices appear to be more volatile in comparison to the smoothly moving natural gas and coal prices.

Fig1.

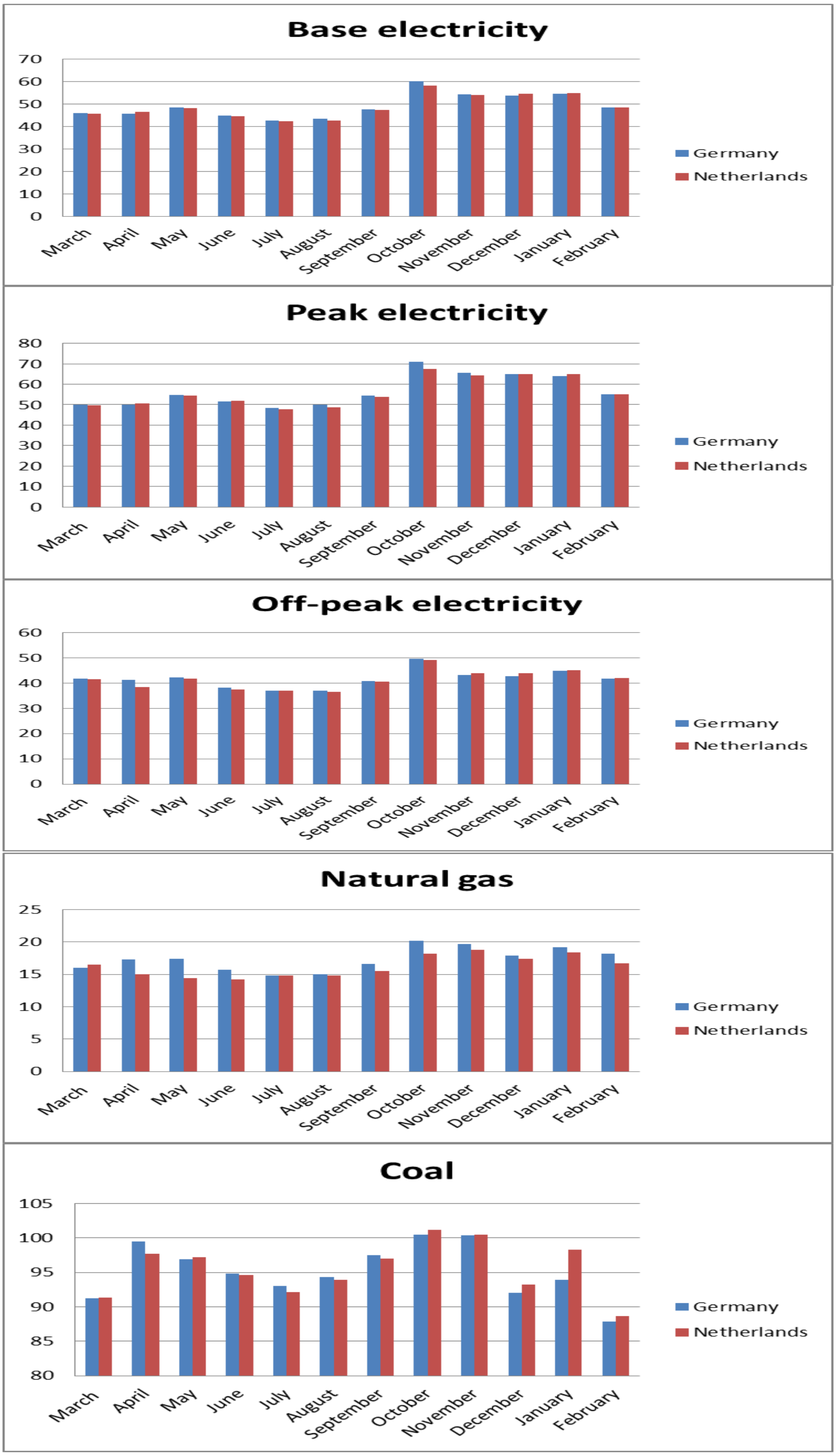




3.2 *Monthly averages*

All monthly average electricity, natural gas and coal prices are plotted in fig 2. In the average households electricity and gas are being used much more in the winter compared to the summer. This would mean that the prices of these commodities should cost more in the winter compared to the summer. The figures show clearly that starting from October most prices are higher compared to earlier months. For coal another price distribution holds, it shows low prices in the summer and winter months and high prices in the remaining months, especially in Autumn. Reason for this can be that coal is an industrial product and not directly used by households.

Fig 2.


Base electricity
70
60
50
40
30
20
10
0
March
April
May
June
July
August
September
October
November
December
January
February
Germany
Netherlands
Peak electricity
80
70
60
50
40
30
20
10
0
March
April
May
June
July
August
September
October
November
December
January
February
Germany
Netherlands
Off-peak electricity
60
50
40
30
20
10
0
March
April
May
June
July
August
September
October
November
December
January
February
Germany
Netherlands
Natural gas
25
20
15
10
5
0
March
April
May
June
July
August
September
October
November
December
January
February
Germany
Netherlands
Coal
105
100
95
90
85
80
March
April
May
June
July
August
September
October
November
December
January
February
Germany
Netherlands

4 Methodology

To be successful in risk management one needs real understanding of price movements within financial markets. One can focus on returns when applying risk management or focus on prices. Correlation is based on returns between two return processes and its use is only consistent in the short-run. The problem that occurs with correlation is that the calculated ratio changes from day to day, this indicates that the two return processes are not jointly stationary. Furthermore the daily changing correlation implies that correlation based hedges require frequent rebalancing. Also an important shortcoming of correlation based hedging is that it cannot reveal any dynamic causal relationships, because it is a static measure (Carol Alexander, 1999). In order to achieve a, perhaps, more successive result in risk management, practitioners should also consider the long-run.

4.1 Stationarity

The vast majority of econometric theory is based upon the assumption of stationarity. If the variables in the regression model are not stationary, then it can be proved that the standard assumptions for asymptotic analysis will not be valid. This means that the standard "*t*-ratios" will not follow a *t*-distribution, so that a valid hypothesis of regression parameters will not be possible. Consequently, for many years econometricians simply removed deterministic components (e.g. drifts and trends) from data to achieve stationarity. However, stationary series should at least have constant unconditional mean and variance over time. This condition cannot be satisfied because of the dynamic nature of economics even after removing deterministic terms (Dolado, Gonzalo and Marmol; 1999).

Many practitioners of stationarity ignored these shortcomings until Granger an Newbold (1974) and Nelson and Plosser (1982) pointed out the econometric implications of non-stationarity and the dangers of running *spurious* regressions. These authors mainly focused on the implications of dealing with integrated variables, which are an important group of non-stationary variables. These are derived from unit roots which lead to stochastic trends, with innovations to an integrated process being permanent instead of temporal.

On the other hand statisticians following the influential approach by Box and Jenkins (1970), supported the framework of changing integrated time series into stationary ones by sequential differencing before applying to the model. This means that removing unit roots through differencing has been seen as a requirement for regression analyses.
Still there were some authors that criticized this way of thinking. Among others Sargan (1964), Hendry and Mizon (1978) and Davidson et al. (1978) started to criticize the framework of dynamic models in terms of differenced variables only. This criticism is especially because of the difficulties in deriving the long-run equilibrium from the estimated model. After all, deviations from the long-run equilibrium will bring along a misspecification error since future changes in that set of variables will be affected.

4.2 ***Cointegration***

In 1981 Granger came with a theory that solved the inadequacies. He stated that a vector of variables, all which achieve stationarity after differencing, could have linear combinations which are stationary in levels. In the footsteps of his paper Engle and Granger (1987) were the first to address the idea of integrated variables sharing an equilibrium relation which turned out to be either stationary or have a lower degree of integration than the original series and they called this relationship, *cointegration*.

‘’Two price processes are cointegrated if there is a linear combination of these prices that is stationary, such linear combination is called the ‘cointegration vector’. The cointegration vector is a spread, often taken to be a difference in log prices so that the error correction model is based on returns. So generally speaking when spreads are stationary, prices are cointegrated. Of course prices may deviate in the short term, and correlations may be low at times, but they are ‘tied together’ by a long term common trend because of the mean reversion in the spread’’ (Carol Alexander 1999).

Mostly commodity price series show to be integrated of order 1, *I(1)*, or non-stationary. In such case standard techniques like Linear Regression, to estimate relationships between a few variables gives biased results or it can lead to a misrepresentation of the phenomenon. The order of integration of a time series is mostly tested by the Dickey Fuller unit root test applied to an AR(1)[1] process. The cointegration testing procedure will be shown in the following section.

4.2.1 Cointegration modeling

The main goal of this paper is to test for cointegration between coal, gas and electricity. First the Augmented Dickey Fuller unit root test (ADF) is used to determine whether each price series is stationary. The ADF test is conducted by implementing the coal, gas and electricity price series into the following regression:

$$\Delta Yt \ = \ \delta 0 \ + \ \delta 1 \, Y\mathrm{t} - 1 \ + \textstyle\sum_{i=2}^{4} \delta i \, \Delta Yt - (i - 1) + \ ut \qquad (1)$$

The lag amounts of the dependent variables, for elimination of autocorrelation, are set to 3 following the Emery and Liu (2002) approach. The ADF test uses the null hypotheses that a series is non-stationary and expects the lagged level of the series, δ_1, is not significantly different from zero. Y_t is the coal, gas or electricity price. When a series is non-stationary, the original time series prices will be differenced once and the test will be repeated again. This process is repeated enough times to arrive at stationary series.

The next step is to determine whether the different combinations e.g. natural gas-electricity or coal-electricity are cointegrated. This is tested by the Engle-Granger (1987) cointegration test. This test resembles the Augmented Dickey Fuller test, but is applied to residuals from each combination of electricity and natural gas or coal prices. The residuals are produced by the two following equations:

---

[1] $Y_t = py_{t-1} + x'_t\delta + \varepsilon_t$

$$\mathrm{ELEC\,t} = \alpha + \beta 1 * \mathrm{GASt} + \varepsilon \mathrm{t} \tag{2}$$

$$\mathrm{ELEC\,t} = \alpha + \beta 1 * \mathrm{COALt} + \varepsilon \mathrm{t} \tag{3}$$

In the remainder of this paper the residuals from equation 2 and 3, will be referred to as the Abnormal Price of electricity at time t, APt. The residuals of equation 2 and 3 are used as input in the Engle-Granger (1987) test. This test uses the null hypotheses that two series are not cointegrated and expects the lagged level of the series, α_1, is not significantly different from zero.

$$\Delta APt = \alpha 0 + \alpha 1\, AP\mathrm{t} - 1 + \sum_{j=2}^{4} \alpha j\, \Delta APt - (j-1) + vt \tag{4}$$

4.3 Error correction model

Based on the relationship between two time series, the Error correction model gives how the prices adjust to deviations from the long-run equilibrium. The models are described by the underlying Equations where the error-correction term, AP_{t-1}, is the lagged error term from the cointegration regression. The input of the models are given under each table. To have an idea of the model, equations 4 and 5 are given. These models contain the variables *m* and *n* these are chosen in such way that a possible serial correlation in ε_{1t} and ε_{2t} are avoided. The *m* and *n* are set to 1.

$$\Delta ELEC\,t = \alpha 0 + \alpha 1\, AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i1\, \Delta\, ELECt - i + \sum_{j=1}^{n} \delta j1\, \Delta GAS\, t - j + \varepsilon 1t \tag{5}$$

$$\Delta GAS\,t = b0 + b1\, AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i2\, \Delta ELEC\, t - i + \sum_{j=1}^{n} \delta j2\, \Delta GAS\, t - j + \varepsilon 2t \tag{6}$$

5 Results

5.1 *Unit root and Cointegration tests*

This chapter consists of tests on actual prices. Tests on logarithmic prices can be found in the appendix. There is a reference to these results under each table.

The results of the ADF unit root test are shown in table 1. These outcomes show that none of the original price series are stationary before differencing.. After first time differencing, tests on all price series resulted in rejecting the hypothesis that electricity, gas or coal prices are non-stationary at the 0.01 level thereby confirming that they are all stationary.

The next step is to perform a cointegration test on the residuals of each combination of electricity prices with natural gas and coal prices. The results of the cointegration test are given in table 2. The coefficient of the lagged value of the abnormal price, α_1, in each combination is significantly different from zero (the Base-Coal prices in the Netherlands are significant at the 0,05 level and the other series are significant at the 0,01 level). This means that the residual series are stationary or equivalently and the electricity with natural gas/coal combinations are all cointegrated.

Tests on logarithmic prices show no major differences with actual prices. Unit root tests give the same significance and cointegration tests stay significant, but sometimes differ on the level of significance.

TABLE 1

Results of Unit Root Tests

Series	***Coefficient of lagged value of series, δ 1***	***t-statistic***	***Coefficient of lagged value of series, δ 1***	***t-statistic***
	Germany		*Netherlands*	
ELECTRICITY:				
Base				
prices:	-0.009	-1.573	-0.006	-1,360
1st difference of prices	-2.404	-19.568*	-2.527	-20.413*
Peak				
prices:	0.012	-1,714	-0.009	-1.459
1st difference of prices	-2.580	-20.043*	-2.820	-22.219*
Off-Peak				
prices:	-0.007	-1.391	-0.005	-1.288
1st difference of prices	-2.269	-19.577*	-1.956	-22.601*
GAS:				
prices:	-0.002	-1.477	-0.001	-0.556
1st difference of prices	-0.992	-24.710*	-0.855	-24.648*
COAL:				
prices:	-0.007	-0.795	-0.005	-1.175
1st difference of prices	-0.834	-15.440*	-0.992	-21.413*

Note. The Augmented Dickey-Fuller (1979) unit root test is performed by implementing the following regression to the series, Yt, with lagged values of the dependent variable included to eliminate autocorrelation.

$$\Delta Yt = \delta 0 + \delta 1\, Yt - 1 + \sum_{i=2}^{4} \delta i\, \Delta Yt - (i-1) + ut$$

The null hypothesis that a series is non stationary is rejected at the 0.05 and 0.01 levels if the t-statistic is less than -2.86 and -3.43, respectively. When a series is non-stationary, the original time series prices will be differenced once and the test will be repeated again. This process is repeated enough times to arrive at stationary series. Tests on natural logarithmic prices are shown in the appendix, table 16.

* significant at 0.01 level.

** significant at 0.05 level.

Table 2
Cointegration Test

	Coefficient of lagged value of AP, α_1	*t statistic*	*Coefficient of lagged value of AP, α_1*	*t statistic*
AP-Series	*Germany*		*Netherlands*	
Base-gas	-0.2512	-6.3568*	-0.1663	-4.9434*
Base-coal	-0.1312	-4.8008*	-0.1107	-4.2278**
Peak-gas	-0.2220	-5.7899*	-0.1953	-5.2471*
Peak-coal	-0.1305	-4.6784*	-0.1252	-4.3865*
Off peak-gas	-0.2740	-6.8080*	-0.1215	-4.3488*
Off peak-coal	-0.1643	-5.4218*	-0.1106	-4.3447*

Note. The Augmented Engle–Granger (1979) test is used to determine whether two time series are cointegrated. The test is performed by fitting the following regression where APt is the residual from equation (1) ELECt = α + β1 * GASt or (2) ELECt = α + β1 * GASt . Lagged values of the dependent variable are included to eliminate autocorrelation.

$$\Delta APt = \alpha 0 + \alpha 1\, AP\mathrm{t} - 1 + \sum_{j=2}^{4} \alpha j\, \Delta APt - (j-1) + vt$$

The null hypothesis that the series are *not* cointegrated is rejected at the 0.05 and 0.01 levels if the t-statistic is less than -3.34 and -4.32, respectively.Tests on natural logarithmic prices are shown in the appendix, table 17.

* significant at 0.01 level

** significant at 0.05 level

5.2 *Error correction models*

In tables 3 and 4, the error correction models for German base electricity prices and Dutch base electricity prices are given, all remaining error correction models are given in the appendix. In the models of change in base; peak and off-peak electricity, the coefficient of the lagged abnormal price, AP_{t-1}, is significantly less than zero. On the other hand in the models of change of natural gas prices, the coefficient of the lagged abnormal price is always positive and only significant for off-peak prices. These results demonstrate that electricity prices respond to deviations from the equilibrium relationship, but natural gas prices in combination with base and peak electricity prices do not, in both Germany and the Netherlands. Off-peak prices show bidirectional long-run causality with natural gas. One would expect that natural gas shows significance in the error correction models of peak electricity rather than off-peak electricity, because in peak hours the demand for electricity is relatively higher. This higher demand would normally expected to be answered by natural gas, since natural gas is more flexible than other power generation inputs. Therefore, in theory, a change in peak electricity prices should bring along a change in natural gas prices and vice versa.

The models of change in coal prices resulted in Ap_{t-1} coefficients less than zero, however these are only significant for the Netherlands. This means that coal prices respond to deviations from the equilibrium, but only for the Netherlands. There is bidirectional long-run causality between Dutch electricity and coal prices. Although both electricity and coal are responding to disequilibrium, there is a difference in the magnitude of response. In the model of the change in Dutch base electricity prices, a 1% change in coal prices leads to a 17,62 % correction of the disequilibrium through base electricity prices. The correction in the model of change in Dutch coal prices, at a 1% change of Dutch base electricity prices, is only 2,03%.

The fact that natural gas prices are, except for the combination with off-peak prices, not responding to deviations from the equilibrium does not make sense at first sight, because a reduction of electricity production should bring along a shrinkage in the demand for natural gas and therefore a decrease in its price. The asymmetric reaction rather makes sense because of the fact that natural gas is a very important ingredient for electricity generation and therefore electricity is dependent of natural gas. In contrast, natural gas is used for many other purposes than electricity generation and therefore is more independent and does not get effected as much when electricity demand changes. A similar statement can be given for the small respond of coal, since coal compared to natural gas can be used for less purposes. These results imply that electricity and coal are more dependent of each other compared to natural gas.

Different from tests on actual prices, logarithmic prices show short-run causality from base electricity to natural gas in Germany. For the Netherlands the bidirectional long-run causality between base electricity and coal disappears and becomes unidirectional from coal to base electricity. Natural gas with logarithmic prices show bidirectional long-run causality with base electricity, instead of unidirectional from natural gas to base electricity. All remaining differences are shown in the appendix.

Table 3
Error correction models
Base electricity prices Germany

	Dependent variable Elec		*Dependent variable Gas*		*Dependent variable Elec*		*Dependent variable Coal*	
	coefficient	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*
Intercept	0.0972	0.7386	-0.0145	0.5446	-0.1085	0.7122	-0.0209	0.8069
APt-1	-0,3351	0.0000*	0.0001	0.0961	-0.1948	0.0000*	-0.0125	0.1078
ΔElec t-1	-0,1785	0.0000	0.0047	0.1540	-0.2542	0.0000	0.0269	0.0165*
ΔGas t-1	-0,0679	0.8877	0.0172	0.6693	X	X	X	X
ΔCoal t-1	X	X	X	X	-0.1710	0.2150	0.0696	0.0831
R2	0.2308		0.0139		0.1901		0.0159	
Durbin-Watson	2.0421		1.9724		2.0938		2.0357	

Note. The error correction model describes how fast the cointegrating variables adjust to the deviations from the long-run equilibrium relationships.The speed of adjustment is given by the coefficient of the error correction term,Ap t-1,in the equations shown below.The Durbin-Watson d-statistic confirmed that the choice of m=n=1 eliminates serial autocorrelation in ε1t and ε2t. Tests on natural logarithmic prices are shown in the appendix, table 18.

*significant at 0.05 level

$$\Delta ELEC\ t\ = \alpha 0\ +\ \alpha 1\ AP\mathrm{t} - 1\ + \sum_{i=1}^{m} \gamma i1\ \Delta\ ELECt - i + \sum_{j=1}^{n} \delta j1\ \Delta GAS\ t - j +\ \varepsilon 1t$$

$$\Delta GAS\ t\ =\ b0\ +\ b1\ AP\mathrm{t} - 1\ + \sum_{i=1}^{m} \gamma i2\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j2\ \Delta GAS\ t - j +\ \varepsilon 2t$$

$$\Delta ELEC\ t\ = \alpha 0\ +\ \alpha 1\ AP\mathrm{t} - 1\ + \sum_{i=1}^{m} \gamma i1\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j1\ \Delta COAL\ t - j +\ \varepsilon 1t$$

$$\Delta COAL\ t\ =\ b0\ +\ b1\ AP\mathrm{t} - 1\ + \sum_{i=1}^{m} \gamma i2\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j2\ \Delta COAL\ t - j +\ \varepsilon 2t$$

Table 4
Error correction models
Base electricity prices Netherlands

	Dependent variable Elec		*Dependent variable Gas*		*Dependent variable Elec*		*Dependent variable Coal*	
	coefficient	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*
Intercept	-0.0838	0.7343	-0.0097	0.6379	-0.0917	0.7115	-0.0235	0.7726
APt-1	-0.2401	0.0000*	0.0051	0.0570	-0.1762	0.0000*	-0.0203	0.0175*
ΔElec t-1	-0.2399	0.0000	0.0008	0.8161	-0.2774	0.0000	0.0134	0.2833
ΔGas t-1	0.1220	0.7980	0.1437	0.0003	X	X	X	X
ΔCoal t-1	X	X	X	X	0.1546	0.2127	-0.0066	0.8714
R2	0.2067		0.0288		0.1999		0.0094	
Durbin-Watson	2.0782		1.9897		2.1059		2.0145	

Note. The error correction model describes how fast the cointegrating variables adjust to the deviations from the long-run equilibrium relationships. The speed of adjustment is given by the coefficient of the error correction term,Ap t-1,in the equations shown below.The Durbin-Watson d-statistic confirmed that the choice of m=n=1 eliminates serial autocorrelation in ε1t and ε2t. Tests on natural logarithmic prices are shown in the appendix, table 19.

*significant at 0.05 level

$$\Delta ELEC\ t = \alpha 0 + \alpha 1\ AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i1\ \Delta\ ELECt - i + \sum_{j=1}^{n} \delta j1\ \Delta GAS\ t - j + \varepsilon 1t$$

$$\Delta GAS\ t = b0 + b1\ AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i2\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j2\ \Delta GAS\ t - j + \varepsilon 2t$$

$$\Delta ELEC\ t = \alpha 0 + \alpha 1\ AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i1\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j1\ \Delta COAL\ t - j + \varepsilon 1t$$

$$\Delta COAL\ t = b0 + b1\ AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i2\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j2\ \Delta COAL\ t - j + \varepsilon 2t$$

5.3 *Inter-country cointegration tests*

Table 5
Cointegration Testing
Between Germany and the Netherlands

Ap series	*Coefficient of lagged value of AP, α_1*	*t statistic*
Base-base	-0.873392	-12.0797*
Peak-peak	-0.829526	-11.7086*
Off peak- off peak	-1.1103	-9.0116*

Note. The Augmented Engle–Granger (1979) test is used to determine whether two time series are cointegrated. The test is performed by fitting the following regression where APt is the residual from equation (1) ELECt = α + β1 * GASt or (2) ELECt = α + β1 * COALt . Lagged values of the dependent variable are included to eliminate autocorrelation.

$$\Delta APt = \alpha 0 + \alpha 1\, AP\mathrm{t} - 1 + \sum_{j=2}^{4} \alpha j\, \Delta APt - (j-1) + vt$$

The null hypothesis that the series are *not* cointegrated is rejected at the 0.05 and 0.01 levels if the t-statistic is less than - 3.34 and -4.32, respectively. Tests on natural logarithmic prices are shown in the appendix, table 24.
* significant at 0.01 level
** significant at 0.05 level

Interesting results are found for inter-country cointegration. Tests for cointegration between the same commodity in different countries are shown in table 5. The coefficient of the lagged level of the abnormal price, α_1, is significantly less than zero for all tested price series. This means that the residuals are stationary or equivalently and therefore the combination between base prices, peak prices and off-peak prices are cointegrated. It is irrelevant to test for cointegration between natural gas and coal, because of the fact that these commodities are imported from abroad. The main differences between natural gas and coal prices can be linked to transaction costs. While the differences between electricity prices cannot be explained by transaction costs only, since electricity is self-generated (differently) in both countries. There is no difference in significance of natural logarithmic cointegration tests.

5.4 Inter-country electricity error correction models

Table 6, on the next page, gives results of the error correction models between Dutch and German electricity prices. In the models of the change in base; peak and off-peak electricity for Germany, the coefficient of the lagged abnormal price, AP_{t-1}, is significantly less than zero. Tests for the Netherlands resulted in negative and insignificant coefficients of the lagged abnormal price, AP_{t-1}, for base and off-peak prices and resulted in a positive and insignificant coefficient for peak prices. Considering Germany the coefficients are very high, 0,8445 for base, 0,7134 for peak and 0,9894 for off-peak prices. These results imply that huge responds will occur every day when prices deviate from equilibrium. At a 1% change of Dutch electricity prices, German base prices will respond with 84,45 %, peak will respond with 71,34 % and off-peak with 98,94 %. Furthermore in a cointegration relationship between Dutch and German electricity, the Dutch prices have the leading role. A leading role of the Netherlands is also the case at shorter horizons. Regarding the estimated coefficients on past changes in electricity prices, ΔG_elec_{t-1} and ΔNL_elec_{t-1}, only ΔNL_elec_{t-1} is exogenously significant in the error correction models of German electricity prices, this suggests unidirectional short-run causality from Dutch electricity prices to German electricity prices. Error correction models of natural logarithmic prices show the same results.

Table 6
Inter Country
Error correction models

	Dependent variable German base		*Dependent variable Dutch base*		*Dependent variable German peak*		*Dependent variable Dutch peak*		*Dependent variable German off-peak*		*Dependent variable Dutch off-peak*	
	coefficient	*P value*	*coefficient*	*P value*	*coefficient*	*P value*						
Intercept	0.0170	0.9610	0.0054	0.9867	-0.0325	0.9493	-0.0647	0.8929	0.1254	0.6138	0.0928	0.6765
AP t-1	-0.8445	0.0000*	-0.0102	0.9262	-0.7134	0.0000*	0.0950	0.3804	-0.9894	0.0000*	-0.0362	0.7245
ΔG_Elec t-1	-0.0703	0.4182	-0.0682	0.4008	-0.1803	0.0434	-0.1203	0.1518	0.1390	0.0911	0.0849	0.2487
ΔNL_Elec t-1	-0.2234	0.0218*	-0.2577	0.0047	-0.2276	0.0187*	-0.2601	0.0043	-0.2096	0.0273*	-0.2704	0.0015
R2	0.2092		0.1002		0.2289		0.1458		0.2204		0.0417	
Durbin-Watson	2.1102		2.3372		2.1454		2.3351		2.1300		2.2923	

Note. The error correction model describes how fast the cointegrating variables adjust to the deviations from the long-run equilibrium relationships.The speed of adjustment is given by the coefficient of the error correction term,Ap t-1,in the equations shown below.The Durbin-Watson d-statistic confirmed the choice of m=n=1 eliminates serial autocorrelation in ε1t and ε2t. Tests on natural logarithmic prices are shown in the appendix, table 25.

*significant at 0.05 level

$$\Delta G\_Elect \; = \alpha 0 \; + \; \alpha 1 \; AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i1 \; \Delta \; G\_Elect - i + \sum_{j=1}^{n} \delta j1 \; \Delta NL\_Elec \; t - j + \; \varepsilon 1t$$

$$\Delta NL\_Elect \; = b0 \; + \; b1 \; AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i2 \; \Delta \; G\_Elect - i + \sum_{j=1}^{n} \delta j2 \; \Delta NL\_Elec \; t - j + \; \varepsilon 2t$$

5.5 Shutdown of Nuclear reactors in Germany

In march 2011 German Chancellor Angela Merkel ordered to shut down seven of the 17 nuclear reactors in Germany (The seven reactors to be shut down immediately were Neckarwestheim 1, Philippsburg 1, Biblis A and B, Isar 1, Unterweser and Brunsbüttel). Eventually all nuclear power plants should be closed by 2021 and Germany should rely completely on other forms of energy. One of the main reasons for this drastic change in energy production is the Fukushima Daiichi disaster in Japan. A major earthquake occurred on March 11th in Fukushima, categorised as 9.0 Mw on the moment magnitude scale. The earthquake caused tsunamis which lead to radiation releases and endangered the health of life in that area.

Before the new policy, about 22.6 % of German electricity is generated by Nuclear energy. Coal provides more than 42 %; natural gas carries 13.6 % and renewable energy (e.g. solar/wind) 16.5 %; the remainder is produced by other sources.

The shutdown of seven nuclear plants at the end of march 2011 provides us to test for cointegration before and after the shutdown of nuclear plants. Both periods before and after are set to 140 days.

5.6 Unit root and Cointegration tests before and after the shutdown of nuclear reactors.

The results of the ADF unit root test are shown in table 15 (appendix). These outcomes show that almost none of the original price series are stationary before differencing. After first time differencing, tests on all price series resulted in rejecting the hypothesis that electricity, and coal prices are non-stationary at the 0.01 level thereby confirming that they are all stationary. The same results are obtained when using natural logarithms.

Cointegration test (table 7) show somewhat surprising results. In the period before the shutdown all combinations of electricity and coal; gas prices are cointegrated. After the shutdown only the combinations of peak electricity-coal and peak electricity-natural gas prices are cointegrated. The decrease in cointegration after the shutdown can be linked to the fact that, German policy is to involve renewable energy in electricity production in greater extent and therefore the cointegration of base and off-peak electricity with coal and gas could be disappeared. It is remarking that only peak prices are cointegrated after the shutdown. This relation could make sense because during peak hours, electricity demand is the highest. Therefore renewable energy could not be able to answer this greater demand while especially gas and in less extend coal can. Based on flexibility, natural gas should be more cointegrated after the shutdown compared to coal, however coal shows a slightly higher cointegration coefficient. This may be explained by the fact that coal provides more than 42 % and natural gas carries 13.6 % of electricity production. Within the German electricity generation structure, it may be easier to answer the greater demand in the peak hours with electricity production by coal. The same significance is obtained when using natural logarithms.

Table 7
Cointegration Test
Germany before and after the close of Nuclear plants

	Coefficient of lagged value of AP, α_1	*t statistic*	*Coefficient of lagged value of AP, α_1*	*t statistic*
AP-Series	*Before*		*After*	
Base-coal	-0.5033	-4.3553*	-0.3549	-3.1448
Peak-coal	-0.5809	-4.6057*	-0.5394	-3.8193**
Off peak-coal	-0.3741	-3.8279**	-0.2501	-2.8704
Base-gas	-0.5370	-4.3698*	-0.3701	-3.2213
Peak-gas	-0.6467	-4.7522*	-0.5354	-3.8494**
Off peak-gas	-0.3690	-3.6992**	-0.2487	-2.8219

Note. The Augmented Engle–Granger (1979) test is used to determine whether two time series are cointegrated. The test is performed by fitting the following regression where APt is the residual from equation 1 ELECt = α + β1 * GASt.

$$\Delta APt = \alpha 0 + \alpha 1\, AP\mathrm{t} - 1 + \sum_{j=2}^{4} \alpha j\, \Delta APt - (j-1) + vt$$

The null hypothesis that the series are *not* cointegrated is rejected at the 0.05 and 0.01 levels if the t-statistic is less than -3.34 and -4.32, respectively. Tests on natural logarithmic prices are shown in the appendix, table 27.

* significant at 0.01 level

** significant at 0.05 level

5.7 Error correction models before the shutdown of Nuclear reactors.

Tables 8 and 9, give results of the error correction models before the shutdown of nuclear plants. In the models of the change in base; peak and off-peak electricity in combination with coal, the coefficient of the lagged abnormal price, AP_{t-1}, is significantly less than zero. In the models of change of coal prices, the coefficient of the lagged abnormal price, AP_{t-1}, is always positive but only significant for the combinations of coal-base and coal-off peak. The significant relationships between base; off-peak electricity with coal and also significance in the other way around suggest bidirectional long-run causality between these prices. In contrast, the model of change of peak prices results in long-run causality from coal to peak electricity prices. Furthermore, regarding the estimated coefficients on past changes, $\Delta Elec_{t-1}$ and $\Delta Coal_{t-1}$, only electricity prices are exogenously significant in the error correction models of coal. This suggests short-run causality from electricity to coal prices.

In the models of change in base; peak and off-peak electricity in combination with natural gas, the coefficient of the lagged abnormal price, AP_{t-1}, is significantly less than zero. In contrast, in the models of change of natural gas prices, the coefficient of the lagged abnormal price, AP_{t-1}, is always positive and insignificant. This relationship suggest long-run causality from natural gas to electricity. There is no evidence of short-run causality between peak electricity and natural gas prices.

Tests on natural logarithmic prices give somewhat different results. In the long-run causality from coal to peak electricity prices become bidirectional. The bidirectional causal relation between coal and off-peak electricity becomes unidirectional from coal to off-peak prices. In the short-run no differences occur. Error correction models between electricity and natural gas do not differ from tests on actual prices.

Table 8
Error correction models
Germany Coal prices before the close of Nuclear plants

	Dependent variable Base		*Dependent variable Coal*		*Dependent variable Peak*		*Dependent variable Coal*		*Dependent variable Off-peak*		*Dependent variable Coal*	
	coefficient	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*
Intercept	0.1577	0.7805	0.1886	0.1801	0.2089	0.7776	0.1869	0.1874	0.1088	0.8160	0.1910	0.1732
AP t-1	-0.5293	0.0000*	0.0474	0.0451	-0.6086	0.0000*	0.0314	0.1069	-0.4208	0.0000*	0.0548	0.0298
ΔElec t-1	-0.1673	0.0482	-0.0539	0.0105*	-0.1733	0.0397	-0.0350	0.0298*	-0.1206	0.1584	-0.0686	0.0078*
ΔCoal t-1	-0.0185	0.9555	0.1748	0.0350	-0.0414	0.9239	0.1765	0.0346	0.0014	0.9959	0.1707	0.0386
R2	0.3366		0.0783		0.3872		0.0638		0.2493		0.0852	
Durbin-Watson	2.0098		2.1008		2.0231		2.0838		1.9955		2.0653	

Note. The error correction model describes how fast the cointegrating variables adjust to the deviations from the long-run equilibrium relationships.The speed of adjustment is given by the coefficient of the error correction term,Ap t-1,in the equations shown below.The Durbin-Watson d-statistic confirmed that the choice of m=n=1 eliminates serial autocorrelation in ε1t and ε2t. Tests on natural logarithmic prices are shown in the appendix, table 28.

$$\Delta ELEC\ t\ = \alpha 0\ +\ \alpha 1\ AP\mathrm{t}-1\ +\sum_{i=1}^{m}\gamma i1\ \Delta\ ELECt-i+\sum_{j=1}^{n}\delta j1\ \Delta COAL\ t-j+\ \varepsilon 1t$$

*significant at 0.05 level

$$\Delta COAL\ t\ =\ b0\ +\ b1\ AP\mathrm{t}-1\ +\sum_{i=1}^{m}\gamma i2\ \Delta ELEC\ t-i+\sum_{i=1}^{n}\delta j2\ \Delta COAL\ t-j+\ \varepsilon 2t$$

Table 9
Error correction models
Germany Natural gas prices before the close of Nuclear plants

	Dependent variable Base		*Dependent variable Gas*		*Dependent variable Peak*		*Dependent variable Gas*		*Dependent variable Off-peak*		*Dependent variable Gas*	
	coefficient	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*
Intercept	0.2090	0.7089	0.0809	0.0521	0.2406	0.7410	0.0813	0.0520	0.1913	0.6810	0.0815	0.0493
AP t-1	-0.5854	0.0000*	0.0082	0.2503	-0.6898	0.0000*	0.0039	0.5170	-0.4282	0.0000*	0.0115	0.1189
Elec t-1	-0.1443	0.0900	-3.0000	0.9955	-0.1344	0.1112	0.0003	0.9508	-0.1281	0.1368	0.0008	0.9150
Gas t-1	-0.8951	0.4494	-0.0304	0.7278	-0.7174	0.6420	-0.0352	0.6897	-1.2095	0.2167	-0.0355	0.6808
R2	0.3568		0.0166		0.4115		0.0081		0.2613		0.0274	
Durbin-Watson	2.0081		1.9795		2.0108		1.9801		2.0083		1.9768	

Note. The error correction model describes how fast the cointegrating variables adjust to the deviations from the long-run equilibrium relationships.The speed of adjustment is given by the coefficient of the error correction term,Ap t-1,in the equations shown below.The Durbin-Watson d-statistic confirmed that the choice of m=n=1 eliminates serial autocorrelation in ε1t and ε2t. Tests on natural logarithmic prices are shown in the appendix, table 29.

$$\Delta ELEC\,t = \alpha 0 + \alpha 1\, AP\mathrm{t}-1 + \sum_{i=1}^{m} \gamma i1\, \Delta\, ELECt-i + \sum_{j=1}^{n} \delta j1\, \Delta GAS\, t-j + \varepsilon 1t$$

*significant at 0.05 level

$$\Delta GAS\,t = b0 + b1\, AP\mathrm{t}-1 + \sum_{i=1}^{m} \gamma i2\, \Delta ELEC\, t-i + \sum_{j=1}^{n} \delta j2\, \Delta GAS\, t-j + \varepsilon 2t$$

5.7.1 Error correction models after the shutdown of nuclear reactors

Error correction models for the period after the shutdown of nuclear reactors are shown in table 10. This table only contains combinations of peak electricity and coal /natural gas prices, this is due to the fact that only these combinations are cointegrated after the shutdown (see table 7). The results are somewhat different compared to the period before the close of the nuclear plants. In the model of the change of peak as well as the model of change of coal prices, the coefficient of the lagged abnormal price, AP_{t-1}, is less than zero. However, the coefficient for coal is not significant while the coefficient for peak is. The value of the AP_{t-1} coefficient of -0.7804 suggests that peak prices change with a magnitude of 78.04 % when coal prices change with 1%. This model suggests that coal in a model with peak prices has the leading role in the long-run.

Similar findings are shown for the combination of peak electricity and natural gas. In both models of change the coefficient of the lagged abnormal price, AP_{t-1}, is less than zero and again only peak electricity is significant. This means that natural gas has the leading role in the long-run. The AP_{t-1} coefficient of -0.7749 in the model of change of peak electricity prices suggests that, a 77.49 % change will follow if natural gas prices change with 1%. Both error correction models show no evidence of short-run causality.

Tests on logarithmic prices give the same outcomes for the combination of peak electricity and coal prices. Different outcomes occur between peak electricity and natural gas. The uni-directional long-run causality from natural gas to coal becomes bidirectional.

Table 10
Error correction models
Germany after the close of Nuclear plants

	Dependent variable Peak		*Dependent variable Coal*		*Dependent variable Peak*		*Dependent variable Gas*	
	coefficient	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*
Intercept	-0.0286	0.9624	-0.1194	0.2336	0.0487	0.9367	-0.0076	0.8166
AP t-1	-0.7804	0.0000*	-0.0320	0.0727	-0.7749	0.0000*	-0.0114	0.0527
ΔElec t-1	0.0233	0.7875	0.0197	0.1677	0.0170	0.8483	-0.0010	0.8345
ΔCoal t-1	-0.7672	0.1347	0.0766	0.3636	X	X	X	X
ΔGas t-1	X	X	X	X	-0.6651	0.6708	0.1234	0.1398
R2	0.3940		0.0306		0.3778		0.0668	
Durbin-Watson	1.9688		2.0179		1.9891		1.9737	

Note. The error correction model describes how fast the cointegrating variables adjust to the deviations from the long-run equilibrium relationships. The speed of adjustment is given by the coefficient of the error correction term,Ap t-1, in the equations shown below. The Durbin-Watson d-statistic confirmed that the choice of m=n=1 eliminates serial autocorrelation in ε1t and ε2t. Tests on natural logarithmic prices are shown in the appendix, table 30.

$$\Delta ELEC\,t = \alpha 0 + \alpha 1\,AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i1\,\Delta\,ELECt - i + \sum_{j=1}^{n} \delta j1\,\Delta COAL\,t - j + \varepsilon 1t$$

*significant at 0.05 level

$$\Delta COAL\,t = b0 + b1\,AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i2\,\Delta ELEC\,t - i + \sum_{j=1}^{n} \delta j2\,\Delta COAL\,t - j + \varepsilon 2t$$

6 Conclusion

Making use of daily price data for the period 10-10-2008 till 07-12-2011 for Germany and the Netherlands, this paper examined the short and long-run dynamics among and between electricity, natural gas and coal prices. Three different combinations are focused on. The relationship between electricity, natural gas and coal within the same country, the relationship of electricity prices between countries and the relationship between electricity, coal and natural gas before and after the shutdown of 7 nuclear reactors in Germany.

Cointegration evidence between electricity and fuel prices within the same country are found for both Germany and the Netherlands. A unidirectional long-run causal relationship from coal to electricity is detected in Germany and bidirectional long-run causality in the Netherlands. Except for the combination with off-peak electricity, natural gas shows unidirectional long-run causality in both Germany and the Netherlands. In the short-run only causality is detected from German peak electricity to coal prices.

Inter-country cointegration tests show cointegration between base, peak and off-peak prices. The error correction models between German and Dutch electricity prices show unidirectional long-run causality from Dutch electricity to German electricity prices. The short-run dynamics are unidirectional in the same direction, from the Netherlands to Germany. These results indicate that the German and Dutch electricity markets are integrated.

The final part of this paper provides tests on German electricity, coal and natural gas prices before and after the shutdown of 7 important nuclear reactors. There is evidence of cointegration between all combinations of electricity and coal/gas before the shutdown. After the shutdown only the combination of peak; coal and peak-gas are cointegrated. Unidirectional long-run causality from coal to electricity prices and unidirectional short-run causality from electricity to coal prices is detected. Similar to coal, error correction models between electricity and natural gas show unidirectional long-run causality from natural gas to electricity prices. There is no short-run causality between electricity and natural gas.

For the period after the shutdown, error correction models give evidence of unidirectional long-run causality from coal to peak electricity prices and bi-directional long-run causality between peak electricity and natural gas. There is no evidence of short-run causality for the period after the shutdown.

Tests on logarithms prices show no major differences with tests on actual prices. Unit root tests and cointegration tests resulted in slightly different coefficients but the same level of significance. Likewise error correction models also show different coefficients and in some cases differences in significance occur. However, inter-country error correction models show no differences. Overall, the presented results should be quite robust.

The long-run cointegration relationship between electricity and fuels can be explained by the fact that both natural gas and coal play important roles in electricity generation. A possible explanation for the asymmetric long-run causality between natural gas and electricity is that, natural gas is a very important ingredient for electricity generation and therefore electricity is highly dependent of natural gas. However, natural gas is used for many other purposes than electricity generation and therefore natural gas is more independent and does not get effected as much when electricity demand changes. Coal, in contrast shows bidirectional causality (for the Netherlands) and seems to get effected when electricity prices change. Compared to natural gas, coal is often used for electricity production and less for other purposes, therefore the bidirectional causality could make sense. Off course the same relationship would be expected for coal in Germany, since German electricity is mainly produced by coal (42%). According to the results it seems that coal in Germany does have other purposes than electricity generation.

The decrease in cointegration after the shutdown of 7 nuclear centrals, could be the result of German policy, which is to involve renewable energy more in electricity production. The main goal is to make electricity production more safe by completely removing nuclear power centrals between now and 2021. It is not surprising that only peak prices and natural gas/coal prices are cointegrated after the shutdown, because peak hours are characterized by flexible and often greater demand. It could be the case that renewable energy sources are not able to answer this greater demand, while especially gas and coal can.

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8 Appendix

Table 11
Error correction models
Off- Peak electricity prices Germany

	Dependent variable Elec		*Dependent variable Gas*		*Dependent variable Elec*		*Dependent variable Coal*	
	coefficient	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*
Intercept	-0.0565	0.7870	-0.0145	0.5414	-0.0665	0.7548	-0.0218	0.7999
APt-1	-0.3399	0.0000*	0.0118	0.0035*	-0.2321	0.0000*	-0.0133	0.2500
ΔElec t-1	-0.1127	0.0054	0.0054	0.2407	-0.1737	0.0000	0.0198	0.2097
ΔGas t-1	-0.0243	0.9449	0.0207	0.6045	X	X	X	X
ΔCoal t-1	X	X	X	X	-0.1723	0.0848	0.0682	0.0907
R2	0.2020		0.0258		0.1716			
Durbin-Watson	2.0091		1.9669		2.0430		2.0281	

Note. The error correction model describes how fast the cointegrating variables adjust to the deviations from the long-run equilibrium relationships. The speed of adjustment is given by the coefficient of the error correction term,Ap t-1,in the equations shown below.The Durbin-Watson d-statistic confirmed that the choice of m=n=1 eliminates serial autocorrelation in ε1t and ε2t. Tests on natural logarithmic prices are shown in the appendix, table 20.

*significant at 0.05 level

$$\Delta ELEC\ t = \alpha 0 + \alpha 1\ AP\mathrm{t}-1 + \sum_{i=1}^{m} \gamma i1\ \Delta\ ELECt - i + \sum_{j=1}^{n} \delta j1\ \Delta GAS\ t - j + \varepsilon 1t$$

$$\Delta GAS\ t = b0 + b1\ AP\mathrm{t}-1 + \sum_{i=1}^{m} \gamma i2\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j2\ \Delta GAS\ t - j + \varepsilon 2t$$

$$\Delta ELEC\ t = \alpha 0 + \alpha 1\ AP\mathrm{t}-1 + \sum_{i=1}^{m} \gamma i1\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j1\ \Delta COAL\ t - j + \varepsilon 1t$$

$$\Delta COAL\ t = b0 + b1\ AP\mathrm{t}-1 + \sum_{i=1}^{m} \gamma i2\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j2\ \Delta COAL\ t - j + \varepsilon 2t$$

Table 12
Error correction models
Off- Peak electricity prices Netherlands

	Dependent variable Elec		*Dependent variable Gas*		*Dependent variable Elec*		*Dependent variable Coal*	
	coefficient	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*
Intercept	-0.0622	0.7161	-0.0096	0.6399	-0.0664	0.6955	-0.0232	0.7751
APt-1	-0.1728	0.0000*	0.0075*	0.0203*	-0.1771	0.0000*	-0.0237	0.0467*
ΔElec t-1	-0.1717	0.0000	0.0017	0.7294	-0.1788	0.0000	0.0187	0.3206
ΔGas t-1	-0.0879	0.7900	0.1434	0.0003	X	X	X	X
ΔCoal t-1	X	X	X	X	-0.0046	0.9573	-0.0054	0.8938
R2	0.1276		0.031899		0.1417		0.0068	
Durbin-Watson	2.0651		1.9889		2.0741		2.0081	

Note. The error correction model describes how fast the cointegrating variables adjust to the deviations from the long-run equilibrium relationships. The speed of adjustment is given by the coefficient of the error correction term,Ap t-1,in the equations shown below.The Durbin-Watson d-statistic confirmed that the choice of m=n=1 eliminates serial autocorrelation in ε1t and ε2t. Tests on natural logarithmic prices are shown in the appendix, table 21.

*significant at 0.05 level

$$\Delta ELEC\ t = \alpha 0 + \alpha 1\ AP\mathrm{t}-1 + \sum_{i=1}^{m} \gamma i1\ \Delta\ ELECt - i + \sum_{j=1}^{n} \delta j1\ \Delta GAS\ t - j + \varepsilon 1t$$

$$\Delta GAS\ t = b0 + b1\ AP\mathrm{t}-1 + \sum_{i=1}^{m} \gamma i2\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j2\ \Delta GAS\ t - j + \varepsilon 2t$$

$$\Delta ELEC\ t = \alpha 0 + \alpha 1\ AP\mathrm{t}-1 + \sum_{i=1}^{m} \gamma i1\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j1\ \Delta COAL\ t - j + \varepsilon 1t$$

$$\Delta COAL\ t = b0 + b1\ AP\mathrm{t}-1 + \sum_{i=1}^{m} \gamma i2\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j2\ \Delta COAL\ t - j + \varepsilon 2t$$

Table 13
Error correction models
Peak electricity prices Germany

	Dependent variable Elec		*Dependent variable Gas*		*Dependent variable Elec*		*Dependent variable Coal*	
	coefficient	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*
Intercept	-0.1390	0.7367	-0.0147	0.5410	-0.1529	0.7174	-0.0209	0.8069
APt-1	-0.3240	0.0000*	0.0017	0.4143	-0.2008	0.0000*	0.0099	0.0772
ΔElec t-1	-0.2315	0.0000	0.0031	0.1667	-0.2974	0.0000	0.0211	0.0063*
ΔGas t-1	-0.0785	0.9097	0.0124	0.7573	X	X	X	X
ΔCoal t-1	X	X	X	X	-0.2016	0.3088	0.0718	0.0735
R2	0.2548		0.0073		0.2209		0.0188	
Durbin-Watson	2.0780		1.9760		2.1289		2.0389	

Note. The error correction model describes how fast the cointegrating variables adjust to the deviations from the long-run equilibrium relationships. The speed of adjustment is given by the coefficient of the error correction term,Ap t-1,in the equations shown below.The Durbin-Watson d-statistic confirmed that the choice of m=n=1 eliminates serial autocorrelation in ε1t and ε2t. Tests on natural logarithmic prices are shown in the appendix, table 22.

*significant at 0.05 level

$$\Delta ELEC\;t = \alpha 0 + \alpha 1\;AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i1\;\Delta\;ELECt - i + \sum_{j=1}^{n} \delta j1\;\Delta GAS\;t - j + \varepsilon 1t$$

$$\Delta GAS\;t = b0 + b1\;AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i2\;\Delta ELEC\;t - i + \sum_{j=1}^{n} \delta j2\;\Delta GAS\;t - j + \varepsilon 2t$$

$$\Delta ELEC\;t = \alpha 0 + \alpha 1\;AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i1\;\Delta ELEC\;t - i + \sum_{j=1}^{n} \delta j1\;\Delta COAL\;t - j + \varepsilon 1t$$

$$\Delta COAL\;t = b0 + b1\;AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i2\;\Delta ELEC\;t - i + \sum_{i=1}^{n} \delta j2\;\Delta COAL\;t - j + \varepsilon 2t$$

Table 14
Error correction models
Peak electricity prices Netherlands

	Dependent variable Elec		*Dependent variable Gas*		*Dependent variable Elec*		*Dependent variable Coal*	
	coefficient	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*
Intercept	-0.1073	0.7656	-0.0097	0.6385	-0.1199	0.7414	-0.0235	0.7727
APt-1	-0.2884	0.0000*	0.0029	0.1482	-0.1977	0.0000*	-0.0157	0.0135*
ΔElec t-1	-0.2667	0.0000	0.0005	0.8385	-0.3159	0.0000	0.0094	0.2610
ΔGas t-1	0.3234	0.6416	0.1440	0.0003	X	X	X	X
ΔCoal t-1	X	X	X	X	0.3032	0.0947	-0.0055	0.8918
R2	0.2570		0.0258		0.2428		0.0100	
Durbin-Watson	2.0916		1.9898		2.1250		2.0166	

Note. The error correction model describes how fast the cointegrating variables adjust to the deviations from the long-run equilibrium relationships. The speed of adjustment is given by the coefficient of the error correction term,Ap t-1,in the equations shown below.The Durbin-Watson d-statistic confirmed that the choice of m=n=1 eliminates serial autocorrelation in ε1t and ε2t. Tests on natural logarithmic prices are shown in the appendix, table 24.

*significant at 0.05 level

$$\Delta ELEC\;t = \alpha 0 + \alpha 1\;AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i1\;\Delta\;ELECt - i + \sum_{j=1}^{n} \delta j1\;\Delta GAS\;t - j + \varepsilon 1t$$

$$\Delta GAS\;t = b0 + b1\;AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i2\;\Delta ELEC\;t - i + \sum_{j=1}^{n} \delta j2\;\Delta GAS\;t - j + \varepsilon 2t$$

$$\Delta ELEC\;t = \alpha 0 + \alpha 1\;AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i1\;\Delta ELEC\;t - i + \sum_{j=1}^{n} \delta j1\;\Delta COAL\;t - j + \varepsilon 1t$$

$$\Delta COAL\;t = b0 + b1\;AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i2\;\Delta ELEC\;t - i + \sum_{j=1}^{n} \delta j2\;\Delta COAL\;t - j + \varepsilon 2t$$

Table 15

Results of Unit Root Tests

Germany before and after the close of Nuclear plants

	Coefficient of lagged value of series, δ_1	***t-statistic***	***Coefficient of lagged value of series, δ_1***	***t-statistic***
Series	*Before the closing*		*After the closing*	
ELECTRICITY:				
Base				
prices:	0.001	0.039	-0.004	-0.463
1st difference of prices	-2.727	-10.218*	-3.001	-10.783*
Peak				
prices:	-0.002	-0.112	-0.003	-0.322
1st difference of prices	-2.894	-10.570*	-3.375	-11.858*
Off-Peak				
prices:	0.001	0.125	-0.005	-0.664
1st difference of prices	-2.057	-11.295*	-1.748	-13.792*

Note. The Augmented Dickey-Fuller (1979) unit root test is performed by implementing the following regression to the series, Yt, with lagged values of the dependent variable included to eliminate autocorrelation.

$$\Delta Yt = \delta 0 + \delta 1\, Y\mathrm{t} - 1 + \sum_{i=2}^{4} \delta i\, \Delta Yt - (i-1) + ut$$

The null hypothesis that a series is non stationary is rejected at the 0.05 and 0.01 levels if the t-statistic is less than -2.86 and -3.43, respectively. When a series is non-stationary, the original time series prices will be differenced once and the test will be repeated again. This process is repeated enough times to arrive at stationary series. Tests on natural logarithmic prices are shown in the appendix, table 26.

* significant at 0.01 level.

8.1 Tests on logarithmic prices

TABLE 16
Results of Unit Root Test (natural logarithms)

	Coefficient of lagged value of series, δ_1	***t-statistic***	***Coefficient of lagged value of series, δ_1***	***t-statistic***
Series	*Germany*		*Netherlands*	
ELECTRICITY:				
Ln_Base				
prices:	-0.001	-0.626	-0.001	-0.623
1st difference of prices	-2.497	-19.501*	-2.456	-19.449*
Ln_Peak				
prices:	-0.0012	-0.656	-0.001	-0.632
1st difference of prices	-2.766	-20.592*	-2.796	-21.079*
Ln_Off-Peak				
prices:	-0.001	-0.570	-0.001	-0.608
1st difference of prices	-2.373	-19.522*	-2.133	-18.199*
LN_GAS:				
prices:	-0.001	-0.681	-0.001	-0.525
1st difference of prices	-1.020	-25.348*	-0.970	-24.070*
LN_COAL:				
prices:	-0.001	-0.365	-0.001	-0.259
1st difference of prices	-0.846	-15.236*	-1.012	-25.118*

Note. The Augmented Dickey-Fuller (1979) unit root test is performed by implementing the following regression to the series, Yt, with lagged values of the dependent variable included to eliminate autocorrelation.

$$\Delta Yt = \delta 0 + \delta 1\, Y\mathrm{t} - 1 + \sum_{i=2}^{4} \delta i\, \Delta Yt - (i-1) + ut$$

The null hypothesis that a series is non stationary is rejected at the 0.05 and 0.01 levels if the t-statistic is less than -2.86 and -3.43, respectively. When a series is non-stationary, the original time series prices will be differenced once and the test will be repeated again. This process is repeated enough times to arrive at stationary series.

* significant at 0.01 level.

** significant at 0.05 level.

Table 17
Cointegration Test (natural logarithms)

AP-series	*Coefficient of lagged value of AP, α1*	*t statistic*	*Coefficient of lagged value of AP, α1*	*t statistic*
	Germany		*Netherlands*	
ln(Base-gas)	-0.2936	-6.6584*	-0.1585	-4.8297*
ln(Base-coal)	-0.1835	-5.2993*	-0.1307	-4.4320*
ln(Peak-gas)	-0.2738	-6.1927*	-0.1954	-5.1612*
ln(Peak-coal)	-0.1765	-5.0421*	-0.1517	-4.6056*
ln(Off peak-gas)	-0.1208	-4.2920**	-0.0614	-3.4167**
ln(Off peak-coal)	-0.2610	-6.5220*	-0.1364	-4.7593*

Note. The Augmented Engle–Granger (1979) test is used to determine whether two time series are cointegrated. The test is performed by fitting the following regression where APt is the residual from equation (1) ELECt = α + β1 * GASt or (2) ELECt = α + β1 * GASt . Lagged values of the dependent variable are included to eliminate autocorrelation.

$$\Delta APt \;=\; \alpha 0 \;+\; \alpha 1\; AP\mathrm{t} - 1 \;+ \sum_{j=2}^{4} \alpha j\; \Delta APt - (j-1) +\; vt$$

The null hypothesis that the series are *not* cointegrated is rejected at the 0.05 and 0.01 levels if the t-statistic is less than -3.34 and -4.32, respectively.
* significant at 0.01 level
** significant at 0.05 level

Table 18
Error correction models
Base electricity prices Germany (natural logarithms)

	Dependent variable Elec		*Dependent variable Gas*		*Dependent variable Elec*		*Dependent variable Coal*	
	coefficient	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*
Intercept	-0.0015	0.8211	-0.0005	0.6957	-0.0017	0.8038	-0.0002	0.8520
APt-1	-0.3876	0.0000*	0.0104	0.2061	-0.2740	0.0000*	-0.0067	0.1593
ΔElec t-1	-0.2207	0.0000	0.0262	0.0017*	-0.2839	0.0000	0.0132	0.0187*
ΔGas t-1	-0.0155	0.9351	-0.0009	0.9821	X	X	X	X
ΔCoal t-1	X	X	X	X	-0.3082	0.2659	0.0226	0.5759
R2	0.2868		0.0331		0.2580		0.0100	
Durbin-Watson	2.0464		1.9777		2.0878		2.0271	

Note. The error correction model describes how fast the cointegrating variables adjust to the deviations from the long-run equilibrium relationships. The speed of adjustment is given by the coefficient of the error correction term,Ap t-1,in the equations shown below.The Durbin-Watson d-statistic confirmed that the choice of m=n=1 eliminates serial autocorrelation in ε1t and ε2t.

*significant at 0.05 level

$$\Delta ELEC\; t \;= \alpha 0 \;+\; \alpha 1\; AP\mathrm{t} - 1 \;+ \sum_{i=1}^{m} \gamma i1\; \Delta\; ELECt - i + \sum_{j=1}^{n} \delta j1\; \Delta GAS\; t - j +\; \varepsilon 1t$$

$$\Delta GAS\; t \;=\; b0 \;+\; b1\; AP\mathrm{t} - 1 \;+ \sum_{i=1}^{m} \gamma i2\; \Delta ELEC\; t - i + \sum_{j=1}^{n} \delta j2\; \Delta GAS\; t - j +\; \varepsilon 2t$$

$$\Delta ELEC\; t \;=\; \alpha 0 \;+\; \alpha 1\; AP\mathrm{t} - 1 \;+ \sum_{i=1}^{m} \gamma i1\; \Delta ELEC\; t - i + \sum_{j=1}^{n} \delta j1\; \Delta COAL\; t - j +\; \varepsilon 1t$$

$$\Delta COAL\; t \;=\; b0 \;+\; b1\; AP\mathrm{t} - 1 \;+ \sum_{i=1}^{m} \gamma i2\; \Delta ELEC\; t - i + \sum_{j=1}^{n} \delta j2\; \Delta COAL\; t - j +\; \varepsilon 2t$$

Table 19
Error correction models
Base electricity prices Netherlands (natural logarithms)

	Dependent variable Elec		*Dependent variable Gas*		*Dependent variable Elec*		*Dependent variable Coal*	
	coefficient	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*
Intercept	-0.0013	0.7919	-0.0004	0.7547	-0.0014	0.7740	-0.0002	0.8285
APt-1	-0.2251	0.0000*	0.0163	0.0438*	-0.2089	0.0000*	-0.0100	0.0579
Elec	-0.2894	0.0000	-0.0163	0.1018	-0.3006	0.0000	0.0055	0.4265
Gas	0.0647	0.6797	0.0326	0.4185	X	X	X	X
Coal	X	X	X	X	0.0813	0.7156	-0.0235	0.5651
R2	0.2279		0.0088		0.2315		0.0061	
Durbin-Watson	2.0786		2.0034		2.0958		2.0091	

Note. The error correction model describes how fast the cointegrating variables adjust to the deviations from the long-run equilibrium relationships. The speed of adjustment is given by the coefficient of the error correction term,Ap t-1,in the equations shown below.The Durbin-Watson d-statistic confirmed that the choice of m=n=1 eliminates serial autocorrelation in ε1t and ε2t.

*significant at 0.05 level

$$\Delta ELEC\ t = \alpha 0 + \alpha 1\ AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i1\ \Delta\ ELECt - i + \sum_{j=1}^{n} \delta j1\ \Delta GAS\ t - j + \varepsilon 1t$$

$$\Delta GAS\ t = b0 + b1\ AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i2\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j2\ \Delta GAS\ t - j + \varepsilon 2t$$

$$\Delta ELEC\ t = \alpha 0 + \alpha 1\ AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i1\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j1\ \Delta COAL\ t - j + \varepsilon 1t$$

$$\Delta COAL\ t = b0 + b1\ AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i2\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j2\ \Delta COAL\ t - j + \varepsilon 2t$$

Table 20
Error correction models
Off-peak electricity prices Germany (natural logarithms)

	Dependent variable Elec		*Dependent variable Gas*		*Dependent variable Elec*		*Dependent variable Coal*	
	coefficient	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*
Intercept	-0.0011	0.8768	-0.0005	0.6889	-0.0013	0.8506	-0.0002	0.8488
APt-1	0.1801	0.0000*	-0.0138	0.0176*	-0.3369	0.0000*	-0.0048	0.3440
Elec	-0.3226	0.0000	0.0324	0.0000*	-0.2356	0.0000	0.0086	0.1126
Gas	-0.1176	0.5801	0.0112	0.7777	X	X	X	X
Coal	X	X	X	X	-0.4026	0.1651	0.0219	0.5887
R2	0.2041		0.0591		0.2656		0.0048	
Durbin-Watson	2.0744		1.9569		2.0320		2.0230	

Note. The error correction model describes how fast the cointegrating variables adjust to the deviations from the long-run equilibrium relationships. The speed of adjustment is given by the coefficient of the error correction term,Ap t-1,in the equations shown below.The Durbin-Watson d-statistic confirmed that the choice of m=n=1 eliminates serial autocorrelation in ε1t and ε2t.

*significant at 0.05 level

$$\Delta ELEC\ t = \alpha 0 + \alpha 1\ AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i1\ \Delta\ ELECt - i + \sum_{j=1}^{n} \delta j1\ \Delta GAS\ t - j + \varepsilon 1t$$

$$\Delta GAS\ t = b0 + b1\ AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i2\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j2\ \Delta GAS\ t - j + \varepsilon 2t$$

$$\Delta ELEC\ t = \alpha 0 + \alpha 1\ AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i1\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j1\ \Delta COAL\ t - j + \varepsilon 1t$$

$$\Delta COAL\ t = b0 + b1\ AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i2\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j2\ \Delta COAL\ t - j + \varepsilon 2t$$

Table 21
Error correction models
Off-peak electricity prices Netherlands (natural logarithms)

	Dependent variable Elec		*Dependent variable Gas*		*Dependent variable Elec*		*Dependent variable Coal*	
	coefficient	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*
Intercept	-0.0012	0.7878	-0.0004	0.7463	-0.0013	0.7720	-0.0002	0.8289
APt-1	0.0752	0.0002*	-0.0161	0.0040*	-0.2054	0.0000*	-0.0093	0.0970
Elec	-0.2635	0.0000	-0.0121	0.2738	-0.2044	0.0000	0.0048	0.5469
Gas	-0.0696	0.6272	0.0333	0.4063	X	X	X	X
Coal	X	X	X	X	-0.0945	0.6340	-0.0232	0.5705
R2	0.1118		0.0145		0.1693		0.0046	
Durbin-Watson	2.0988		2.0011		2.0629		2.0057	

Note. The error correction model describes how fast the cointegrating variables adjust to the deviations from the long-run equilibrium relationships. The speed of adjustment is given by the coefficient of the error correction term,Ap t-1,in the equations shown below.The Durbin-Watson d-statistic confirmed that the choice of m=n=1 eliminates serial autocorrelation in ε1t and ε2t.

*significant at 0.05 level

$$\Delta ELEC\,t = \alpha 0 + \alpha 1\,AP\mathrm{t}-1 + \sum_{i=1}^{m} \gamma i1\,\Delta\,ELECt-i + \sum_{j=1}^{n} \delta j1\,\Delta GAS\,t-j + \varepsilon 1t$$

$$\Delta GAS\,t = b0 + b1\,AP\mathrm{t}-1 + \sum_{i=1}^{m} \gamma i2\,\Delta ELEC\,t-i + \sum_{j=1}^{n} \delta j2\,\Delta GAS\,t-j + \varepsilon 2t$$

$$\Delta ELEC\,t = \alpha 0 + \alpha 1\,AP\mathrm{t}-1 + \sum_{i=1}^{m} \gamma i1\,\Delta ELEC\,t-i + \sum_{j=1}^{n} \delta j1\,\Delta COAL\,t-j + \varepsilon 1t$$

$$\Delta COAL\,t = b0 + b1\,AP\mathrm{t}-1 + \sum_{i=1}^{m} \gamma i2\,\Delta ELEC\,t-i + \sum_{j=1}^{n} \delta j2\,\Delta COAL\,t-j + \varepsilon 2t$$

Table 22
Error correction models
Peak electricity prices Germany (natural logarithms)

	Dependent variable Elec		*Dependent variable Gas*		*Dependent variable Elec*		*Dependent variable Coal*	
	coefficient	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*
Intercept	-0.0017	0.8181	-0.0006	0.6902	-0.0020	0.8009	-0.0002	0.8511
APt-1	-0.4024	0.0000*	0.0062	0.4039	-0.2855	0.0000*	-0.0069	0.1084
ΔElec t-1	-0.2466	0.0000	0.0166	0.0216*	-0.3103	0.0000	0.0120	0.0131*
ΔGas t-1	0.0122	0.9556	-0.0093	0.8166	X	X	X	X
ΔCoal t-1	X	X	X	X	-0.3271	0.3046	0.0231	0.5680
R2	0.3135		0.0178		0.2843		0.0112	
Durbin-Watson	2.0769		1.9890		2.1246		2.0248	

Note. The error correction model describes how fast the cointegrating variables adjust to the deviations from the long-run equilibrium relationships. The speed of adjustment is given by the coefficient of the error correction term,Ap t-1,in the equations shown below.The Durbin-Watson d-statistic confirmed that the choice of m=n=1 eliminates serial autocorrelation in ε1t and ε2t.

*significant at 0.05 level

$$\Delta ELEC\,t = \alpha 0 + \alpha 1\,AP\mathrm{t}-1 + \sum_{i=1}^{m} \gamma i1\,\Delta\,ELECt-i + \sum_{j=1}^{n} \delta j1\,\Delta GAS\,t-j + \varepsilon 1t$$

$$\Delta GAS\,t = b0 + b1\,AP\mathrm{t}-1 + \sum_{i=1}^{m} \gamma i2\,\Delta ELEC\,t-i + \sum_{j=1}^{n} \delta j2\,\Delta GAS\,t-j + \varepsilon 2t$$

$$\Delta ELEC\,t = \alpha 0 + \alpha 1\,AP\mathrm{t}-1 + \sum_{i=1}^{m} \gamma i1\,\Delta ELEC\,t-i + \sum_{j=1}^{n} \delta j1\,\Delta COAL\,t-j + \varepsilon 1t$$

$$\Delta COAL\,t = b0 + b1\,AP\mathrm{t}-1 + \sum_{i=1}^{m} \gamma i2\,\Delta ELEC\,t-i + \sum_{i=1}^{n} \delta j2\,\Delta COAL\,t-j + \varepsilon 2t$$

Table 23
Error correction models
Peak electricity prices Netherlands (natural logarithms)

	Dependent variable Elec		*Dependent variable Gas*		*Dependent variable Elec*		*Dependent variable Coal*	
	coefficient	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*
Intercept	-0.0014	0.8203	-0.0004	0.7565	-0.0016	0.7986	-0.0002	0.8288
APt-1	-0.2942	0.0000*	0.0121	0.1027	-0.2486	0.0000*	-0.0092	0.0513
ΔElec t-1	-0.3120	0.0000	-0.0135	0.0894	-0.3353	0.0000	0.0047	0.3935
ΔGas t-1	0.1745	0.3726	0.0332	0.4114	X	X	X	X
ΔCoal t-1	X	X	X	X	0.1740	0.5335	-0.0223	0.5826
R2	0.2906		0.0070		0.2842		0.0063	
Durbin-Watson	2.0942		2.0036		2.1241		2.0099	

Note. The error correction model describes how fast the cointegrating variables adjust to the deviations from the long-run equilibrium relationships. The speed of adjustment is given by the coefficient of the error correction term,Ap t-1,in the equations shown below.The Durbin-Watson d-statistic confirmed that the choice of m=n=1 eliminates serial autocorrelation in ε1t and ε2t.

*significant at 0.05 level

$$\Delta ELEC\ t\ = \alpha 0\ +\ \alpha 1\ AP\mathrm{t}-1\ + \sum_{i=1}^{m} \gamma i1\ \Delta\ ELECt - i + \sum_{j=1}^{n} \delta j1\ \Delta GAS\ t - j +\ \varepsilon 1t$$

$$\Delta GAS\ t\ =\ b0\ +\ b1\ AP\mathrm{t}-1\ + \sum_{i=1}^{m} \gamma i2\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j2\ \Delta GAS\ t - j +\ \varepsilon 2t$$

$$\Delta ELEC\ t\ =\ \alpha 0\ +\ \alpha 1\ AP\mathrm{t}-1\ + \sum_{i=1}^{m} \gamma i1\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j1\ \Delta COAL\ t - j +\ \varepsilon 1t$$

$$\Delta COAL\ t\ =\ b0\ +\ b1\ AP\mathrm{t}-1\ + \sum_{i=1}^{m} \gamma i2\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j2\ \Delta COAL\ t - j +\ \varepsilon 2t$$

Table 24
Cointegration Tests
Between Germany and the Netherlands (natural logarithms)

Ap series	*Coefficient of lagged value of AP, α1*	*t statistic*
Base-base	-0.8662	-11.3110*
Peak-peak	-0.8044	-10.8670*
Off peak- off peak	-0.9594	-12.0993*

Note. The Augmented Engle–Granger (1979) test is used to determine whether two time series are cointegrated. The test is performed by fitting the following regression where APt is the residual from equation (1) ELECt = α + β1 * GASt or (2) ELECt = α + β1 * COALt . Lagged values of the dependent variable are included to eliminate autocorrelation.

$$\Delta APt\ =\ \alpha 0\ +\ \alpha 1\ AP\mathrm{t}-1\ + \sum_{j=2}^{4} \alpha j\ \Delta APt - (j-1) +\ vt$$

The null hypothesis that the series are *not* cointegrated is rejected at the 0.05 and 0.01 levels if the t-statistic is less than - 3.34 and -4.32, respectively.

* significant at 0.01 level
** significant at 0.05 level

Table 25
Inter Country
Error correction models (natural logarithms)

	Dependent variable German base		*Dependent variable Dutch base*		*Dependent variable German peak*		*Dependent variable Dutch peak*		*Dependent variable German off-peak*		*Dependent variable Dutch off-peak*	
	coefficient	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*
Intercept	-0.0020	0.7611	-0.0016	0.7642	-0.0025	0.7477	-0.0018	0.7822	-0.0014	0.8258	-0.0013	0.7765
AP t-1	-1.0672	0.0000*	-0.1464	0.0813	-1.0584	0.0000*	-0.1743	0.0856	-0.8963	0.0000*	0.0610	0.3278
ΔG_Elec t-1	0.0286	0.7013	0.0731	0.2238	0.0469	0.5782	0.0994	0.1747	0.0006	0.9915	0.0399	0.3660
ΔNL_Elec t-1	-0.4154	0.0000*	-0.4797	0.0000	-0.5255	0.0000*	-0.5642	0.0000	-0.2218	0.0035*	-0.3383	0.0000
R2	0.2983		0.1667		0.2957		0.2154		0.2820		0.0998	
Durbin-Watson	2.1059		2.1763		2.1881		2.2319		2.0377		2.1454	

Note. The error correction model describes how fast the cointegrating variables adjust to the deviations from the long-run equilibrium relationships.The speed of adjustment is given by the coefficient of the error correction term,Ap t-1,in the equations shown below.The Durbin-Watson d-statistic confirmed the choice of m=n=1 eliminates serial autocorrelation in ε1t and ε2t.

*significant at 0.05 level

$$\Delta G\_Elect \ = \alpha 0 \ + \ \alpha 1 \ AP\mathrm{t} - 1 \ + \sum_{i=1}^{m} \gamma i1 \ \Delta \ G\_Elect - i + \sum_{j=1}^{n} \delta j1 \ \Delta NL\_Elec \ t - j + \ \varepsilon 1t$$

$$\Delta NL\_Elect \ = b0 \ + \ b1 \ AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i2 \ \Delta \ G\_Elect - i + \sum_{j=1}^{n} \delta j2 \ \Delta NL\_Elec \ t - j + \ \varepsilon 2t$$

Table 26

Results of Unit Root Tests

Germany before and after the close of Nuclear plants (natural logarithms)

Series	***Coefficient of lagged value of series, δ_1***	***t-statistic***	***Coefficient of lagged value of series, δ_1***	***t-statistic***
	Before the closing		*After the closing*	
ELECTRICITY:				
Base				
prices:	0.001	0.328	-0.001	-0.296
1st difference of prices	-2.751	-10.005*	-3.053	-10.893*
Peak				
prices:	0.001	0.202	-0.000	-0.125
1st difference of prices	-2.881	-10.181*	-3.424	-12.028*
Off-Peak				
prices:	0.001	0.372	-0.001	-0.489
1st difference of prices	-2.117	-11.561*	-2.562	-9.480*

Note. The Augmented Dickey-Fuller (1979) unit root test is performed by implementing the following regression to the series, Yt, with lagged values of the dependent variable included to eliminate autocorrelation.

$$\Delta Yt = \delta 0 + \delta 1\, Yt-1 + \sum_{i=2}^{4} \delta i\, \Delta Yt-(i-1) + ut$$

The null hypothesis that a series is non stationary is rejected at the 0.05 and 0.01 levels if the t-statistic is less than -2.86 and -3.43, respectively. When a series is non-stationary, the original time series prices will be differenced onceand the test will be repeated again. This process is repeated enough times to arrive at stationary series.

* significant at 0.01 level.

Table 27

Cointegration Test

Germany before and after the close of Nuclear plants (natural logarithms)

AP-Series	*Coefficient of lagged value of AP, α_1*	*t statistic*	*Coefficient of lagged value of AP, α_1*	*t statistic*
	Before		*After*	
Base-coal	-0.5332	-4.3919*	-0.3898	-3.3103
Peak-coal	-0.6698	-4.8743*	-0.5749	-3.9665**
Off peak-coal	-0.3762	-3.8323**	-0.2951	-3.0630
Base-gas	-0.6014	-4.5521*	-0.4026	-3.3037
Peak-gas	-0.7814	-5.1877*	-0.5676	-3.9775**
Off peak-gas	-0.3758	-3.7225**	-0.2955	-3.0341

Note. The Augmented Engle–Granger (1979) test is used to determine whether two time series are cointegrated. The test is performed by fitting the following regression where APt is the residual from equation 1 $ELECt = \alpha + \beta 1 * GASt$.

$$\Delta APt = \alpha 0 + \alpha 1\, APt-1 + \sum_{j=2}^{4} \alpha j\, \Delta APt-(j-1) + vt$$

The null hypothesis that the series are *not* cointegrated is rejected at the 0.05 and 0.01 levels if the t-statistic is less than -3.34 and -4.32, respectively.

* significant at 0.01 level

** significant at 0.05 level

Table 28

Error correction models

Germany coal prices before the close of Nuclear plants (natural logarithms)

	Dependent variable Base		*Dependent variable Coal*		*Dependent variable Peak*		*Dependent variable Coal*		*Dependent variable Off-peak*		*Dependent variable Coal*	
	coefficient	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*
Intercept	0.0038	0.7646	0.0018	0.1486	0.0024	0.8456	0.0018	0.1432	0.0052	0.7293	0.0018	0.1541
AP t-1	-0.5741	0.0000*	0.0197	0.0418*	-0.0105	0.0000*	0.0005	0.0275*	-0.6936	0.0000*	0.0155	0.0786
ΔElec t-1	-0.1690	0.0454	-0.0212	0.0106*	-0.1433	0.0987	-0.0217	0.0116*	-0.1497	0.0749	-0.0161	0.0208*
ΔCoal t-1	-0.2092	0.8048	0.1513	0.0683	0.0905	0.9142	0.1442	0.0816	-0.5720	0.5708	0.1534	0.0661
R2	0.3645		0.0714		0.2397		0.0750		0.4226		0.0613	
Durbin-Watson	2.0072		2.1107		2.0245		2.0733		2.0177		2.1004	

Note. The error correction model describes how fast the cointegrating variables adjust to the deviations from the long-run equilibrium relationships.The speed of adjustment is given by the coefficient of the error correction term,Ap t-1,in the equations shown below.The Durbin-Watson d-statistic confirmed the choice of m=n=1 eliminates serial autocorrelation in ε1t and ε2t.

*significant at 0.05 level

$$\Delta ELEC\ t = \alpha 0 + \alpha 1\ AP\mathrm{t}-1 + \sum_{i=1}^{m} \gamma i1\ \Delta\ ELECt - i + \sum_{j=1}^{n} \delta j1\ \Delta COAL\ t-j + \varepsilon 1t$$

$$\Delta COAL\ t = b0 + b1\ AP\mathrm{t}-1 + \sum_{i=1}^{m} \gamma i2\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j2\ \Delta COAL\ t-j + \varepsilon 2t$$

Table 29

Error correction models

Germany gas prices before the close of Nuclear plants (natural logarithms)

	Dependent variable Base		*Dependent variable Gas*		*Dependent variable Peak*		*Dependent variable Gas*		*Dependent variable Off-peak*		*Dependent variable Gas*	
	coefficient	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*
Intercept	0.0048	0.7009	0.0049	0.0441	0.0053	0.6665	0.0049	0.0417	0.0046	0.7545	0.0049	0.0441
AP t-1	-0.6526	0.0000*	0.0119	0.5182	-0.0108	0.0000*	0.0007	0.0887	-0.7966	0.0000*	0.0119	0.5182
ΔElec t-1	-0.1348	0.1128	-0.0003	0.9826	-0.1530	0.0797	-0.0007	0.9666	-0.0978	0.2473	-0.0003	0.9826
ΔGas t-1	-0.3972	0.3716	-0.0296	0.7340	-0.6516	0.1432	-0.0270	0.7536	-0.2286	0.6646	-0.0296	0.7340
R2	0.3891		0.0068		0.2558		0.0291		0.4487		0.0068	
Durbin-Watson	2.0043		1.9909		2.0433		1.9847		1.9982		1.9909	

Note. The error correction model describes how fast the cointegrating variables adjust to the deviations from the long-run equilibrium relationships.The speed of adjustment is given by the coefficient of the error correction term,Ap t-1,in the equations shown below.The Durbin-Watson d-statistic confirmed the choice of m=n=1 eliminates serial autocorrelation in ε1t and ε2t.

*significant at 0.05 level

$$\Delta ELEC\ t = \alpha 0 + \alpha 1\ AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i1\ \Delta\ ELECt - i + \sum_{j=1}^{n} \delta j1\ \Delta GAS\ t - j + \varepsilon 1t$$

$$\Delta GAS\ t = b0 + b1\ AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i2\ \Delta ELEC\ t - i + \sum_{j=1}^{n} \delta j2\ \Delta GAS\ t - j + \varepsilon 2t$$

Table 30
Error correction models
Germany after the close of Nuclear plants (natural logarithms)

	Dependent variable Peak		*Dependent variable Coal*		*Dependent variable Peak*		*Dependent variable Gas*	
	coefficient	*P value*	*coefficient*	*P value*	*coefficient*	*P value*	*coefficient*	*P value*
Intercept	-0.0005	0.9595	-0.0010	0.2296	0.0008	0.9416	-0.0003	0.8117
AP t-1	-0.8004	0.0000	-0.0147	0.0839	-0.7968	0.0000	-0.0309	0.0354
ΔElec t-1	0.0122	0.8880	0.0085	0.2073	0.0091	0.9181	0.0001	0.9922
ΔCoal t-1	-1.6141	0.1397	0.0809	0.3387	X	X	X	X
ΔGas t-1	X	X	X	X	-0.4044	0.5254	0.1110	0.1844
R2	0.4076		0.0291		0.3932		0.0667	
Durbin-Watson	1.9718		2.0122		1.9892		1.9775	

Note. The error correction model describes how fast the cointegrating variables adjust to the deviations from the long-run equilibrium relationships.The speed of adjustment is given by the coefficient of the error correction term,Ap t-1, in the equations shown below. The Durbin-Watson d-statistic confirmed that the choice of m=n=1 eliminates serial autocorrelation in ε1t and ε2t.

*significant at 0.05 level

$$\Delta ELEC\,t = \alpha 0 + \alpha 1\, AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i1\, \Delta\, ELECt - i + \sum_{j=1}^{n} \delta j1\, \Delta COAL\, t - j + \varepsilon 1t$$

$$\Delta COAL\, t = b0 + b1\, AP\mathrm{t} - 1 + \sum_{i=1}^{m} \gamma i2\, \Delta ELEC\, t - i + \sum_{j=1}^{n} \delta j2\, \Delta COAL\, t - j + \varepsilon 2t$$