University of St. Gallen (HSG)

Master's Thesis

Cointegration in Spot Price Energy Markets

An Analysis Using the Kalman Filter

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Abstract

The liberalization process in European electricity markets was initiated in the 1990s and has been led by the United Kingdom and the Scandinavian countries. One of the key assumptions of liberalization theory is that the opening-up of national markets would break up existing monopolistic price setting power, increase the efficiency of the markets, and let prices converge. This thesis investigates whether the three electricity markets of Switzerland, Austria, and Germany are integrated and converge towards one single price. Based on a cointegration analysis and an application of the Kalman filter, three exchange-traded spot prices are investigated. The data set on hand contains hourly spot prices from 1 January 2007 until 31 July 2009. In this thesis, robust results for a cointegration relationship between the German and the Austrian spot price over the entire observation period are found. Moreover, some evidence is found that the two prices are cointegrated with the Swiss electricity spot price whereas the respective results prove to be very sensitive. However, by decoupling the price series it can be shown that during the summer half year, all three prices are strongly cointegrated and the Law of One Price applies. These results are robust.

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Abbreviations

ADF test	Augmented Dickey Fuller test
AIC	Akaike Information Criterion
APG	Austrian Power Grid
BFE	Swiss Federal Office of Energy
DF test	Dickey Fuller test
ECM	Error correction model
EEX	European Energy Exchange
EnBW	Energie Baden-Württemberg
EU	European Union
EXAA	Energy Exchange Austria
HPP	hydroelectric power plant
IfnE	Ingenieurbüro für neue Energien
LR	Likelihood ratio
OLS	Ordinary Least Square
p.	page(s)
PWC	PriceWaterhouceCoopers
TIRAG	Tiroler Regelzone AG
VKW	Vorarlberger Kraftwerke AG

1. Introduction

Since the liberalization process in European electricity markets was initiated by the Scandinavian countries and the United Kingdom at the end of the 1990s, these markets have become a focus of national and international politics. Furthermore, they have gradually begun to catch the attention of researchers from different academic disciplines. Today a broad range of studies which investigate the progress as well as the implications of electricity markets' liberalization is available. While especially Germany but also Austria were among the early movers, Switzerland was one of the latest countries in Europe to enter the liberalization process of electricity markets. Hence, the electricity price for the Swiss market area was also the latest to be traded on an energy exchange at the end of 2006.

One of the key assumptions of liberalization theory is that the opening-up of national markets would break up existing monopolistic price setting power, increase the efficiency of the markets, and let prices converge. The objective of this thesis is to investigate whether the three electricity markets of Switzerland, Austria, and Germany are integrated and converge towards one single price. If the latter is the case, the Law of One Price applies (de Vany and Walls 1993). The analysis in this thesis will follow a comprehensive approach and consider a static as well as a dynamic dimension complementarily. With regard to the static dimension, the relationships between the three prices will be tested applying findings from cointegration theory. In a further step, including a dynamic dimension, a time-varying Beta-coefficient will be estimated in order to further assess the strength of these relationships and in order to evaluate how they evolve over time. For that purpose, a filter which was introduced by Rudolf E. Kalman (1960) will be applied.

The data set on hand contains the series of three exchange traded spot prices, namely the spot price for the German/Austrian market area traded on the European Energy Exchange (EEX) in Leipzig, Germany, the spot price for the German/Austrian market area traded on the Austrian Energy Exchange (EXAA) in Vienna, Austria, and the spot price for the Swiss market area traded on the German EEX as well. The observation period is between 1 January 2007 and 31 July 2009.

Technical characteristics make electricity spot prices a challenging object for econometric analyses. For instance, time series of electricity prices exhibit extensive seasonality which is due to different facts. Firstly, the demand for electricity for example is very seasonal as well. Moreover, electricity belongs to the few types of commodities that are practically not storable (there are some exceptions). Beside the seasonality, high variances make electricity spot price series challenging for many conventional econometric models. This thesis tries to account especially for the first fact, the seasonality of the prices, in different regards.

The thesis will be structured as follows. To start, in **chapter 2,** the three markets Germany, Austria, and Switzerland will be described with regard to their respective way of implementing the liberalization of the electricity business and their role in the international electricity market. Furthermore, the two market places where the three prices considered are traded will be explained. Subsequently, in **chapter 3**, the data set composed of the hourly series of the three electricity prices at interest will be discussed with an emphasis on the different types of seasonality that are inherent in electricity spot prices. Applying two well-known cointegration concepts in **chapter 4**, namely the two-step approach of Engle and Granger (1987) and the cointegration methodology introduced by Johansen (1988), shall give a first evidence of the strength of the relationships between the tree prices. Due to the extensive intraday seasonality in the price series, not only daily average prices but also single hourly prices will be analysed when applying the procedure of Engle and Granger. In **chapter 5**, the estimation of an error correction model will shed light on whether the found cointegration relation(s) can be confirmed according to the Granger Representation Theorem. For the dynamic part of the analysis, the time-varying Beta-coefficients of all price combinations will be estimated in **chapter 6** using a discrete Kalman filter. Subsequently, the series will be decomposed into a summer and a winter part in order to gain more insight into the role of the seasonal component which is inherent in the prices. As a conclusion and in order to provide an overview of all the results, these are summed up and some economic interpretation will be provided in **chapter 7**.

2. Electricity Markets in Germany, Austria, and Switzerland

2.1. Liberalizing Electricity Markets

Typically, a liberalization process in the electricity market can be divided into three stages, as explained by Stender (2008). In a first step, any hurdles that impede the entrance of potential participants into the market are abolished. This opens the different parts of the industry's value chain such as production, trade, and distribution to new companies. As there may be room for competition discrimination, in a second step, integrated power companies are forced by law to unbundle their value chain to a level that allows fair competition. In a third step, the enhanced transparency resulting from the previous two actions enables an increase in cost reduction potential in areas of the electricity business which are natural monopolies. The changes in the power grid business are an example showing this development (p. 19-20).

Among the countries mentioned in this thesis, Germany has got the most liberalized electricity market, Austria is slightly behind with it and Switzerland's electricity market holds the most prominent backlog. Subsequently, the liberalization processes of these tree countries will be discussed in detail.

2.1.1. Germany

The liberalization of electricity markets within the European Union was initiated by the enacting of the EU directive (Directive 96/92/EC) in December 1996. In 1998 the New German Energy Law (Energiewirtschaftsgesetz EnWG) was established. This was a judicial framework that transformed the European directive into national law and induced the liberalization of energy markets in Germany. The principal aim of the new law was to reduce the amount of special provisions which had been applied for the conduction-bound power industry to a minimum. Since then, the supply side of the German electricity market has undergone a structural transformation process characterized by mergers, cooperation and strategic partnerships. The most intense concentration took place at the very beginning of the liberalization process when eight former power supply firms merged to four large companies (RWE, E.ON, Vattenfall, and EnBW). Overall, these four new market participants were in possession of more than 80 percent of the domestic production capacities after merger (Krisp 2008, p.153-155).

As the European Union considered the energy markets' liberalization progressions to be too slowly, it enacted a so-called accelerating directive in 2003 (Directive 2003/54/EC) which was transformed into

German national law in 2005. Among other things, the new act required that vertically integrated companies with more than 100.000 clients had to operationally and legally demerge their areas of production, mains operation, and distribution (Konstantin 2006, p. 70).

There are currently four German power transmission grids operated by four companies. The Vattenfall power grid covers more or less the area of the former German Democratic Republic, the E.ON power grid is located in the horizontal centre of the country and reaches from the very north to the very south, the RWE power grid stretches across the states Nordrhein-Westfalen, Hessen, Rheinland Pfalz, Saarland, and parts of Bavaria, and the EnBW power grid exclusively covers the state Baden-Württemberg (see Figure 1). However, some changes are still to come in the near future. In early 2009, E.ON voluntarily agreed to sell its stake of the German power grid system in order to settle a dispute with the EU authorities which was risen due to antitrust law concerns.

Figure 1. Power Transmission Grids in Germany

Note: The German transmission system is divided into four areas which are operated by the four companies E.ON, RWE, Vattenfall, and EnBW.

Referring to the framework described above, the today's German electricity market can be seen between the second and the third step of the liberalization process, together with Italy and France. In early 2009, an incentive based regulation was introduced by the German state (Stender 2008, p. 21). However, despite all efforts to liberalize, the situation of competition in the German electricity market is still said to be heavily unsatisfying by the public as well as by experts[1]. Many of these experts

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[1] See Erdmann (2009) or Melzer (2007).

criticize that the market participants on the supply side abuse their market power. This, they say, became possible because the concentration of electricity production capacities was in the hands of very few companies. Furthermore, they state that the utility industry benefited from extensive profits but nevertheless failed to ensure sufficient investments into transmission and production capacities (Erdmann 2009, p. 11).

Table 1 depicts the cross-border activities of the German electricity industry between 1999 and 2008. The statistics indicate that since 2003 the export balance has always been positive. This means there has been sold more electricity abroad every year than there has been bought in from neighbouring countries. Having a look at the country breakdown of the year 2008, we learn that the main export partners of Germany are the Netherlands, followed by Austria and Switzerland, the two other markets considered in the thesis on hand. Switzerland and Austria have both always been major partners concerning Germany's electricity exports.

Table 1. Imports and Exports of Electricity in Germany

in GWH

Calendar Years 1999-2008

	exports	imports	**net exports**
1999	39'448	40'510	**-1'062**
2000	42'877	45'031	**-2'154**
2001	43'741	46'465	**-2'724**
2002	44'463	51'091	**-6'628**
2003	53'267	48'203	**5'064**
2004	50'808	48'186	**2'622**
2005	61'427	56'862	**4'565**
2006	65'441	48'467	**16'974**
2007	62'508	45'953	**16'555**
2008	61'770	41'670	**20'100**

Calendar Year 2008 - Country Breakdown

	exports	imports	**net exports**
France	867	10'572	**-9'705**
Belg.&Lux.	4'148	0	**4'148**
Netherlands	18'858	828	**18'030**
Denmark	1'413	9'211	**-7'798**
Switzerland	13'989	3'476	**10'513**
Austria	15'055	7'012	**8'043**
Poland	5'576	95	**5'481**
Others	1'864	10'476	**-8'612**
Total	61'770	41'670	**20'100**

Note: Import and export figures of Germany between 1999 and 2008 in GWH (Source: Federal Statistical Office Germany, 2009, found on 20 September 2009, on http://www.destatis.de). Import and export figures published by the statistical offices may partially contain estimated values. Hence, discrepancies between the different statistics shown can exist for the three countries.

2.1.2. Austria

In answer to the EU directive from December 1996, Austria devised a new electricity law that came into effect in February 1999 and which can be considered as the initiation of the liberalization process of the country's electricity market. This law can be seen as responsible for the transformation of the directive of the European Union into national law. However, at this time it was not meant yet to liberalize the Austrian market entirely by this law. A complete liberalization was implemented when a supplement of the before stated electricity law was put into force in October 2001. The reason why this supplement has been enacted was a widely spread dissatisfaction with the stepwise opening-up of the electricity market. Small and medium sized companies felt discriminated compared to large-sized firms and wanted to profit from the liberalization as well. Since October 2001, end consumers in Austria have the right to freely choose their electricity supplier (E-Control 2002, p. 15). Overall, Austria is little behind Germany in the liberalization process, but still clearly ahead of Switzerland.

The import and export activities between 2002 and 2008 are illustrated in Table 2. Austria has always been a country which imports more electricity than it exports. Its main trading partners have always been Germany and the Czech Republic on the import side and Germany and Switzerland traditionally on the export side. While total export figures have been rather stable over the past years, imports have been growing.

Table 2. Imports and Exports of Electricity in Austria

in GWH

Calendar Years 1999-2008

	exports	imports	**net exports**
2002	14'676	15'375	**-699**
2003	13'389	19'002	**-5'613**
2004	13'548	16'629	**-3'080**
2005	17'732	20'397	**-2'665**
2006	14'407	21'257	**-6'850**
2007	15'511	22'131	**-6'620**
2008	14'933	19'796	**-4'862**

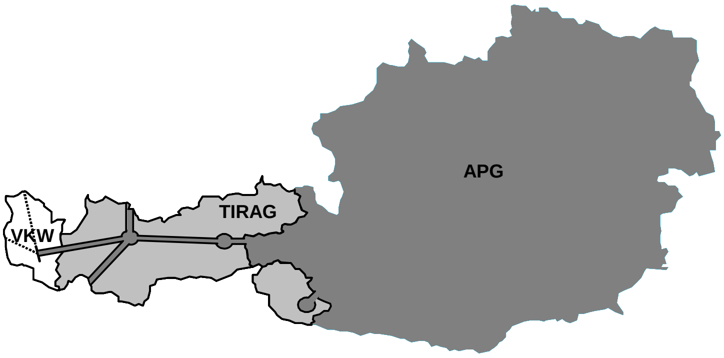
Calendar Year 2008 - Country Breakdown

	exports	imports	**net exports**
Germany	3'804	12'757	**-8'953**
Switzerland	7'447	106	**7'341**
Liechtenstein	204	0	**204**
Italy	1'360	2	**1'358**
Slowenia	1214	874	**340**
Hungary	847	722	**125**
Czech Rep.	56	5335	**-5'279**
Total	14'932	19'796	**-4'864**

Note: Import and export figures of Austria between 2002 and 2008 in GWH (Source: E-Control, 2009, found on 20 September 2009, on http://www.e-control.at).

In Austria there is one main transmission grid, namely the VERBUND Austrian Power Grid (APG) which covers most of the country. Besides, there are two smaller players in the western part of the country, the Tiroler Regelzone AG (TIRAG) and the Vorarlberger Kraftwerke AG (VKW) (see Figure 2). The Austrian power grids are all subject to the regulation authority E-Control (VERBUND APG, 2008, p. 14).

Figure 2. Power Transmission Grids in Austria



Note: The Austrian transmission system is divided into three areas which are operated by the three companies VERBUND APG, TIRAG, and VKW (Source: VERBUND APG, 2006).

2.1.3. Switzerland

According to the Swiss Federal Department of Foreign Affairs (2009), the quantity of electricity that crosses the country's borders corresponds to the domestic consumption quantity. Among others, this fact makes Switzerland an important actor in the international trade of electricity in Europe. Until recently, the Swiss electricity market was exclusively guided by the primacy of public services whose only duty it was to supply all domestic consumers with electricity. The historical strength of public services in Swiss politics and the distinct monopolistic structures of the respective markets are one reason why the Swiss electricity market was among the latest to be liberalized in all Europe. In 2002, when it was due for approval, the Swiss public voted against a liberalization of the Swiss electricity market. However, only one year later the federal court opened the Swiss electricity market forming a judicial standpoint by granting a "case by case carriage" of power through the different national transmission grids (Association of Swiss electricity companies VSE[2], 2009). Despite this conviction which was based on the Swiss antitrust law, an according legislation to make an implementation possible was still lacking and hence a remake of the liberalization law had to be launched. Finally, after some handling time, in March 2007, the Swiss parliament voted in favour of the new Swiss Electricity Supply Law (Stromversorgungsgesetz StromVG) which came into force as of 15 July 2007 and which paved the way to a liberalized Swiss electricity market. This law constitutes a national judicial basis for a possible agreement with the European Union and contains the following main points: In a first step large clients (i.e. clients with a volume of at least 100 MWH per year) and all 900

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[2] German name: Verband Schweizerischer Elektrizitätsunternehmen

distributors may freely choose their electricity supplier as of 1 January 2009. In a second step, as of 1 January 2010, there shall be a free choice of electricity supplier for all end consumers as well. Furthermore, a general initiative to use renewable energies and an impulse to use electricity more efficiently shall be fostered (Federal Department of Foreign Affairs, 2009).

In line with the law, all regional power grids are consolidated and operated by an independent single company, namely Swissgrid. Swissgrid began to run its business in December 2006 and operates the entire Swiss high-voltage network with a total length of 6.000 kilometres (Swissgrid, 2006).

According to Stender (2008), Switzerland is currently about to implement the first two steps of the liberalization process, which is opening the market for new firms and unbundling the value chain of the electricity business. So far, an incentive based regulation is not planned. However, in order to maintain the attractiveness of the Swiss business location, it can be assumed that sooner or later this will become an issue (p. 22).

Table 3. Imports and Exports of Electricity in Switzerland

in GWH

Calendar Years 1999-2008

	exports	imports	**net exports**
1999	47'293	37'064	**10'229**
2000	46'990	39'920	**7'070**
2001	68'407	57'963	**10'444**
2002	51'620	47'112	**4'508**
2003	45'464	42'352	**3'112**
2004	38'393	37'690	**703**
2005	40'734	47'084	**-6'350**
2006	46'085	48'788	**-2'703**
2007	50'630	48'568	**2'062**
2008	51'408	50'273	**1'135**

Calendar Year 2008 - Country Breakdown

	exports	imports	**net exports**
Germany	14'919	14'292	**627**
France	11'830	30'546	**-18'716**
Italy	23'330	3'099	**20'231**
Austria	964	2'287	**-1'323**
Others	365	49	**316**
Total	51'408	50'273	**1'135**

Note: Import and export figures of Switzerland between 1999 and 2008 in GWH (Source: Swiss Federal Office of Energy, 2009).

Especially due to its high production capacities from hydroelectric power plants (HPP)[3] Switzerland typically exports power on a calendar year basis (see Table 3). With the exception of the years 2005 and 2006, for the last 20 calendar years, Switzerland has always registered a net export balance. However, during the year, the import and export balances are subject to strong seasonal patterns. During the winter months the production capacity of HPPs is constrained as many mountain lakes are frozen and hence the export balance uses to be negative (Swiss Federal Office of Energy 2009,

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[3] According to the Swiss Federal Office of Energy (2009), the hydroelectric power represents 56.1% of the whole electricity production in Switzerland (p. 3).

p. 34). The statistics show that there is a very intense trade of power with Switzerland's neighbouring countries. Table 3 illustrates the exports and imports to and from the four main trading partners of Switzerland, namely Germany, France, Italy, and Austria. Almost half of the exports go to Italy, a situation that has been stable for years. This results from the fact that, over the last few years, Italy has always had production capacities that were fairly below the domestic demand for electricity. Having a look at the statistics of the last years, in contrast to Italy, the net exports to France, Germany, and Austria proved to be negative by the majority[4]. An analysis of the wholesale electricity prices indicate that in the past, Switzerland has mostly benefited from the international electricity trade with its neighbours. For example, prices for electrical power in Italy have usually been much higher than in the other exporting neighbouring countries due to the drastic shortage in domestic electricity supply. Moreover, Swiss hydroelectric power can easily be exported during peak hours when prices are higher.

2.2. Market Venues

2.2.1. European Energy Exchange (EEX)

Two of the three prices investigated in this thesis, namely the price for the Austrian/German market area, PHELIX, and the price for the Swiss market area, SWISSIX, are traded on the European Energy Exchange (EEX) which is domiciled in Leipzig (Germany). The EEX in Leipzig resulted from the merger of the LPX (Leipzig Power Exchange) and the EEX Frankfurt at the beginning of 2001. The Swiss electricity price index SWISSIX was first traded on 11 December 2006 and already after one and a half year, 20 Swiss institutional electricity traders were registered (IfnE 2007, p. 16).

Figure 3 depicts the weekly traded volumes on the EEX for the two market areas Germany/Austria (with data from 1 January 2003 until 31 July 2009) and Switzerland (with data from 1 January 2007 until 31 July 2009). The chart shows a tremendous increase in trading volume of spot contracts for both market areas over the last years. Note that the scale in the graph is logarithmic. Today the weekly traded volume of spot contracts on the EEX is 2.3 million MWH for the German/Austrian and 163.000 MWH for the Swiss market area, respectively. According to PWC (2007) the EEX is the most

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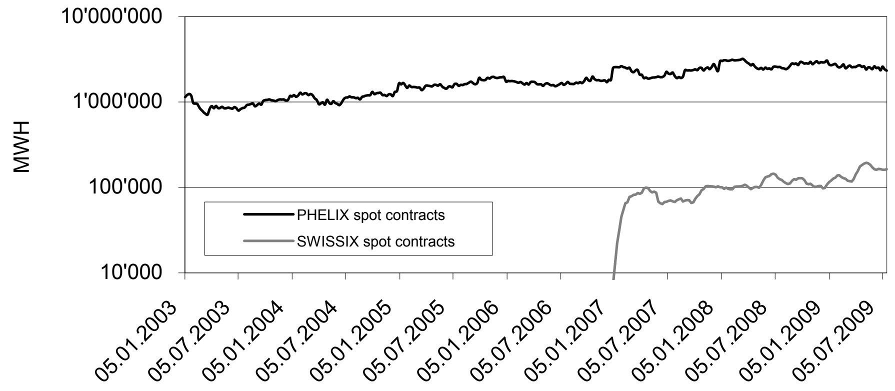
[4] For details refer to the Swiss electricity statistics which are published on a yearly basis and which can be found on the webpage of the Swiss Federal Office of Energy (http://www.bfe.admin.ch/themen/00526/00541/00542/00630/index.html?lang=de&dossier_id=00765).

liquid exchange market for electricity traders in Central Europe, followed by the EXAA, the energy exchange in Austria, described in the subsequent paragraph (p. 6).

There are two main contract types traded on the EEX, namely block contracts and hourly contracts. Hourly contracts refer to a certain quantity of power that is delivered at a certain hour of a certain day. The second type of contract offered on the EEX is the block contract. Such contracts refer to a defined time window during which electricity is traded. Block contracts can roughly be divided into base load contracts being relevant to time windows with rather low prices and peak load contracts applying to times of the day when consumption and thus prices are rather high. Prices for block contracts will not be of interest in this thesis.

Figure 3. PHELIX and SWISSIX Trading Volumes



Note: Trading volumes of spot contracts for the German/Austrian and the Swiss Market Area. Block contracts are included. (Source: EEX, 2009, found on 6 September 2009, on http://www.eex.com.)

The EEX offers two types of pricing modes, an auction trading system and a continuous trading system, whereas not both modes are applicable to the same type of contract. Hourly contracts are exclusively traded in an auction system. The EEX distinguishes between three ways of how bids for hourly contracts can be made. In a price-dependent hourly bid, participants from the demand side as well as from the supply side (power plant operators) make price bids for certain quantities of power for an hour of the subsequent day. Buy bids are labelled with positive numbers and sell bids are marked with negative numbers. In a price-independent hourly bid, price bids are made without referring to certain quantities. The third type is hourly bids for physical fulfilment of futures contracts. This mode allows market participants to combine the financial settlement of a futures position with the physical settlement of a spot market transaction (EEX 2007, p. 16-25).

Generally, after the submission deadline for bids has expired, the supply and demand bids are brought together by the exchange and through an auction procedure the hourly prices of the following day are computed (EEX 2007, p. 25). During the weekend and on public holidays, the exchange is closed. Hence, on the last trading day before the weekend of the public holiday, not only the contracts for the next day are negotiated but also the contracts for the first day after the weekend or the public holiday, respectively (p. 8).

In contrast to hourly contracts, block contracts are not traded exclusively in an auction mode on the EEX but also in a continuous one. In a continuous trading market, different bids are matched immediately and participants do not have to wait until the prices are determined. Prices for block contracts will not be considered in the thesis at hand. When the trading for the Swiss market area was initiated, only hourly contracts were available. Today also block contracts are offered for SWISSIX products. In addition to spot contracts, also futures contracts are traded on the EEX. However, as futures prices will not be considered in this thesis, these contract types are not described in this paragraph.

Beside the German grids RWE Transportnetz Strom, EON Netz, Vattenfall Europe Transmission, and EnBW Transportnetz (see Figure 1), also the VERBUND Austrian Power Grid and the national power grid of Switzerland, namely the Swissgrid, may distribute electricity based on contracts that are negotiated on the EEX (EEX 2007, p. 16).

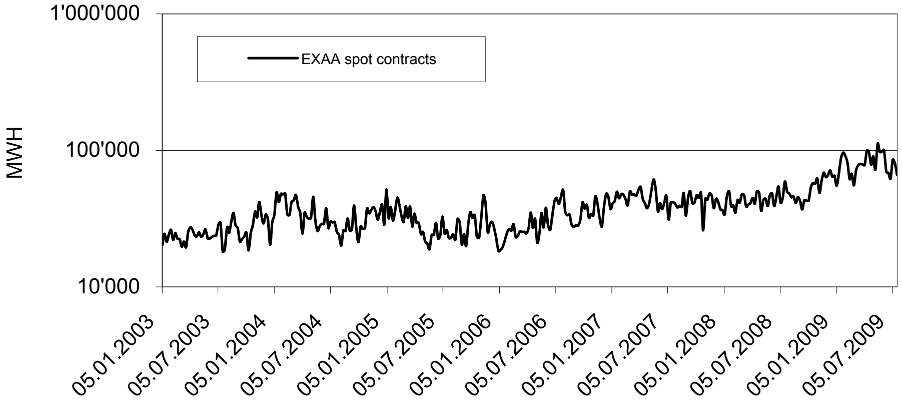
2.2.2. Energy Exchange Austria (EXAA)

The EXAA in Vienna is the Austrian energy exchange and was founded on 8 June 2001. On 21 March 2002, spot contracts were traded for the first time. In 2004, the trading area was expanded to the German control area of E.ON and in 2005 the control area of RWE was added. As stated by EXAA (2009) the group plans to expand its business to Central and South Eastern Europe in the medium term. In January 2009, 63 companies from 14 countries participated in energy trading on the EXAA, whereas most of the foreign companies were of German origin.

Figure 4 depicts the development of the weekly traded volume of hourly spot contracts over the last 6½ years (with data from 1 January 2003 until 31 July 2009) which shows a clear uptrend over time. While at the beginning of 2003, the weekly traded volume of spot contracts used to be between 20.000 and 25.000 MWH, the traded volume today amounts to three to four times as much. However, the volumes on the EXAA market are still well below the volumes on the European Energy Exchange (EEX) in Leipzig.

On theEXAA, spot electricity contracts can be traded for every single hour of the day through an auction mechanism. In addition to hourly contracts, also block contracts such as the bEXAlunch, the bEXAmoon or the bEXAoffice can be traded. Similarly to the EEX, all spot contracts with delivery date on Saturdays and on Sundays are traded on Fridays as well.

Figure 4. EXAA Trading Volume



Note: Trading volumes for the German/Austrian market area. Block contracts are not included herein (Source: EXAA, 2009, found on 6 September 2009, on http://www.exaa.at)

The products traded on the EXAA can be delivered at all distribution points of the Austrian grids VERBUND APG, TIRAG, and VKW as well as at all distribution points of the German transmission grids operated by RWE and E.ON. Contracts traded on the EXAA cannot be delivered at any distribution points of the Vattenfall, the EnBW or the Swissgrid transmission grids.

3. Data Set

In this chapter the data set used in the analyses of this thesis is described. The term “PHELIX” stands for the spot price for the German/Austrian market area traded on the EEX, “EXAA” for the spot price for the German/Austrian market area traded on the EXAA, and “SWISSIX” stands for the spot price for the Swiss market area traded on the EEX. Furthermore, the terms "German price", "Austrian Price", and "Swiss price" will be used when referring to the PHELIX, the EXAA, and the SWISSIX price, respectively.

3.1. Descriptive Statistics

For all analyses in this thesis hourly spot prices or daily average spot prices („day-ahead“) from Monday, 1 January 2007 to Friday, 31 July 2009 will be used. Hence, the term “prices” in this thesis constantly refers to spot prices.

All data studied herein can be downloaded from http://www.exaa.at (for EXAA prices) and http://www.eex.com (for PHELIX and SWISSIX prices). The SWISSIX has the shortest price history with no price information available before 16 December 2006 and limits the period of observation to 19 months, namely the time between Monday, 1 January 2007 and Friday, 31 July 2009. After sorting out all weekend prices (find reasoning below in paragraph 3.2), there is a dataset of 24 hourly time series available for the three prices with 675 observations each. As all prices are in EUR, no currency conversion is required.

Table 4. Descriptive Statistics of Daily Average Prices

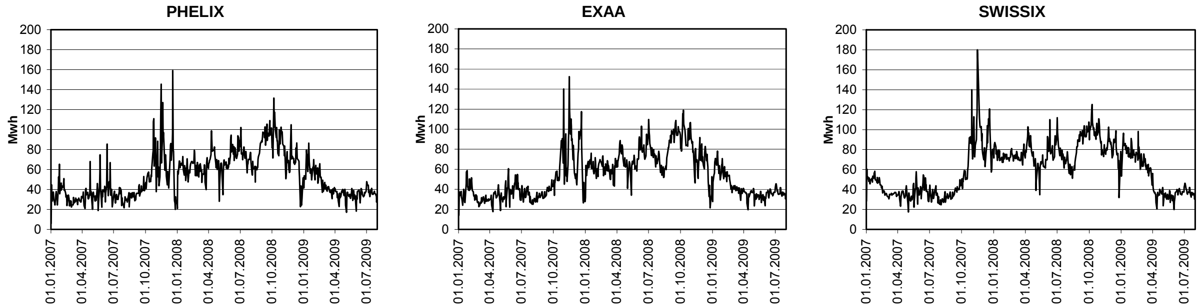
	PHELIX	EXAA	SWISSIX
Mean	53.86	54.42	61.49
Median	49.31	49.65	62.94
Maximum	158.97	152.38	179.90
Minimum	5.80	14.00	17.54
Standard Deviation	22.63	22.72	24.89
Skewness	0.79	0.76	0.55
Kurtosis	3.46	3.05	3.29

Table 4 depicts the descriptive statistics for the daily average prices, computed according to

$$P_{daily\ average} = \frac{1}{24} \sum_{i=Hour\ 1}^{Hour\ 24} P_i \ . \qquad (3.1)$$

The means of the German (EUR 53.86) and the Austrian (EUR 54.42) price series are rather equal whereas the mean of the Swiss electricity spot price (EUR 61.49) is 14% or 13% higher, respectively. Beside the mean and the median price, the standard deviation is higher for the Swiss market as well. The maximum and minimum prices and particularly the standard deviations for the three prices give a first indication of the vast short-run price movements one faces in electricity spot markets. All three prices are positively skewed and exhibit a kurtosis that is slightly larger than the kurtosis of a normal distribution. For a graphical illustration, the three average price series are plotted in Figure 5.

Figure 5. Daily Average Price Series



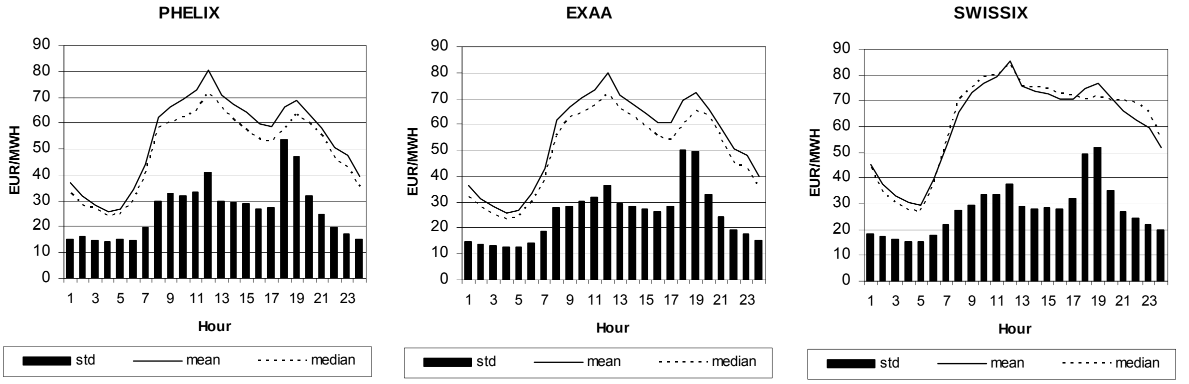
In the subsequent paragraph, hourly price series are investigated in order to detect the characteristic price patterns and different types of seasonality of electricity spot prices. The appendix can be consulted for corresponding tables with hourly descriptive statistics (see page 61).

3.2. Seasonality

The multitude of seasonal patterns makes the behaviour of electricity prices one of the most complicated among all commodities (Blöchlinger 2008, p. 7). Additionally, power prices are subject to characteristic changes throughout the day. This is shown in Figure 6 where the mean and the median prices as well as the standard deviations (denoted by “std” in the graphs) for all hours over the entire observation period are plotted. Prices are higher during peak hours when the demand for electricity increases and lower during hours when less power is required, especially at night. In the existing data set, the maximum mean price at noon (hour 12) for PHELIX (EXAA, SWISSIX) amounts to EUR 80.19 (79.69, 85.65) whereas the maximum mean price at the evening peak (hour 19) is EUR 68.80 (72.29, 76.87). These price levels are significantly higher than the lowest mean prices of EUR 25.79 (25.92, 30.29) which can be observed at hour 4 for all three prices. Beside the prices, also the variances and standard deviations display cyclical patterns. The observed prices’ standard deviations at a certain hour are represented by bars in Figure 6. Similar to the prices, the standard deviations are higher during peak hours. Moreover, they are significantly higher during the evening peak than during the noon peak. The highest standard deviation for PHELIX (EXAA, SWISSIX) is at hour 18 (18, 19) and amounts to EUR 53.63 (50.29, 52.04). The lowest values can be observed at hour 4 (4, 5) and amount to EUR 14.32 (12.48, 15.07).

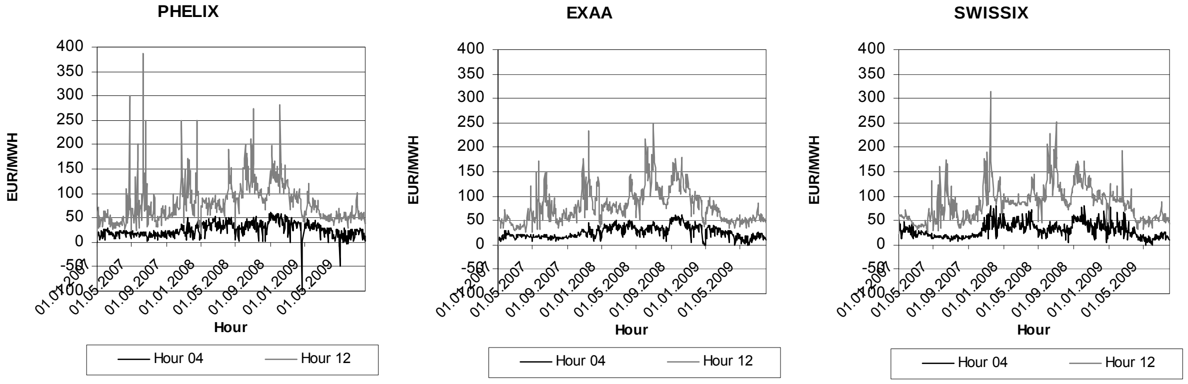
In Figure 7 the plotted prices for hours 4 (black line) and 12 (grey line) over the entire observation period additionally depict the typical time variance of prices and their unsteadiness for different hours of the day. While the spot prices for hour 4, a time frame when demand on the market is understandably low, have low volatilities and generally are on a lower level, the spot prices at hour 12, one of the peak hours, are higher and show greater variability.

Figure 6. Intraday Seasonality (I)



Note: Mean and median prices (EUR/MWH) and standard deviations (denoted as std) for all hours of the day.

Figure 7. Intraday Seasonality (II)



Note: Prices (EUR/MWH) for the hours 4 (black line) and 12 (grey line) over the entire observation period.

Table 5 contains the mean spot prices for each day of the week. Obviously, electricity spot prices are significantly lower during the weekend than during working days. This fact might be ascribed to the electricity demand from industrial customer which is much lower on Saturdays and Sundays. In order to dispose of the seasonal influences caused by weekend prices, all Saturday and Sunday spot prices are dropped from the data set.

Table 5. Means of Daily Average Prices for Different Days

Mean	Mon	Tue	Wed	Thu	Fri	Sat	Sun
PHELIX	52.20	55.41	55.90	55.16	50.61	41.47	32.34
EXAA	52.61	56.71	55.75	55.10	51.92	41.52	32.45
SWISSIX	60.06	63.38	62.25	62.07	59.67	52.61	43.59

Distinctive differences in price patterns do not only exist throughout the day or the week but also between different seasons. In winter for instance, one can observe two price peaks during the day – one around noon and one around 7 in the evening – whereas in summer there is no specific evening peak. This fact is an explication why, in Figure 6, the evening peaks of the daily average series are slightly lower than the noon peaks.

4. Cointegration Tests

In this chapter it will be tested how many cointegration relations exist among the three electricity spot prices. Firstly, a theoretical part will introduce the terms “stationarity”, “unit root” and “spurious regression” which form a fundamental starting point for the concept of cointegration. Secondly, a selection of former studies referring to cointegration in electricity markets will be presented. Thirdly, two different cointegration techniques will be described and applied, namely the two-step approach by Engle and Granger (1987) and the Johansen approach (1988) which is based on an error correction model.

4.1. Theoretical Framework

In order to perform analyses and testing procedures in econometrics, one often requires time series to be stationary, meaning that their variables have a constant distribution over time. As for instance shown by Kirchgässner and Wolters (2008, p. 13-14), the definition of stationarity can be divided into three parts:

(i) *Mean Stationarity:* A process is mean stationary if $E[x_t] = \mu_t = \mu$ is constant over time.

(ii) *Variance Stationarity:* A process is variance stationary if $V[x_t] = E[(x_t - \mu_t)^2] = \sigma^2$ is constant and finite over time.

(iii) *Covariance Stationarity:* A process is covariance stationary if $Cov[x_t, x_s] = E[(x_t - \mu_t)(x_s - \mu_s)] = \gamma(|s - t|)$ is only a function of the distance between two variables and does not depend on the point of time itself.

A process is said to be weakly stationary if (i) to (iii) is provided. A much narrower definition of stationarity (i.e. strict stationarity) would be satisfied if the covariance of a process was not only constant for a certain distance in time but also for any point in time. However, in the majority of cases one requires processes only to be weakly stationary. Furthermore, given a process is weakly stationary and normally distributed, all requirements for stationarity in the strict sense are satisfied (Harvey 1981, p. 23). The term “stationary” in this thesis is constantly referring to the weak form of stationarity.

If a non-stationary process gets stationary after taking first differences, it is referred as to be integrated of order 1, i.e. $I(1)$. Processes which exhibit stationarity before any transformation are denoted as $I(0)$, namely processes of order zero.

One of the best known types of non-stationary processes are so-called unit root processes. As the term already implies, these types of time series have a unit root, meaning that 1 is a solution for the characteristic equation of the process. As done by Verbeek (2008, p. 280-281) the unit root characteristic can be shown by introducing the most simple form of a unit root process which is an AR(1) process

$$y_t = \theta y_{t-1} + \varepsilon_t \tag{4.1}$$

with $\theta = 1$ and $\varepsilon_t \sim N(0, \sigma^2)$. If taking variances on both sides of equation (4.1), one receives

$$V\{y_t\} = V\{y_{t-1}\} + \sigma^2 \tag{4.2}$$

for which no finite solution, as required by the definition of variance stationarity, exists – except for the case where the variance equals zero. The characteristic equation of (4.1) is given by

$$(1 - \theta L)y_t = \varepsilon_t \tag{4.3}$$

with L denoting the lag operator[5]. Since $E[\varepsilon_t] = 0$, 1 is a solution for equation (4.3), this process is referred to as a random walk.

Non-stationary processes are attempted to be avoided in an econometric working environment as, unlike stationary processes, they do not fluctuate around a constant level and have a tendency for their spread to vastly change over time (Harvey 1981, p. 3). For most econometric estimations and testing procedures, stationarity of time series is an important assumption. One of the most problematic issues with respect to non-stationary series is that the OLS method is unable to deliver a consistent estimator. In the case of non-stationary time series, covariances are ill-defined as the original processes do not fluctuate around a constant mean over time. This problematic is often

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[5] For a detailed introduction into the construction of characteristic equations of AR, MA, and ARMA processes refer to Verbeek (2008, p. 278-279).

illustrated by introducing an example in which two independently generated random walks (non-stationary processes) are regressed against each other leading to a high R-squared so that one could easily think that causality exists between the two variables. The reason why the OLS estimator finds a significant relationship is that the error terms of the estimated regression are non-stationary. This phenomenon of a mistakenly assumed relationship is referred to as spurious regression (Verbeek 2008, p. 327). However, Engle and Granger (1987) show that there exists an exception to the spurious regression case. They point out that the situation can exist where two time series X_t and Y_t, which are both $I(d)$ and thus non-stationary by definition if $d > 0$, can be unified in a linear combination

$$z_t = X_t - \beta Y_t \tag{4.4}$$

such that z_t is $I(d-1)$ (p. 251-276). The most common case is where $d=1$ and the linear combination of the two variables leads to a stationary relationship. If so, X and Y are said to be cointegrated and they share a common trend. This means that even though short-term deviations may exist, the variables are in a long-term equilibrium and never infinitely disperse. If equation (4.4) is estimated by means of an OLS regression, the OLS estimator will be super consistent for β in the case of a cointegrating relationship, meaning that it converges to β at a much faster rate than in a conventional linear relationship. In the cointegration regression equation (4.4) β is called the cointegrating parameter (Verbeek 2008, p. 327-329).

In situations where economic theory suggests two variables to be related in the long-run, a cointegrating relationship can often be observed. This may be the case particularly for macro economic variables such as GDP, income or exchange rates.

4.2. Cointegration Studies in Electricity Markets

Market integration has often been investigated by applying cointegration theory. With regard to electricity markets, a handful of examples can be mentioned. Six electricity markets in the Western United States have been investigated by Mjelde, Bessler and Jerko (2002) in order to assess the number of cointegration vectors. Their results show that the markets tend to indicate five cointegration vectors after taking into account the variability in temperature between the different geographical regions. These findings confirm the results of earlier analyses performed by de Vany and Walls (1999) who found that the electricity markets of the Western United States show evidence of efficiency seven years after the beginning of the deregulation. Their analyses are based on the estimation of an error correction model (see chapter 5). For many European markets, researchers have come to similar conclusions. Bower (2002) for instance analysed electricity markets of 15 members of the European Union for market integration. He concluded that all markets seem to be well-integrated delivering significant results with the exception of Spain which, according to him, might be caused by the country's geographical location and its limited possibilities for cross-border transmission of electricity. Bower found the German electricity market to be especially well cointegrated with Sweden, Finland, and Denmark, but rather weakly with Norway which, according to him, is also in this case caused by the geographical location of the latter. In order to investigate if European electricity markets develop towards a single price, Robinson (2007) performed a convergence analysis for nine countries by using several methods and findings from cointegration theory. He used a rather long data set containing observations from 1978 to 2003 and found that for most countries a price convergence has occurred. Overall, it can be stated that in the majority of the studies, liberalized electricity markets are found to be quite well cointegrated if taking geographical differences (i.e. most of all temperatures and geographical location) into account. Beside electricity markets, also prices for other energy commodities have been investigated for market integration through a cointegration approach[6].

4.3. The Two-Step Approach of Engle and Granger

4.3.1. Methodology

There are several approaches that allow investigating if two (or more) variables are cointegrated. Engle and Granger (1987) have introduced a methodology which can be applied to investigate if there exists a cointegration relation between two variables X_t and Y_t. The procedure contains the following two steps. Firstly, a regression equation

$$Y_t = \beta X_t + \varepsilon_t \tag{4.5}$$

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[6] For example, see Seletis (1994) who performed a cointegration analysis on petroleum futures prices or Leykam (2008) who applied the cointegration method on European natural gas spot markets.

is estimated (a constant can be included). Based on the assumption that there is a strong relationship between the two variables, equation (4.5), in the long-run, should apply for a certain value for the vector β. As stated before, the concept of cointegration allows for short-run deviations from the long-term equilibrium and thus, the regression equation may not hold if observed over only a short time period. The two variables are cointegrated if the error term in equation (4.5) is stationary. To ascertain if this is the case, a stationarity test[7] is applied to ε_t which constitutes the second step and completes the two-step approach of Engle and Granger (Enders 2004, p. 335-336).

A variety of methods allows investigating if a variable or a relation is stationary or not. Subsequently, the so called Augmented Dickey Fuller (ADF) test will be explained. The ADF test is the most common test for this purpose and applied in this thesis as well. The family of Dickey Fuller (DF) tests is, among others, one group of methods to investigate the stationarity of time series and has been developed by Fuller (1976) as well as by Dickey and Fuller (1979, 1981). The simple DF test assumes that the variable considered follows an autoregressive process

$$Y_t = \theta Y_{t-1} + \varepsilon_t \tag{4.6}$$

where ε_t is a noise with a zero mean and a certain variance σ^2. A constant can be included. If in equation (4.6), θ proves to be equal to 1, then the process has a unit root and, therefore, is non-stationary. In order to test this assumption, the null hypothesis $H_0 : \theta = 1$ has to be tested against the alternative $H_1 : \theta < 1$. The OLS estimator for θ is defined by

$$\hat{\theta} = \frac{\sum_{t=2}^{n} Y_t Y_{t-1}}{\sum_{t=2}^{n} Y_{t-1}^2} \tag{4.7}$$

and the test statistic for the null is

$$\tau = \frac{\hat{\theta} - 1}{se(\hat{\theta})} \tag{4.8}$$

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[7] Stationarity tests within the two-step approach are often referred to as "cointegration tests".

with *se* denoting the standard error of the estimator (Hackl 2005, p. 238). The critical values, however, cannot be taken from a standard t-table. Dickey and Fuller (1979) show that, under the mentioned null hypothesis, the test statistic (4.8) is not t-distributed. Therefore, a table with adapted critical values has to be applied[8]. The reason why the test statistic does not even asymptotically follow a t-distribution is mainly because a non-stationary process heavily distorts the distribution of the OLS estimators. It can especially be imagined the case if the null applies and $\theta = 1$. In this case the variance of Y_t is not defined (Verbeek 2008, p. 283).

As the described test procedure is based on a AR(1)-process, the test results will be distorted if the original time series follows an autoregressive process of higher order. To make the method adequate for processes of higher order, equation (4.6) is extended to

$$Y_t = \theta_1 Y_{t-1} + \theta_2 Y_{t-2} + \theta_3 Y_{t-3} + \theta_4 Y_{t-4} + ... + \theta_p Y_{t-\mathrm{p}} + \varepsilon_t \tag{4.9}$$

with *p* denoting the chosen lag length. Also in equation (4.9), a constant can be allowed for. Verbeek shows that in order to test the null hypothesis in this case, equation (4.9) firstly has to be rewritten as

$$\Delta Y_t = \pi Y_{t-1} + c_1 \Delta Y_{t-1} + c_2 \Delta Y_{t-2} + ... + c_{p-1} \Delta Y_{t-p+1} ... + \varepsilon_t \tag{4.10}$$

where $\pi = \theta_1 + \theta_2 + ... + \theta_p - 1$ and all constants c are chosen adequately. In the ADF test, the hypothesis $H_0 : \pi = 0$ represents the unit root, i.e. the non-stationary case, and is also tested with a corresponding t-ratio (p. 286). The appropriate critical values which have to be applied in the ADF test are slightly different from the ones that can be used within the common DF test framework and have, for example, been provided by MacKinnon (1996). Additionally, they are a standard in most statistical software applications today.

The question about how many lags have to be included in equation (4.9) is a very relevant one. One of the most widely applied methods is the determination of the lags using the Akaike Information Criterion (AIC) which will also be used in this thesis. Akaike (1974) proposed that, based on the respective process, the number of lags is chosen to minimize

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[8] A table with appropriate values has been provided by Fuller (1976, p. 373).

$$AIC = \ln \frac{1}{T} \sum_{t=1}^{T} (\hat{u}_t^{(p)})^2 + m \frac{2}{T} \tag{4.11}$$

with $\hat{u}$ denoting the estimated residuals of the AR(p) process, T denoting the number of observations and m denoting the number of estimated parameters, i.e. lags. The basic idea behind this formula is that the resulting value declines with every additional parameter (lag) and at the same time increases due to a so-called punishment term which constitutes the second summand of the equation. There is a variety of other methods to determine the appropriate number of lags. For example, see Kirchgässner and Wolters (2008, p. 56-67). Whichever approach is applied, Enders (2004) proposes to verify that the residuals do not exhibit autocorrelation (p. 193).

Subsequently, the described methodology is applied to the electricity spot prices PHELIX, EXAA, and SWISSIX. Firstly, all time series (as well as their first differences) are tested for stationarity in order to determine whether the series are integrated of order one. Secondly, the linear regressions are formed and finally, the residuals are tested for stationarity by using the same method as when testing the original series.

4.3.2. Empirical Results of Stationarity Tests

An ADF test is performed for the average price series and then for all hourly price series of the three prices. The number of lags is defined by minimizing the AIC. For most of the time series this method yields between 5 and 25 lags. In the ADF test equation an intercept is allowed for. A time trend is not included as it does not prove to be significant in neither of the test equations. As already mentioned above, the AIC criterion often results in a number of lags which is too low. In order to test for stability, the test is performed a second time with 2 and 5 more lags than indicated by the AIC approach. This kind of stability test was performed by other researchers before as well. For instance, when investigating cointegration of North-American natural gas markets, Serletis (1997) applied a similar technique and added two more lags to the ADF test equations[9]. In the present case, adding 2 or 5 lags does not lead to different results for any of the series. Table 6 depicts the test results for the daily average price series.

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[9] This so-called AIC+2 approach was initially proposed by Pantula, Gonzales-Farias and Fuller (1994).

Table 6. Unit Root Test Results for Daily Average Price Series

		t-Statistic		p-value	lags
PHELIX	*y*	-1.767		0.397	24
	Δy	-6.283	***	0.000	23
EXAA	*y*	-1.880		0.342	25
	Δy	-5.735	***	0.000	24
SWISSIX	*y*	-1.738		0.412	15
	Δy	-8.298	***	0.000	14

*Note: Stationarity test results for the ADF test. Significance of rejection of the null hypothesis of no-cointegration on the 99%, 95% and the 90% confidence level is denoted with ***, **, and * using MacKinnon (1996) critical values (as reported by Eviews).*

In terms of daily average prices, the hypothesis of a unit root cannot be rejected for any of the markets. This is an indicator for the electricity spot prices to be non-stationary. Considering hourly prices (we abstain from presenting the results of the respective 72 tests) the hypothesis of a unit root cannot be rejected on a 99% confidence level for almost all of the price series. However, there are two exceptions: the hour 18 of PHELIX and SWISSIX, for which the hypotheses are rejected on a 95% and on a 90% confidence level, respectively, and the hour 19 of SWISSIX for which the hypothesis can be rejected on a 90% confidence level. On the whole, according to the test results, non-stationary price series are indicated. In a next step, first differences are taken meaning that the first lag is subtracted from the original series. When performing the ADF tests again, the non-stationarity hypothesis can be rejected on a confidence level of 99% for all of the average price series as well as for the hourly series of all three prices. This indicates that the spot price series are integrated of order one and that, hence, an important precondition to apply a cointegration framework is fulfilled.

4.3.3. Empirical Results of Cointegration Tests

To test all price pairs for cointegration, equation (4.5) is translated into

$$P_{i,t} = \alpha_{ij} + \beta_{ij} P_{j,t} + \varepsilon_t \qquad (4.12)$$

meaning that the electricity spot price i is regressed on the electricity spot price j. α_{ij} is the intercept, β_{ij} is the cointegration vector for the two prices and ε_t denotes the error term. Afterwards, an ADF test is performed to test whether the residuals exhibit stationarity. The procedure is applied to all combinations for every hour of the day and in both directions in order to see whether the determination of the endogenous and the exogenous variable leads to a difference in the results.

Before looking at the hourly price series, we first apply the cointegration regression equation (4.12) to the daily average price series. The results are depicted in Table 7. For the German-Austrian relationship, the null hypothesis of a unit-root (and thus non-stationarity) can be rejected for both directions and the results prove to be very stable. Furthermore, there is no evidence for autocorrelation when looking at the error terms. Also for the Swiss-Austrian relationship, the ADF test indicates stationarity of the residuals. However, when looking closely at the residuals, there is still high autocorrelation inherent. Furthermore, if the German-Austrian relationship and the Swiss-Austrian relationship both were stationary, also the German-Swiss relationship would be expected to display stationary residuals. However, the German-Swiss relationship does not prove to be stationary, neither when applying the ADF test nor when looking at the plotted residuals. Figure 8 shows the residuals series, derived from the cointegration equations. It can easily be seen that the residuals for the German-Austrian relationship seem to move more or less equally around zero whereas the residuals of the other two series give evidence for serial autocorrelation. The residuals of the Swiss-Austrian relationship, for instance, seem to have notably different variances over time.

Table 7. Cointegration Test Results for Daily Average Price Series

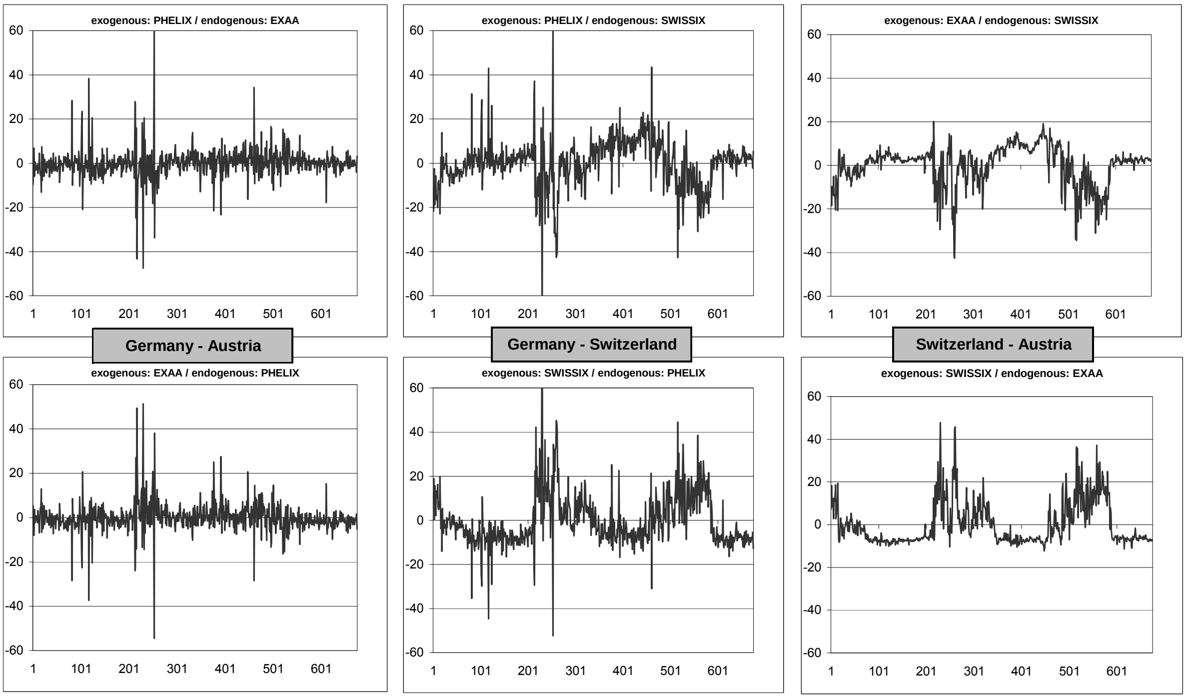
columns: exogenous variable / rows: endogenous variable

	PHELIX		**SWISSIX**		**EXAA**	
	t-Stat.	lags	t-Stat.	lags	t-Stat.	lags
PHELIX			-2.482	23	-4.032 ***	22
SWISSIX	-2.320	23			-3.690 ***	4
EXAA	-3.529 ***	22	-3.633 ***	11		

Note: Results of ADF tests applied to the cointegration relations of the daily average price series. The number of lags were to minimize the AIC. Critical values are applied as proposed by MacKinnon (1996) (as provided by Eviews).

In order to test if the presented findings hold for the hourly prices as well, the method is applied to the hourly series in a next step. The ADF test (cointegration test) t-statistics of the residuals of the different relations are depicted in Table 8. Again, no assumptions with regard to endogeneity or exogeneity of the variables are made yet and therefore, both directions are tested. The results indicate a cointegration relation for a multitude of hours over the day, even for the German-Swiss relation which was not found to be cointegrated when looking at the average price series. However, again, only the results for the German-Austrian price pairs are satisfactorily robust. When verifying the residuals of the other two price pairs for a check, as proposed by Enders (2004, p. 193), there is strong evidence for autocorrelation.

Figure 8. Residuals of Cointegration Equations



Note: Residuals of cointegration equations of daily average prices PHELIX (denoted "Germany"), EXAA (denoted "Austria"), and SWISSIX (denoted "Switzerland").

Table 8. Cointegration Test Results for Hourly Price Series

Endogenous Variable	Exogenous Variable	Hour 1	Hour 2	Hour 3	Hour 4	Hour 5	Hour 6	Hour 7	Hour 8	Hour 9	Hour 10	Hour 11	Hour 12
PHELIX	EXAA	-16.054	-26.465	-26.082	-26.359	-26.822	-3.161	-28.181	-4.059	-4.783	-13.981	-4.612	-5.316
EXAA	PHELIX	-5.065	-4.881	-5.666	-5.718	-5.265	-3.519	-4.325	-3.549	-2.008	-4.045	-2.726	-2.351
PHELIX	SWISSIX	-2.909	-6.226	-6.511	-4.867	-2.693	-3.044	-2.245	-3.112	-2.597	-3.079	-3.079	-3.459
SWISSIX	PHELIX	-1.984	-3.295	-4.734	-3.308	-3.573	-3.166	-1.975	-1.824	-1.797	-2.837	-2.934	-3.146
EXAA	SWISSIX	-2.519	-4.350	-4.877	-5.055	-6.071	-4.190	-2.929	-3.022	-3.557	-5.710	-2.688	-2.759
SWISSIX	EXAA	-2.168	-2.464	-4.794	-2.581	-5.751	-3.113	-2.369	-2.254	-3.172	-3.248	-2.766	-3.027

Endogenous Variable	Exogenous Variable	Hour 13	Hour 14	Hour 15	Hour 16	Hour 17	Hour 18	Hour 19	Hour 20	Hour 21	Hour 22	Hour 23	Hour 24
PHELIX	EXAA	-3.926	-5.394	-5.061	-13.026	-3.507	-3.029	-2.299	-3.435	-4.395	-5.848	-8.706	-7.509
EXAA	PHELIX	-2.755	-3.196	-2.684	-3.735	-3.081	-2.885	-3.449	-3.324	-3.755	-5.017	-4.727	-6.713
PHELIX	SWISSIX	-3.563	-4.041	-2.566	-2.278	-2.610	-3.247	-3.594	-3.145	-2.268	-3.636	-2.186	-2.276
SWISSIX	PHELIX	-3.077	-2.752	-2.182	-2.609	-2.574	-2.996	-3.120	-2.829	-1.927	-2.800	-1.902	-2.114
EXAA	SWISSIX	-5.100	-4.717	-2.475	-4.655	-2.924	-4.002	-4.875	-3.143	-2.389	-2.070	-3.881	-2.225
SWISSIX	EXAA	-4.329	-4.024	-2.550	-3.709	-3.430	-3.781	-4.989	-2.866	-2.067	-2.883	-2.859	-2.837

▓ rejection of H0 at 99% level ▒ rejection of H0 at 95% level ░ rejection of H0 at 90% level

Note: T-statistics of ADF tests applied to the cointegration relations of the hourly price series. The number of lags has been selected to minimize the AIC. The ADF tests have been performed using MacKinnon (1996) critical values (as provided by Eviews).

4.4. The Johansen Cointegration Procedure

4.4.1. Methodology

The approach of Engle and Granger, which is based on an OLS regression, has got several disadvantages. Hargreaves (1994) states the two most important ones. Firstly, when working with economic data there is often a lack of sufficient observations to accurately perform an OLS analysis. Secondly, the OLS estimator can be biased in finite samples. This, because the distribution is non-symmetric (due to the unit root term), and/or because a problem which is known as simultaneity or endogeneity bias can emerge. The latter can be created by the 'long-run' covariation[10] between the error term and the independent (exogenous) variable (p. 88). Another disadvantage of the two-step approach of Engle and Granger is that the method is only suitable for testing bivariate relationships for cointegration. In many cases it would be desirable to be able to test more than only two variables for cointegration.

Due to these disadvantages of Engle's and Granger's method, a second approach which was proposed by Johansen (1988) will be applied in this thesis[11]. This procedure is chosen because it is appropriate for a multivariate framework and thus offers the opportunity to investigate the total number of cointegration relationships existing among the three electricity spot prices simultaneously.

The starting point of Johansen's approach is a vector autoregressive process

$$Y_t = \sum_{j=1}^{p} A_j Y_{t-j} + D_t + U_t \tag{4.13}$$

(system representation) where Y_t is a $n \times 1$ matrix containing the respective prices of all n series (in our case $n = 3$), A_j denotes a $n \times p$ parameter matrix, D represents the deterministic term, U is a white noise process, and p is the order of the autoregressive process. Through the Granger Representation Ttheorem, equation (4.13) can be represented as a vector error correction model

$$\Delta Y_t = -\Pi Y_{t-1} + \sum_{j=1}^{p-1} A_j^* \Delta Y_{t-j} + D_t + U_t \tag{4.14}$$

---

[10] This 'long-run' covariation is defined according to $\sum_{k=0}^{\infty} Cov(x_{t-k}, u_t)$.

[11] Hargreaves (1994, p. 88) lists a number of additional options to the OLS approach of Engle and Granger.

(system representation) with $\Pi = A(1) = I - \sum_{j=1}^{p} A_j$ and $A_j^* = - \sum_{i=j+1}^{p} A_i$ (Kirchgässner and Wolters 2008, p. 219)[12].

The matrix Π in equation (4.14) stands for the long-term relations between the variables of the system. Its rows span the so-called cointegration space that is spanned by the cointegration vectors β which can be derived from the linear stationary combinations given by $\beta' X_t$. Hence, the number of cointegration relations between all variables can be directly derived from the rank r of the matrix Π (Johansen 1988, p. 232).

Three basic cases can be distinguished. Firstly, if $r(\Pi) = 0$, no cointegration vector and thus no linear combination of the different variables exists. Secondly, if $r(\Pi) = n$, the matrix has full rank which makes it invertible. Thirdly, if $0 < r(\Pi) = k < n$, the system contains k linear combinations. If $k = n - 1$, then all variables are pairwise cointegrated (Verbeek 2008, p. 340).

Johansen shows that the rank of the matrix Π can be tested by a so-called trace test. The trace test tests the null hypothesis H_k that the rank of the matrix Π is k against the hypothesis H_n that the rank of the matrix equals n, i.e. the matrix has got full rank. The test is performed with the LR test statistic

$$T_k^{Trace} = -2[\log L_k - \log L_n] = -T \sum_{i=k+1}^{n} \log(1 - \hat{\lambda}_i) \qquad (4.15)$$

starting with $k = 0$ and is repeated until the null hypothesis is rejected for the first time. The stage at which the null is rejected equals the value of the cointegration rank (Hackl 2004, p. 377). Due to the reiterating testing procedure, the final null hypotheses of the test will be that the rank of the matrix is at most k or that there are at most k cointegrating equations, respectively.

In equation (4.15), T is the sample size and $\hat{\lambda}$ are the estimated eigenvalues of the matrix Π. They are estimated using a maximum likelihood procedure. As a result, the test is also named likelihood ratio (LR) test. Similarly to the ADF test, the test statistic does not follow a chi square distribution.

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[12] Find a more detailed explanation on error correction models in chapter 5.

Hence, critical values obtained from simulations have to be utilized (Kirchgässner and Wolters, 2008, p. 223). In this thesis the critical values proposed by MacKinnon, Haug, and Michelis (1999) which are a standard in the econometrics software package Eviews, are applied.

4.4.2. Empirical Results

The multivariate as well as the bivariate procedure proposed by Johansen are applied to the three prices for the daily average series meaning that in the first place, an error correction model is estimated and then a trace test is performed in order to investigate the rank of the respective cointegration matrix. The lag length is selected to minimize the AIC.

Firstly, a cointegration test in the multivariate framework, including all three daily average price series PHELIX, EXAA, and SWISSIX, is performed. If the three prices are cointegrated in pairs, the rank of the cointegration matrix $r(\Pi) = k$ is expected to correspond to $k = 2$. A matrix of full rank, meaning that $r(\Pi) = k = 3$, is not expected as this would imply that the original series are stationary which was rejected by the ADF tests in paragraph 4.3.2. If the matrix proves to have a rank $r(\Pi) = k = 1$, there is one cointegration vector and only one price pair is cointegrated. The results of the multivariate test are depicted in Table 9. The trace test indicates that the rank of the cointegration matrix $r(\Pi)$ is 1 on a 90% confidence level meaning that there is one cointegration relation. The result does not exhibit much sensitivity with regard to the chosen lag length. The resulting lag length when minimizing the AIC is 24 which is rather high. A sensitivity analysis of the AIC for the multivariate as well as for the bivariate tests can be found in the appendix (see p. 62).

Table 9. Johansen Multivariate Cointegration Tests

Hypothesized No. of CE(s)	Eigenvalue	Trace Statistic	p-Value
None	0.025	33.551	0.074
At most 1	0.015	16.778	0.141
At most 2	0.011	7.077	0.122

Note: Unrestricted multivariate cointegration rank test (trace test) for daily average price series as proposed by Johansen (1988) using critical values introduced by MacKinnon, Haug and Michelis (1999). The number of lags was defined according to the AIC method.

The procedure is rerun in a bivariate framework meaning that the three series are tested in pairs. In the bivariate case, according to the test results (see Table 10), only the German-Austrian price pair exhibits a significant cointegration relation on a confidence level of 90%. The p-Value of 0.09 is not very low but the result proves to be very robust when testing it for lag sensitivity and the p-Value even declines slightly in many cases when adding or subtracting a couple of lag lengths. This basically confirms the finding from the multivariate testing procedure that there is one cointegration relation among the three series. The results for the other two pairs are sensitive with regard to the lag length. In the German-Swiss relation for example, adding one more lag results in one significant cointegration vector whereas adding two or three more lags does not change the original results. If the number of lags of originally 15 is reduced by one or two units in the Swiss-Austrian testing framework, the trace test indicates one cointegration vector on a level of 90%. However, if the lag length is expanded by one or more units, the hypothesis of no cointegration relation cannot be rejected. Overall, the selection of the lag length seems to be a critical issue for the Johansen methodology when testing the electricity spot price series.

Overall, it can be stated that, similar to the methodology of Engle and Granger, also the approach proposed by Johansen confirms the existence of one cointegration relation which is between the PHELIX and the EXAA price with very robust results. And again, there is some evidence for the two prices to be cointegrated with the Swiss market price as well but the corresponding results prove to be very unstable with high dependence on the number of lags chosen.

Table 10. Johansen Bivariate Cointegration Tests

Pair: PHELIX/EXAA

Hypothesized No. of CE(s)	Eigenvalue	Trace Statistic	p-Value
None	18.288	20.262	0.091
At most 1	2.873	9.165	0.605

Pair: PHELIX/SWISSIX

Hypothesized No. of CE(s)	Eigenvalue	Trace Statistic	p-Value
None	17.501	20.262	0.115
At most 1	6.486	9.165	0.156

Pair: EXAA/SWISSIX

Hypothesized No. of CE(s)	Eigenvalue	Trace Statistic	p-Value
None	17.461	20.262	0.116
At most 1	4.528	9.165	0.339

Note: Unrestricted bivariate cointegration rank tests (trace tests) for daily average price series as proposed by Johansen (1988) using critical values introduced by MacKinnon, Haug and Michelis (1999). The number of lags was defined according to the AIC method (resulting in between 15 and 24 lags).

5. Error Correction Model

Engle and Granger (1987) stated that if two variables are cointegrated and thus represent a stationary relationship, there exists an error-correction representation of the series relating the change in one variable to past equilibrium errors and to past changes in the two variables (p. 256). Thus, such a representation gives information about how the considered variables behave in the short run. If the above found cointegration relation between PHELIX and EXAA persists, an error correction model (ECM) must exist for the two price series. In the current chapter, this will be verified by estimating and testing an ECM for these two prices.

5.1. Methodology

Representing the ECM of the price series of two cointegrated prices (i.e. the bivariate case), the system denoted by equation (4.14), $\Delta Y_t = -\Pi Y_{t-1} + \sum_{j=1}^{p-1} A_j^{*} \Delta Y_{t-j} + D_t + U_t$, translates into the two equations

$$\begin{aligned}\Delta P_t^{Market\ a} = {} & \textstyle\sum_{i=1}^{p-1} \theta_i^{Market\ a} \Delta P_{t-1}^{Market\ a} + \sum_{i=1}^{p-1} \varphi_i^{Market\ a} \Delta P_{t-1}^{Market\ b} \\ & + \alpha^{Market\ a} (P_{t-1}^{Market\ b} - \beta_2 P_{t-1}^{Market\ a} - \delta) + e_t^{Market\ a}\end{aligned} \tag{5.1a}$$

and

$$\begin{aligned}\Delta P_t^{Market\ b} = {} & \textstyle\sum_{i=1}^{p-1} \theta_i^{Market\ b} \Delta P_{t-1}^{Market\ b} + \sum_{i=1}^{p-1} \varphi_i^{Market\ b} \Delta P_{t-1}^{Market\ a} \\ & + \alpha^{Market\ b} (P_{t-1}^{Market\ b} - \beta_2 P_{t-1}^{Market\ a} - \delta) + e_t^{Market\ b}\end{aligned} \tag{5.1b}$$

where all ΔP_t denote first differences of the price series. The ECM includes a so-called error correction term,

$$\alpha (P_{t-1}^{Market\ b} - \beta_2 P_{t-1}^{Market\ a} - \delta) \tag{5.2}$$

where α can be interpreted as a speed of adjustment parameter. The larger α is, the faster the series will respond to deviations from the long-run equilibrium that is denoted by the second part of the equation (5.2), namely $(P_{t-1}^{Market\ b} - \beta_2 P_{t-1}^{Market\ a} - \delta)$. If α is very small, the response of the series is very hesitant and it will take more time for the prices to become rebalanced. By contrast, the larger α , the faster the system reacts to shocks indicating a strong relationship between the two series. β_2

corresponds to the cointegrating coefficient of the series and δ is a constant according to the constant of the cointegration regression equation, allowing for example for fix transaction and transportation costs. If price series that are integrated of order one are investigated, the left part (i.e. the first difference prices) of the equations must be stationary by definition. Hence, for the equations to be in equilibrium also the right part has to be stationary. As on the right, the first difference prices are stationary and we presume the error terms to be stationary if the two variables are cointegrated, the linear combination that is expressed by the error correction term must be stationary as well (Enders 2004, p. 329).

It is of particular interest whether the speed of adjustment parameters α are significantly different from zero when investigating two related price series. If two variables share a cointegrating relationship, at least one of the parameters α has to be different from zero. In this case, at least one simple (Granger-)causal relation between the two variables exists (Kirchgässner and Wolters 2008, p. 206-207). Moreover, the investigation of the parameter α allows making statements with regard to the exogeneity of the variables. Enders (2004) states that it is possible that one of the speed adjustment parameters cannot be identified as to be significantly different from zero. In this case, prices or markets whose α-parameter is zero, are said to be weakly exogenous, meaning that they do not respond to discrepancies in the long-run price relationship (p. 333-334, p. 368).

5.2. Empirical Results

The error correction model according to the equations (5.1a) and (5.1b) is estimated for the German-Austrian price pair. The number of lags selected by the AIC method amounts to a total of 24 for the German-Austrian relation. Moreover, a constant in the equations is applied. The results are depicted in Table 11. Following the principle of completeness, the results for both directions are reported, although the outcome is exactly the same by definition.

Table 11. Error correction models coefficient significance tests

Cointegration relationship:	*EXAA - βPHELIX*		Cointegration relationship:	*PHELIX - βEXAA*	
	α-coefficient	p-Value		α-coefficient	p-Value
EXAA	-0.410	0.062 *	PHELIX	-0.179	0.517
PHELIX	0.175	0.517	EXAA	0.420	0.062 *

*Note: Likelihood-ratio tests for restrictions on speed adjustment parameters in bivariate error correction models. A *-designated p-value means that the null hypothesis of α=0 can be rejected on a 90% confidence level. The lags were chosen to minimize the AIC. The test-statistics and the critical values follow a chi-squared-distribution.*

In the tests performed, robust results which show that the PHELIX and the EXAA prices are cointegrated are found. As mentioned, if a price pair is cointegrated, at least one of the speed adjustment parameters in equations (5.1a) and (5.1b) has to be different from zero. According to the results in Table 11 this is the case since the null hypothesis that the adjustment parameter of the EXAA series is equal to zero can be rejected on a 90% confidence level. According to the test results, there is no indication that the parameter of the PHELIX series is different from zero. This implies that the PHELIX price is weakly exogenous and only EXAA reacts to discrepancies in the long-run price equilibrium. The significant speed adjustment parameter of EXAA is 0.41 or -0.41, respectively, which is fairly high meaning that the Austrian price reacts quickly if the price relationship is in disequilibrium. Concretely, if in time *t* a disequilibrium of 1 EUR appears, the EXAA will answer correspondingly by 0.41 cents in time *t+1*.

6. The Discrete Kalman Filter

In this paragraph there will be a shift from the static concept of cointegration to a dynamic approach. In order to additionally investigate the relationships between the three electricity spot prices, the time-varying Beta-coefficient of the cointegration regression equation (4.12) will be estimated over the observation period. This approach was for example used by Neumann et al. (2006) to investigate the price relationships of European natural gas markets. For the estimation, a filter will be applied which was proposed by Rudolf E. Kalman (1960) and which is discussed in detail subsequently.

6.1. Methodology

The Kalman filter allows estimating the time-varying state estimator of a linear stochastic system by introducing a set of mathematical equations. The approach applies a recursive procedure and is optimal in the sense of a minimum square linear estimator (Kellerhals 2001, p. 17). Firstly introduced in 1960 by Rudolf E. Kalman, the filter has primarily been used in the field of engineering sciences, for instance in order to track moving objects such as satellites or rockets. Today the Kalman filter approach is also used in many non-engineering applications. There is a number of different types of the Kalman filter. The discussion will be confined to the discrete Kalman filter which is the most straightforward one and which will be used for the analysis. There exists a broad range of possibilities to illustrate the functionality of the Kalman filter. For the subsequent explanation, it is referred to Meinhold and Singpurwalla (1983, p. 123-125) who show in a comprehensible way that Bayes' theorem (1763) from probability theory is directly employed in the approach[13].

6.1.1. Bayesian Formulation

Two linear equations form the centre of the state space form of the Kalman filter approach. The first relates a known quantity F_t to an observed variable Y_t and is called signal, observation, or measurement equation:

$$Y_t = \theta_t F_t + v_t \tag{6.1}$$

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[13] An alternative explanation which also illustrates the functionality of the filter in a comprehensible way is provided by Blöchlinger (2008) or by Harvey (1981). For a more detailed and sophisticated introduction, refer to the original contribution by Kalman (1960).

where θ_t is unobserved and assumed to be governed by another process which is represented by the second characteristic equation, namely the system, state, or transition equation,

$$\theta_t = G_t \theta_{t-1} + w_t , \tag{6.2}$$

where G is a known quantity. Both, the observation error v_t as well as the system equation error w_t, follow a normal probability distribution

$$p(v) \sim N(0,\ V_t) \tag{6.3}$$

$$p(w) \sim N(0,\ W_t) \tag{6.4}$$

in which the means are zero and the variances V_t and W_t may either change or remain constant over time. In addition, also the relationships (6.1) and (6.2) may or may not change over time. Beside the usual linear model assumptions, one also premises independence between v_t and w_t (Welch and Bishop 2006, p. 2). The two differential equations (6.1) and (6.2) represent a most parsimonious form of the state space model. Welch and Bishop (2006) for instance allow for an addition optional control input in equation (6.2). Furthermore, a multivariate representation of the system can be applied.

The estimation of the state of nature θ_t over time can be explained as a direct application of Bayes' theorem

$$Pr\,ob\{Data \mid State\ of\ Nature\} \propto Pr\,ob\{State\ of\ Nature \mid Data\} \tag{6.5}$$

or, alternatively, as

$$P(\theta_t \mid Y_t) \propto P(Y_t \mid \theta_t , Y_{t-1}) \times P(\theta_t \mid Y_{t-1}) . \tag{6.6}$$

In equation (6.6) the part on the right of the proportionality sign denotes the likelihood (first part) and the distribution (second part) for θ before Y_t is observed (i.e. prior distribution) whereas the left part indicates the distribution for θ at time *t* including full information on observation Y_t (i.e. posterior distribution). In his work Bayes (1763) showed that the left and the right part of the depicted equation are proportional to each other. The recursive procedure of the Kalman filter can be divided into two stages as follows.

Stage 1 (prior to observing Y_t). Before Y_t is observed, the estimate for θ_t has to be derived from equation (6.2) and hence is given as $G_t\theta_{t-1} + w_t$ with θ_{t-1} described by the probability statement:

$$(\theta_{t-1} \mid Y_{t-1}) \sim N(\hat{\theta}_{t-1}, \Sigma_{t-1}) \tag{6.7}$$

Since θ_{t-1} is described by equation (6.7), by introducing a common rule of transformation

$$X \sim N(\mu, \Sigma) \Rightarrow CX \sim N(C\mu, C\,\Sigma C')\,, \tag{6.8}$$

the following probability statement

$$(\theta_t \mid Y_{t-1}) \sim N(G_t\hat{\theta}_{t-1}, R_t = G_t\;\Sigma_{t-1}\,G_t' + W_t) \tag{6.9}$$

can be made. It contains the state of knowledge about the state of nature at time *t*.

Stage 2 (after observing Y_t). Before the posterior θ_t can be computed by applying equation (6.6), $P(Y_t \mid \theta_t, Y_{t-1})$ needs to be computed which is equivalent to the likelihood function $\ell(\theta_t \mid Y_t)$. An error term e_t can be introduced now, namely the prediction error, indicating the difference between the observed value of Y in time t and its forecast, given all information available at point $t-1$:

$$e_t = Y_t - \hat{Y}_t = Y_t - F_tG_t\hat{\theta}_{t-1} \tag{6.10}$$

After introducing equation (6.1) and applying Bayes' theorem shown in equation (6.6), one can rewrite equation (6.10) and receives a more accurate description of the state of knowledge about θ_t given all information up to time t:

$$P(\theta_t \mid Y_t, Y_{t-1}) = \frac{P(e_t \mid \theta_t, Y_{t-1}) \times P(\theta_t \mid Y_{t-1})}{\int_{\text{all } \theta_t} P(e_t, \theta_t \mid Y_{t-1})d\theta_t} \tag{6.11}$$

After $P(\theta_t \mid Y_t, Y_{t-1})$ is computed, the filter returns to equation (6.7) replacing information up to $t-1$ by information up to time t and repeats the entire procedure until all information up to $t = n$ has been used.

Meinhold and Singpurwalla (1983) show that there exists a technique which allows to obtain $P(\theta_t \mid Y_t)$ in an easier way. No detailed demonstration will be performed at this point and, for completeness, only final results will be depicted. After introducing some findings from multivariate statistics and making some assumptions that are common practice, it can be shown that the posterior density for θ_t has a mean

$$\hat{\theta}_1 = G_t\hat{\theta}_{t-1} + R_tF_t'(V_t + F_tR_tF_t')^{-1}e_t \tag{6.12}$$

and a variance

$$\Sigma_t = R_t - R_tF_t'(V_t + F_tR_tF_t')^{-1}F_tR_t \tag{6.13}$$

and that in essence, the Kalman filter can be interpreted as an evolution of regression functions of θ_t on e_t. The coefficients as well as the intercepts of these regressions are modified by the iterative filtering process in all the cycles until all information of Y has been used. For a detailed derivation, refer to the respective literature (Meinhold and Singpurwalla 1983, p. 123-125).

Stages 1 and 2 are often characterised as “prediction step” and “updating step”, meaning that in the first part of the algorithm, the filter “predicts” a value for the state of nature and then “updates” it with the additional information available at time *t*. Prior to the first cycle of the filter, initial values have to be assigned to the parameters θ_0, F_1, G_1, V_1, and W_1. In the thesis at hand, this step will be done using a Marquardt algorithm that is standard in the econometrics software Eviews.

6.1.2. Properties and Assumptions

The Kalman filter method is an appealing technique in different aspects. All information will be kept within the model until the last repetition of the algorithm is done and all observations have been used. This feature makes the filter a more adequate method than for instance the rolling regression in which a certain time frame is moved forward and in which, at every stage of the process, the system loses the oldest information. In the Kalman filter framework, all information is transmitted to the next step, mainly through the transition equation (6.2). Another advantage of the application is that the prediction errors, as defined in equation (6.10), are not weighted with a fixed factor. Instead, the weight that is assigned by the so-called Kalman gain[14] changes over time depending on the relative change of the variation of the prediction error to the stochastic part of the measurement equation (6.1) (Boos 1988, p. 46). As an additional advantage, the Kalman filter is able to handle time series not integrated of the same order which is an especially useful property for a wider range of economic relationships (Neumann 2006, p. 727).

In order for the method to yield a minimum mean square linear estimator, some assumptions which mainly refer to linearity and normal distribution are required. Firstly, one has to assume that the two stochastic difference equations, i.e. the measurement equation (6.1) and the transition equation (6.2) are linear. Given the situation that this linearity is not given, there exist advanced concepts which for instance use Taylor series approximations, as shown by Blöchlinger (2008, p. 99). Secondly, the error terms are assumed to be normally distributed. This assumption applies for the error terms of the measurement equation and the transition equation as well as for the prediction errors which represent the difference between the estimation at time *t* before and after Y_t is known.

6.2. Empirical Results

The econometric tests performed so far in this thesis suggest one firm cointegration relationship between the PHELIX price and the EXAA price. At the same time they give partial evidence for the two prices to be also cointegrated with the SWISSIX price whereas the respective results prove to be very unstable and sensitive. In a next step, the Kalman filter is applied to estimate the time-varying Beta-coefficient in the cointegration regression equations of the three price pairs. This shall allow gaining deeper insight about how the price relationships of the electricity markets considered evolve over time and investigating if distinct behaviour patterns can be identified. Within the Kalman filter framework, the measurement equation is defined as

$$P_{i,t} = \alpha_{ij} + \beta_{ij,t} P_{j,t} + \varepsilon_t \tag{6.14}$$

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[14] The Kalman gain is defined as the matrix that minimizes the covariance of the estimate of θ_t , given all information up to Y_t (i.e. posterior estimate). For a detailed definition and derivation refer to Welch and Bishop (2006, p. 3).

where $P_{i,t}$ and $P_{j,t}$ are the two investigated spot prices, α_{ij} is the intercept, $\beta_{ij,t}$ is the time-varying Beta-coefficient, also called the state variable, and ε_t is the error term. The transition equation is defined as

$$\beta_{ij,t} = \beta_{ij,t-1} + \mu_t , \tag{6.15}$$

with μ_t denoting the error term with mean zero and covariance matrix W_t. In combination, equations (6.14) and (6.15) form the state space, i.e. the linear system of the filter. The specification is similar to the one applied by Neumann et al. (2006) meaning that G_t in equation (6.2) is set to unity. The filter will estimate $\beta_{ij,t}$ over time. As stated above, the filter will keep all information when expanding the time window till the end of the observation period. The necessary input parameters for the filter and with them the initial state space model are estimated by Eviews' standard Marquardt algorithm.

So far, no assumption has been made with regard to exogeneity and endogeneity and all results have been similar for either direction. For the analysis in this chapter, in order to prevent an overload of information and illustration, distinct exogenous and endogenous variables for all three price pairs will be determined. The decision which one of the variables is defined to be exogenous or endogenous in equation (6.14), is based on the chronological order of the auctions of the three prices. The first price that is auctioned is the EXAA. Traders have to hand in their buy and sell bids before 10.15 a.m. when all hourly prices for the next day are calculated. Shortly after, the prices are visible to all participants. At 10.30 a.m. the SWISSIX prices are calculated at the EEX in Leipzig and finally, at 12.00 a.m., the PHELIX prices are calculated at the EEX as well. As market participants have full information about the EXAA and SWISSIX day-ahead prices before the submission period for the PHELIX prices closes, the PHELIX price will be defined as the endogenous variable. Due to the short time gap of only several minutes between the communication of the EXAA day-ahead prices and the closing of the submission period for the SWISSIX day-ahead prices, both directions for the Austrian-Swiss relationship will be estimated and illustrated.

The descriptive statistics of the time-variant analysis of the daily average series are summarized in Table 12. All coefficients estimated by the Marquardt algorithm are reported by Eviews to be highly significant with exception of the coefficients for the relation in which the SWISSIX price is defined as the exogenous and the EXAA price as the endogenous variable. Therefore, the respective results are excluded from discussion. The mean of the PHELIX/EXAA Betas of 0.874 is nearest to unity confirming the strong price relationship that has already been detected above. Also the means of the estimated coefficients for the other two relations are rather high but still lower than the means of the German-Austrian price pair. Furthermore, the standard deviation is much lower for the German-Austrian case indicating a smoother behaviour pattern for the time-varying coefficient.

Table 12. Descriptive Statictics of Time-Varying Beta-Coefficients

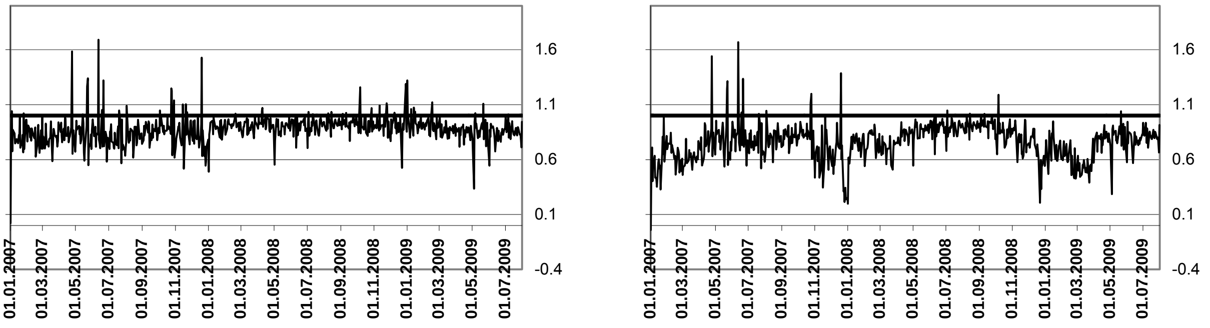
endogenous variable exogenous variable	PHELIX EXAA	PHELIX SWISSIX	SWISSIX EXAA
Mean	0.874	0.759	0.763
Median	0.881	0.785	0.753
Maximum	1.691	1.670	2.263
Minimum	0.020	-0.040	-0.014
Standard Deviation	0.125	0.165	0.268
Observations	675	675	675

Note: Descriptive statistics of Beta-coefficients estimated using the Kalman filter. For the depicted relations, Eviews reports all coefficients to be highly significant.

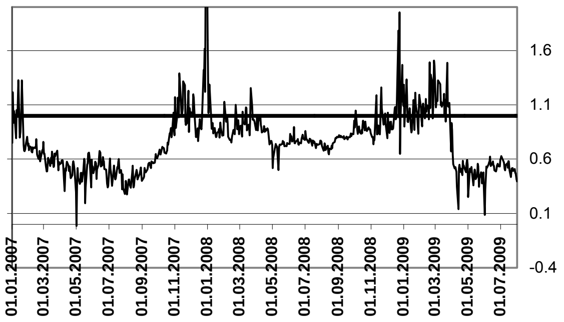
The plotted developments of the state variables in Figure 9 give a more insightful view. Complementary to the above-discussed results, also the estimation of the Beta-coefficients over time gives evidence that the German-Austrian price pair exhibits the strongest price relationship with coefficients moving evenly slightly below unity. Looking at the two other price pairs, a less stable development of the Betas is detected. While it is difficult to identify a clear pattern for the Austrian-Swiss price pair, the Swiss-German relationship seems to exhibit some recurring seasonal patterns. The filtered estimates of the state variable move close to 1 during the summer half year but they diverge as soon as information on the observed prices of the winter half year enters the filter. A comparison between the SWISSIX price on one hand and the PHELIX and the EXAA prices on the other hand shows a significantly positive price difference during the winter months, meaning that the SWISSIX price is clearly higher. From an economic standpoint, a difference in prices as well as in the interaction of the markets is comprehensible. During the summer half year Switzerland can profit from storage capacities caused by hydroelectric power plants (HPPs) and perform extensive arbitrage activities whereas in winter many mountain lakes are frozen, increasing the need for importing electricity. The latter might exert upward pressure on the spot electricity prices.

To sum up the results of the dynamic coefficient analysis, a very strong and stable price relationship between the PHELIX and the EXAA price is confirmed. Additionally, there is evidence of a linkage between the two prices and the SWISSIX price. However, the latter relation seems to be subject to seasonality and is unstable over time. In order to analyse the seasonal discrepancies, the series will be split up and taken under further investigation in the subsequent paragraph.

Figure 9. Time-Varying Beta-Coefficients for Daily Average Prices


endogenous variable: EXAA
endogenous variable: PHELIX

exogenous variable: SWISSIX
endogenous variable: PHELIX


exogenous variable: EXAA
endogenous variable: SWISSIX

6.3. Decomposition of Price Series

As mentioned in the previous paragraph, the results of the Beta-coefficients estimated using the Kalman filter, indicate that not only the prices but also the interaction and the price relationships between the three markets are subject to seasons. Therefore, the three daily average price series will be decomposed into two parts each, namely a summer and a winter part. The summer part of the series contains all observations between 1 May, and 31 October of each year and the winter part includes all observations from 1 November to 30 April. A recomposition of the series results in a summer series consisting of 330 observations and a winter series consisting of 345 observations for each of the spot prices, PHELIX, EXAA, and SWISSIX. The descriptive statistics can be consulted in the appendix (see p. 62). The Kalman filter estimation of the time-varying Beta-coefficients for the summer and winter combinations is rerun separately. For the winter series, the output of the Marquardt algorithm reports no significant coefficients for the Swiss-Austrian relation if defining EXAA as the exogenous variable. Therefore, the respective results will not be presented. The descriptive statistics resulting from the estimation are depicted in Table 13.

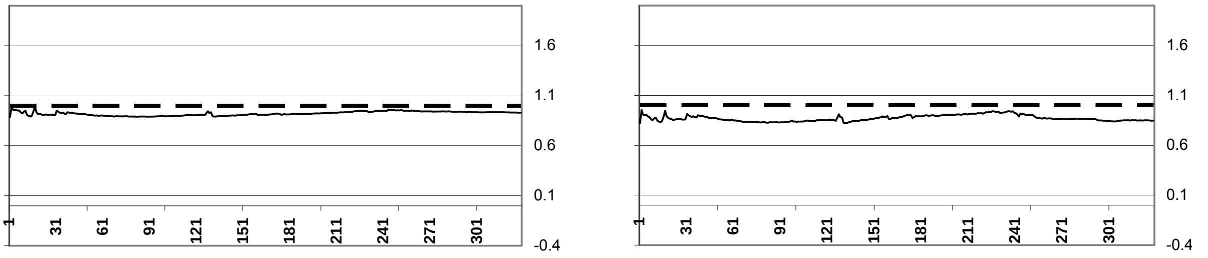
Table 13. Descriptive Statictics of Time-Varying Beta-Coefficients – Summer/Winter Series

	summer series				winter series		
endogenous variable exogenous variable	PHELIX EXAA	PHELIX SWISSIX	SWISSIX EXAA	EXAA SWISSIX	PHELIX EXAA	PHELIX SWISSIX	EXAA SWISSIX
Mean	0.922	0.871	0.965	0.982	0.902	0.670	0.714
Median	0.921	0.863	0.963	0.988	0.907	0.690	0.736
Maximum	0.995	0.952	1.232	1.097	1.436	1.333	0.969
Minimum	0.888	0.822	0.827	0.786	0.117	-0.077	0.281
Standard Deviation	0.020	0.030	0.046	0.035	0.090	0.150	0.135
Observations	330	330	330	330	345	345	345

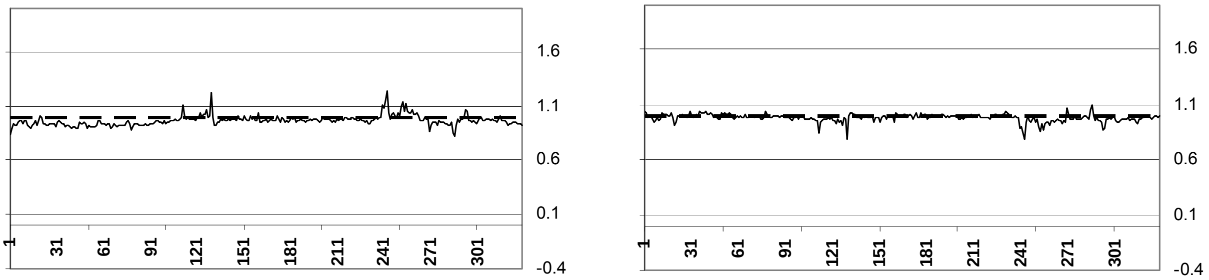
Note: Descriptive statistics of Beta-coefficients for the summer and winter price series estimated using the Kalman filter. For the depicted relations, Eviews reports all coefficients to be highly significant.

As assumed before, it can be identified that the price relationships including the Swiss price are different during the winter from the one in the summer half year. During the summer half year all means are between 0.871 and 0.982 with the Austrian-Swiss relationship exhibiting the mean that is closest to unity. At the same time, the standard deviations of the time-varying coefficients are significantly lower than for the full-year series, ranging from 0.020 (PHELIX/EXAA) to 0.046 (SWISSIX/EXAA). The statistics show that the mean of the filtered estimates of the Beta-coefficient of the German-Austrian relationship in wintertime is not vastly different from the one derived from the summer series. Hence, the price relationship for this pair seems to remain stable during the entire year. In contrast, this is not the case for the price pairs including the SWISSIX price. During the winter half year the relationships between the SWISSIX and the two other spot prices look different than during the summer half year. The significantly lower means of the Betas of 0.670 (German-Swiss relationship) and 0.714 (Austrian-Swiss relationship) indicate that their relationships are less firm during the winter half year. The standard deviations are clearly higher for the winter half year indicating more volatile estimated coefficients. The findings from the descriptive statistics are confirmed by the illustrations in Figure 10 and Figure 11. In Figure 10, the development of the Betas of all price pairs behave very smoothly and close to unity, implying that the Law of One Price holds (Neumann et al. 2006, p. 729). Contrarily, when looking at the filtered estimates of the winter half year in Figure 11, only the German-Austrian price relationship proves to have a stable and strong relationship. The price pairs including the SWISSIX price exhibit time-varying Betas which ever and anon move away from unity implying much weaker price relationships.

Figure 10. Time-Varying Beta-Coefficients for Daily Average Prices - Summer

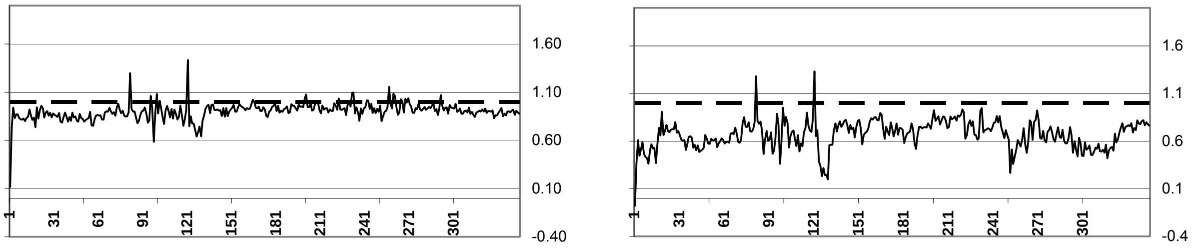

endogenous variable: EXAA
endogenous variable: PHELIX

exogenous variable: SWISSIX
endogenous variable: PHELIX

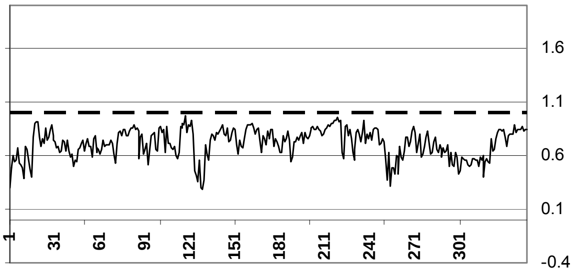

exogenous variable: EXAA
endogenous variable: SWISSIX

exogenous variable: SWISSIX
endogenous variable: EXAA

Figure 11. Time-Varying Beta-Coefficients for Daily Average Prices - Winter


endogenous variable: EXAA
endogenous variable: PHELIX

exogenous variable: SWISSIX
endogenous variable: PHELIX


exogenous variable: SWISSIX
endogenous variable: EXAA

The observed behaviour of the price relationships during different seasons of the year raises the question if there is also a difference in the cointegration relations of the three price pairs when investigating different seasons separately. To analyse this, a cointegration test (trace test) is being performed according to the Johansen procedure (as described and applied in paragraph 4.4). The multivariate framework is applied testing all price pairs simultaneously. Again, the lag lengths are chosen to minimize the AIC. The results of the AIC analysis are documented in the appendix (see p. 64). For the summer series, a lag length of 4 results, which is clearly less than the 24 lags we faced for the full-year series. Investigating the winter series, a value for the AIC is received which is more or less equal for a lag length of 10 and a lag length of 24. Preferring a more parsimonious model, a lag length of 10 is chosen. The results of the trace tests are depicted in Table 14. For the summer series, the rank of the cointegration matrix estimated by the two tests is two on a confidence level of 99% implying that all three prices are cointegrated pairwise during the summer half year. Adding several lags does not change the results meaning that the test output is robust. Running the trace test for the winter series indicates that the cointegration matrix has a rank of two as well. However, the test results prove to be very sensitive. Choosing one, two or three more lags, the test indicates only one cointegration relationship.

To sum up, testing the cointegration matrices of the decomposed price series implies that all three prices are well integrated during the summer half year. For the winter half year, there is also evidence that more than one cointegration vector exists. However, the respective results are not robust.

Table 14. Johansen Multivariate Cointegration Tests – Summer/Winter Series

SUMMER SERIES				*WINTER SERIES*			
Trace-Test:				*Trace-Test:*			
Hypothesized No. of CE(s)	Eigenvalue	Trace Statistic	p-Value	Hypothesized No. of CE(s)	Eigenvalue	Trace Statistic	p-Value
None	0.261	127.850	0.000	None	0.066	43.216	0.006
At most 1	0.077	29.844	0.002	At most 1	0.039	20.236	0.050
At most 2	0.012	3.801	0.443	At most 2	0.021	6.958	0.129

Note: Unrestricted multivariate cointegration rank tests for daily average summer and winter price series as proposed by Johansen (1988) using critical values introduced by MacKinnon, Haug and Michelis (1999). The number of lags were chosen according to the AIC criterion (resulting in 4 and 10 lags, respectively).

7. Conclusion

7.1. Summary

At the beginning it was demonstrated, by using a common ADF test, that the time series on hand are all integrated of order one meaning that the series are non-stationary originally and stationary after taking first differences. Thus, an important precondition to perform a cointegration analysis is fulfilled.

By testing the three prices for cointegration using standard methodologies, i.e. the two-step approach introduced by Engle and Granger and the procedure proposed by Johansen, it could be shown that the PHELIX and the EXAA spot prices are strongly cointegrated. The respective results exhibit high robustness with regard to the chosen lag length in the ADF tests and in the error correction models. Moreover, also graphical analysis did not raise any evidence of autocorrelation or instability in the residuals when applying the Engle/Granger testing procedure to the two prices. In the Johansen testing framework, in which the multivariate approach found one significant cointegration vector, the bivariate analysis confirmed the PHELIX and the EXAA prices to form a cointegrated price pair.

There was also some evidence for the two prices to be cointegrated with the SWISSIX price. For example, the Engle/Granger test, using the daily average series, found that the SWISSIX spot price is cointegrated with the EXAA spot price. However, the plotted residuals of the cointegration equation still exhibited considerable serial correlation. The same applies to the results of many hourly series that suggested a cointegration relationship between the Swiss price and the other two prices. Only the residuals of the German-Austrian price relationship did not exhibit autocorrelation.

Within a bivariate error correction representation it was tested whether one of the two speed adjustment parameters is significantly different from zero. According to the Granger Representation Theorem this has to be the case if a cointegration relationship exists. As expected, it was found that there exists a valid error correction model for the German-Austrian relationship and that the speed adjustment parameter of the EXAA price is significantly different from zero meaning that the EXAA price reacts to discrepancies from the price equilibrium. The PHELIX price, however, proved to be weakly exogenous meaning that it does not respond to price imbalances.

By applying the Kalman filter to estimate the development of the Beta-coefficients in the cointegration equations over time, there was a change towards a dynamic approach. The estimation was based on a state space model with the Beta-coefficient defined as the state variable as it was applied to

European Gas Markets by Neumann et al. (2006). The estimated state variables exhibited the smoothest behaviour and were close to 1 for the German-Austrian relationship. Again, there was partial evidence for the two prices to also have a distinct relationship with the Swiss market price. Especially the development of the Beta-coefficient of the German-Swiss price pair showed that, interrupted by obviously seasonal influences, a close price relationship may exist. A closer look at these seasonal patterns was taken and the original full-year series were decomposed into a summer and a winter half year series for each of the prices.

The filtered Beta-coefficients for the summer series proved to develop closer to zero and had much lower standard deviations than the coefficients of the full-year series, indicating that the relationships between all three prices are generally strong during the summer half year. Applying the Kalman filter estimation to the winter series, price relationships during the winter season were noticed to be explicitly weaker. The estimated coefficients yielded higher standard deviations than in the summer half year meaning that the price relationships are subject to higher variability during the winter half year. The weaker price relationship during the winter months especially applies to the price pairs including the Swiss price whereas the German-Austrian price relationship seems to stay rather strong.

Applying the Johansen testing procedure to the half-year series, it was shown that during the summer half year all prices are cointegrated pairwise with robust results. For the winter half year, there was also evidence for a second cointegration vector, however, it could no be proved that there exists more than one cointegration vector with robust results during this time.

Based on the test results of this thesis, the following main statements can be made: Firstly, the German PHELIX spot price and the Austrian EXAA spot price exhibit a strong relationship over the entire year which is confirmed by different testing methodologies with robust results. As a result it could be stated that for the two prices, the Law of One Price applies. Secondly, some evidence for the two prices to be cointegrated with the SWISSIX spot price exists as well. However, it could not be proved that they are robust for the full-year series in any testing frame work. Thirdly, beside the spot prices themselves, also the price relationships seem to be subject to season. This is especially interesting when observing relationships including the SWISSIX spot price. The analyses performed in this paper imply that during the summer half year all three prices are cointegrated pairwise. There is a clear convergence towards a single price meaning that the Law of One Price applies and market integration exists during the summer time. During the winter half year, again, only the German-

Austrian cointegration relation proves to be robust, whereas there is unstable evidence for a cointegration with the Swiss price.

7.2. Economic Interpretation

The results in the thesis on hand indicate that the PHELIX and the EXAA electricity spot prices converge towards a single price and that for these, the Law of One Price applies. The strong price relationship between the two spot prices seems comprehensible from an economic view. The PHELIX spot contracts traded at the EEX are deliverable on the VERBUND APG which is the power grid covering the largest part of Austria. At the same time, the EXAA spot contracts traded in Vienna can be settled in Germany at any point of the RWE and the E.ON power grid. These two grids represent a considerable part of the overall German transmission grid. Furthermore, the transmission capacities at the German-Austrian border do generally not exhibit bottlenecks, thus any size of electricity can be transported from Austria to Germany and vice versa. Hence, significant price differences would immediately lead to arbitrage activities and therefore, discrepancies in prices would be traded away. The fact that the EXAA price cannot be delivered at the EnBW and the Vattenfall power grids in Germany might be one reason why there exist some minor price differences nevertheless. Furthermore, the auction periods for the two prices do not close at exactly the same time. As a result, the level of information at the two exchanges is different which may also lead to minor price discrepancies.

In Switzerland, the electricity production capacity comes from hydroelectric power plants (HPPs) to a large extent. As many of these HPPs are located in the mountains and contain lakes in their operative systems which are frozen during the winter months, the availability of electricity in Switzerland is considerably tighter in this season. As it has already been mentioned in paragraph 2.1.3, Switzerland has, due to this circumstance, enhanced demand for electricity imports during this period which it covers by buying power mainly from Germany and from France. Both of these countries have sufficient production capacities, especially in the area of nuclear energy. The gap between supply and demand in Switzerland during the winter months might exert an upward pressure on the traded spot price SWISSIX. Moreover, in contrast to the German-Austrian border for instance, transmission capacities at the border with countries that export electricity to Switzerland (mainly France and Germany) are limited, hence imports cannot be expanded infinitely. All mentioned facts may serve as an economic rationale why in this thesis, it was not possible to find robust results for a cointegration relationship between the price for the Swiss market area and the price for the German/Austrian market area for the full-year price series and the winter series.

During the summer half year, especially for Switzerland, the domestic power supply looks different. Due to high production capacities of HPPs, the Swiss power industry is able to pump up energy into mountain lakes, which gives the possibility to make the non-storable good electricity storable to some extent. The electricity is mainly pumped up during base hours when overcapacities exist and then, among others, sold to abroad at peak hours when prices are on higher levels. Thus, price differences between the SWISSIX price and the two prices of the German/Austrian market area can be much better traded away by arbitrage activities than during the winter months.

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Declaration of Authorship

I hereby declare

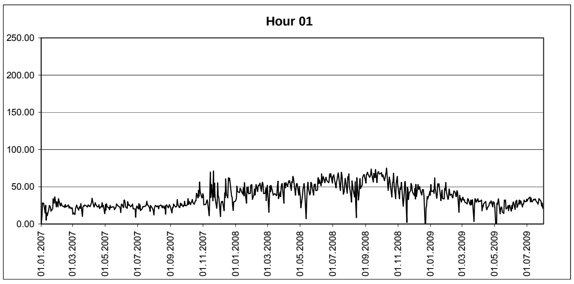
- that I have written this thesis whithout any help from others and without the use of documents and aids other than those stated above,
- that I have mentioned all used sources and that I have cited them correctly according to established academic citation rules.

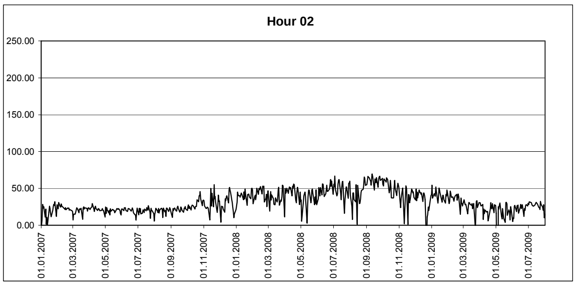
St. Gallen, 16 November 2009

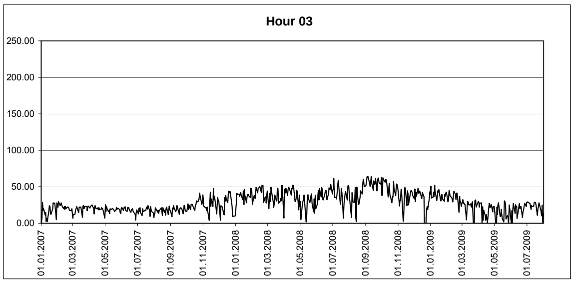
David Erni, B.A. HSG

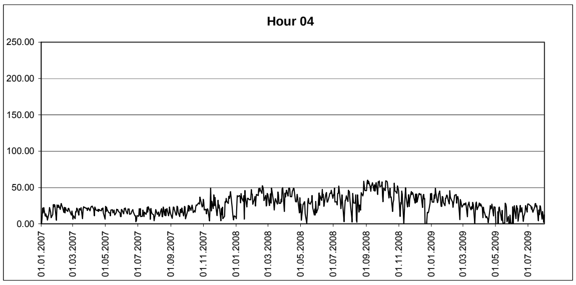
APPENDIX

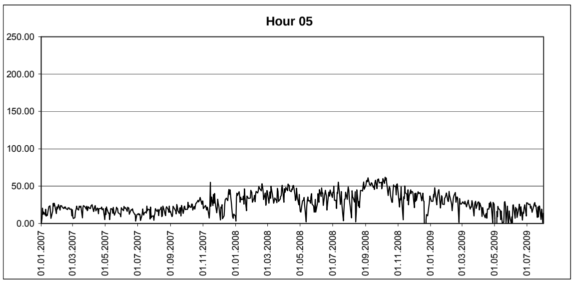
Hourly Spot Prices – *PHELIX* (Hours 1-12)

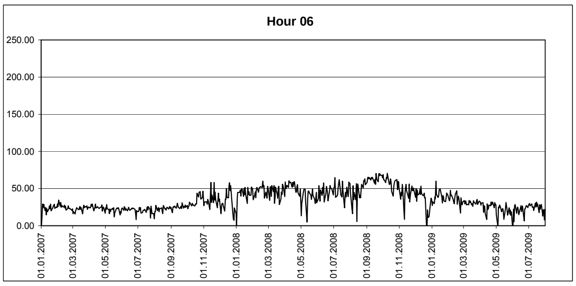


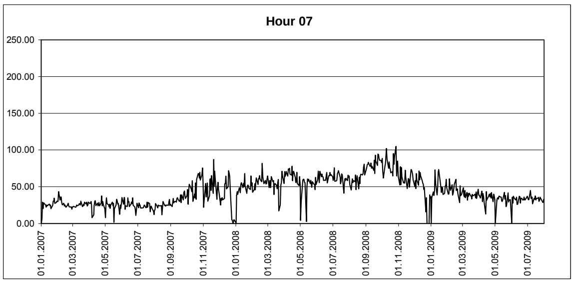


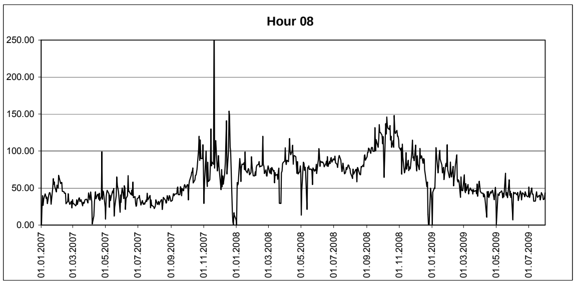


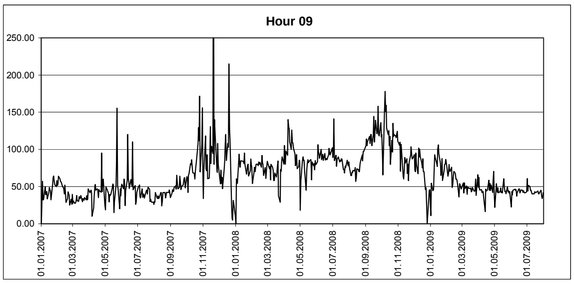


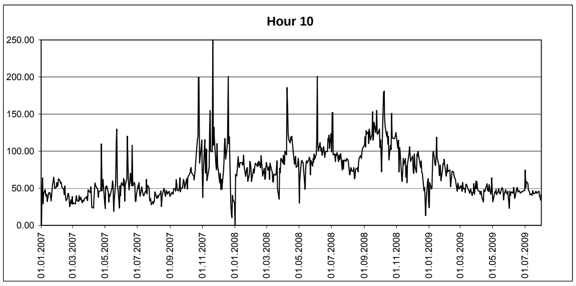


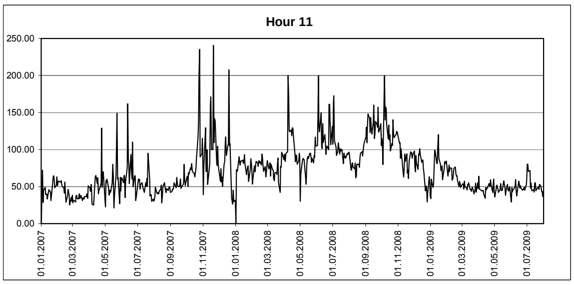


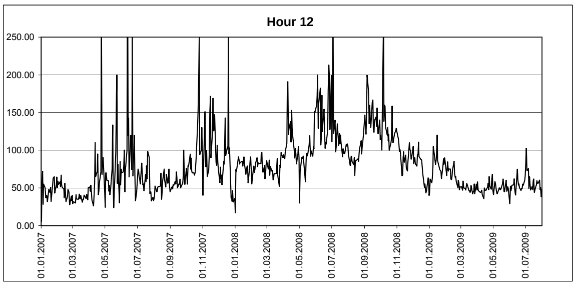




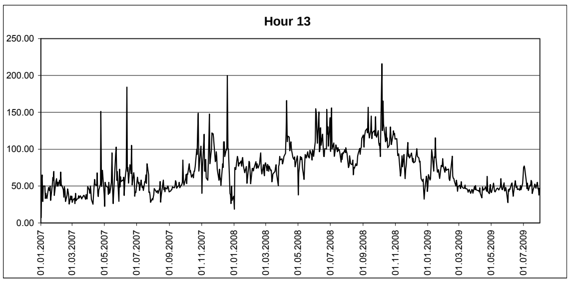








Hourly Spot Prices – *PHELIX* (Hours 13-24)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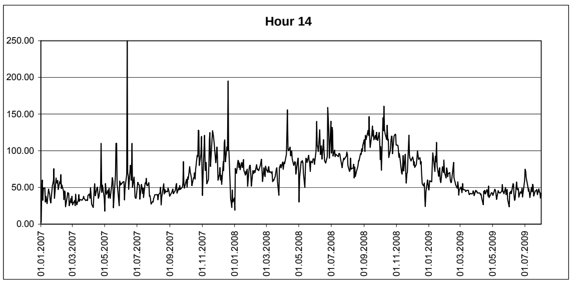
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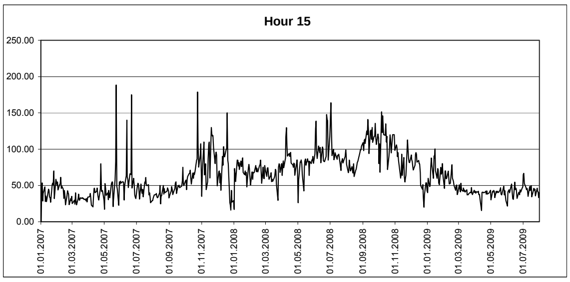
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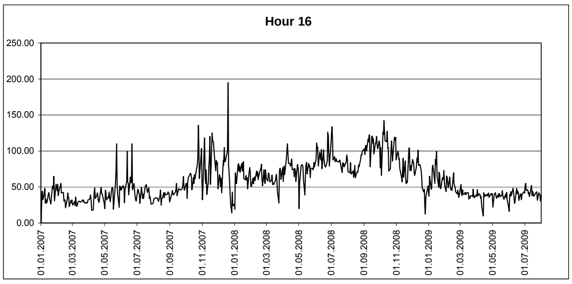
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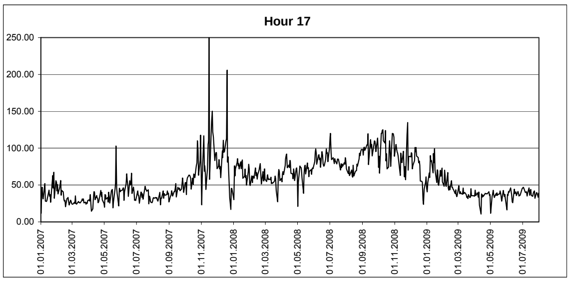
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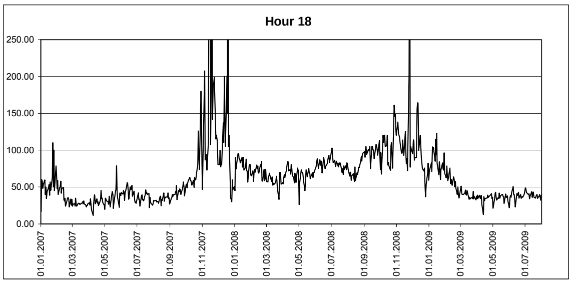
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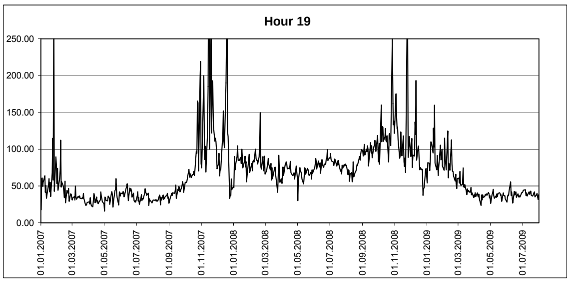
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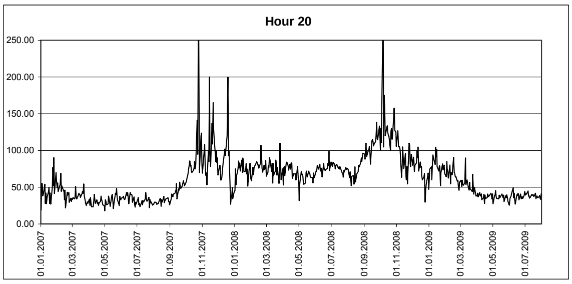
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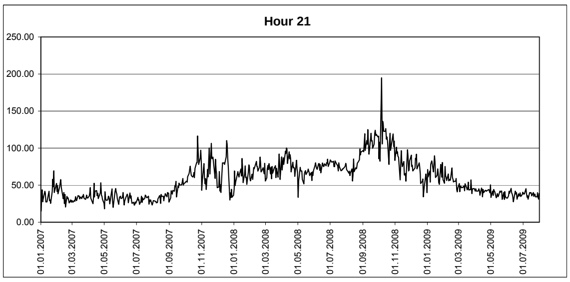
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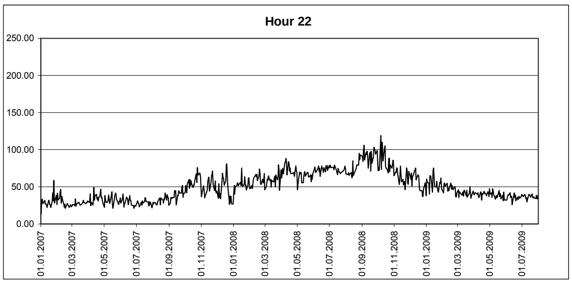
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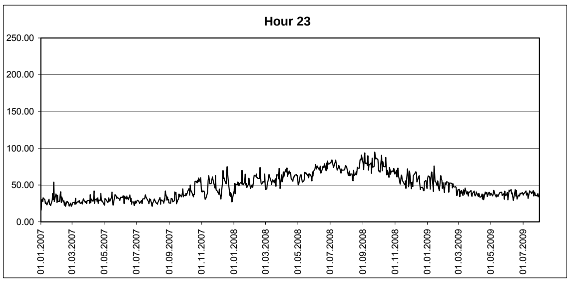
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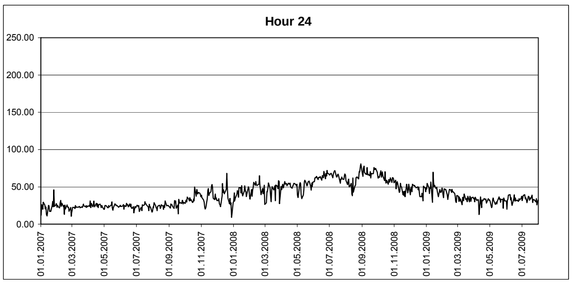
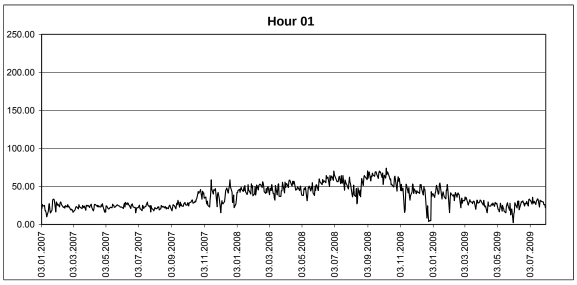
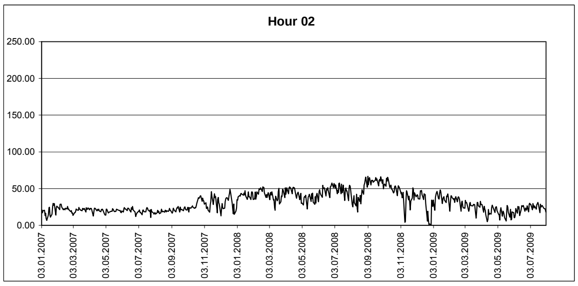
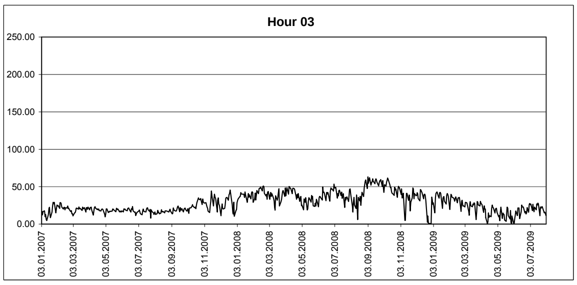
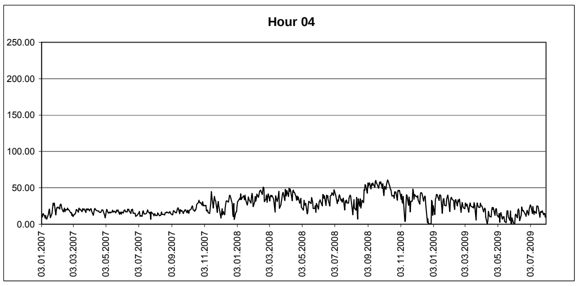

Hour 24

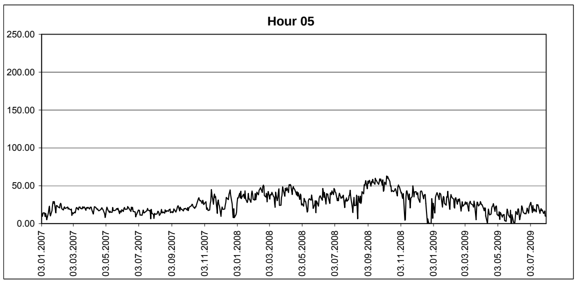
Hourly Spot Prices – *EXAA* (Hours 1-12)

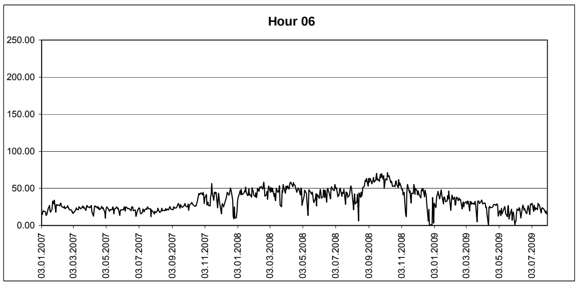


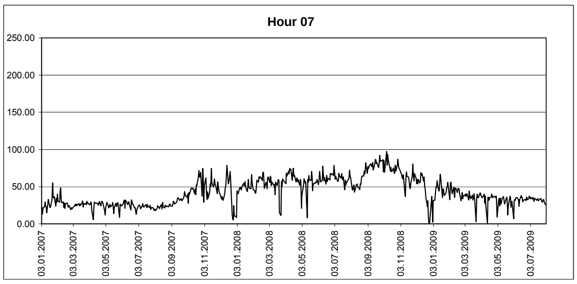


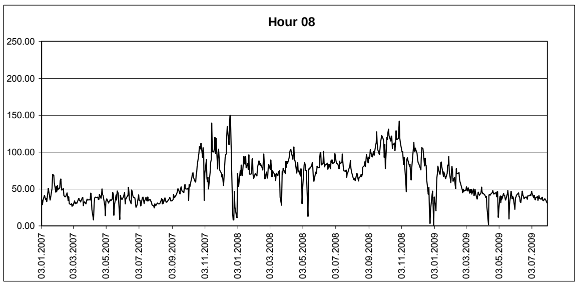


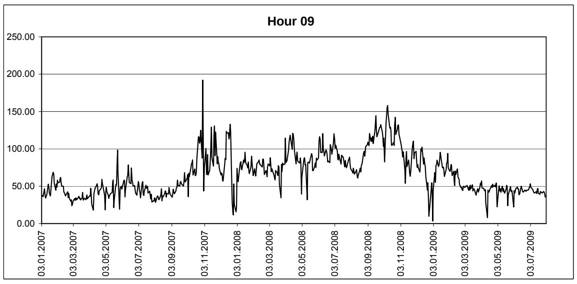


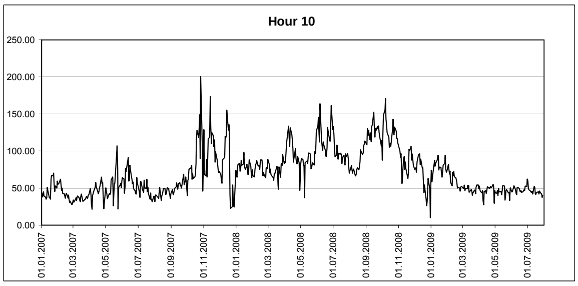


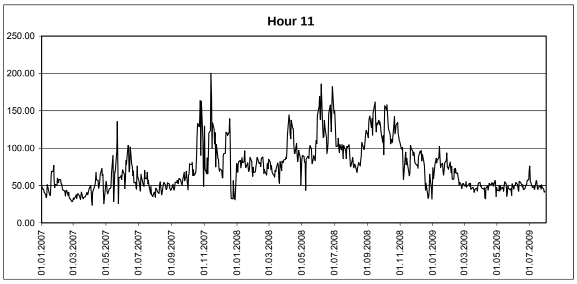


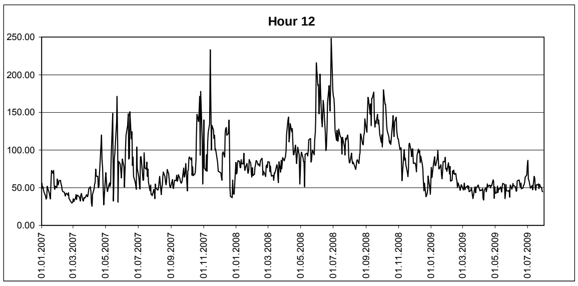




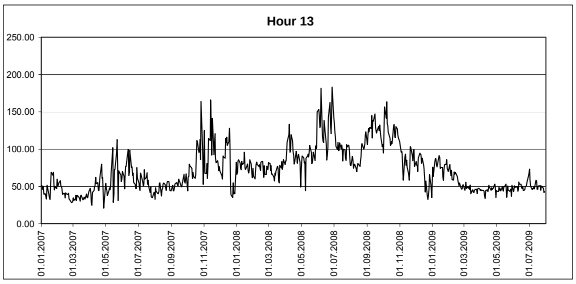


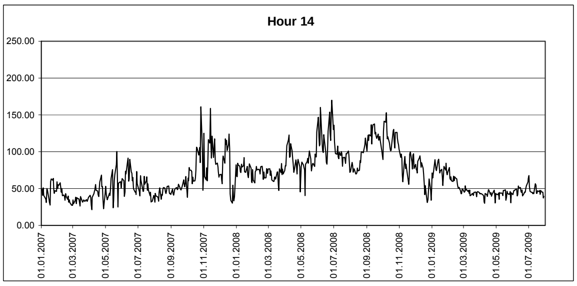






Hourly Spot Prices – *EXAA* (Hours 13-24)


Hour 13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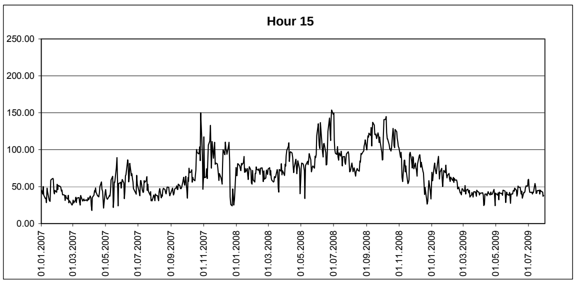
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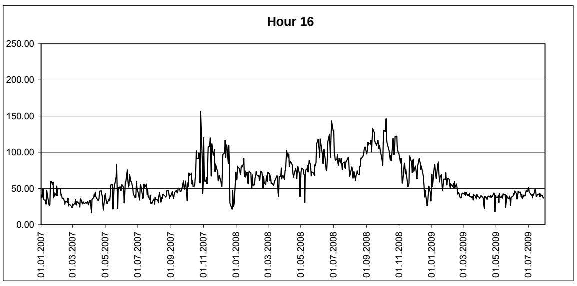
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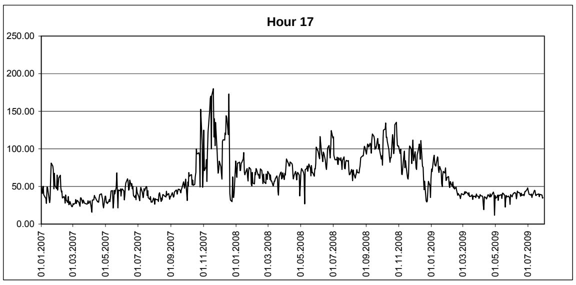
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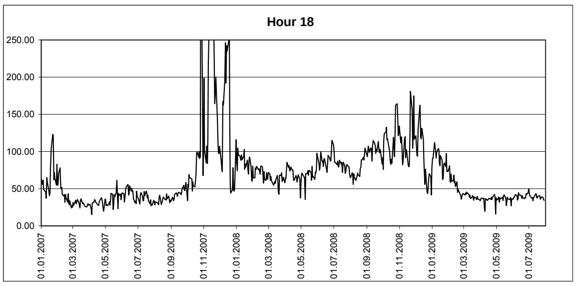
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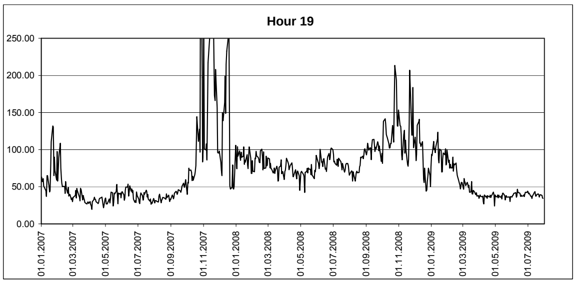
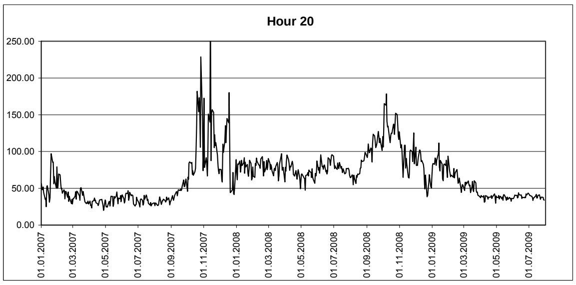

Hour 19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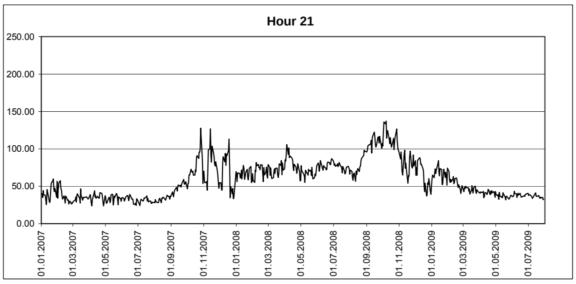
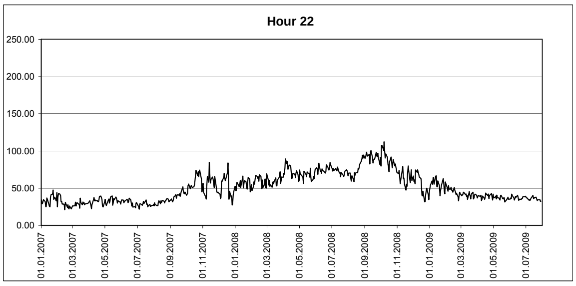
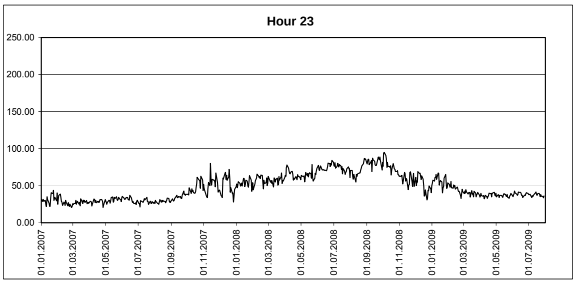
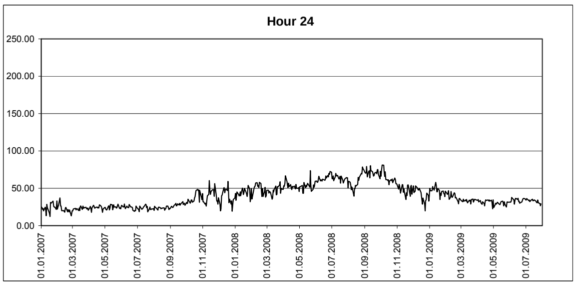
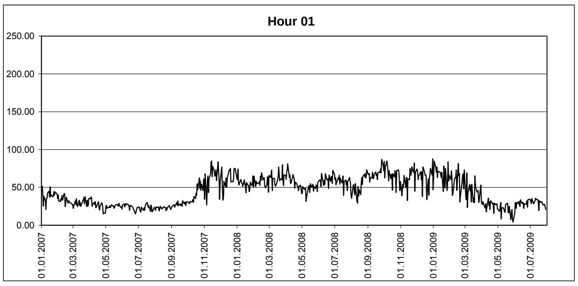

Hour 21

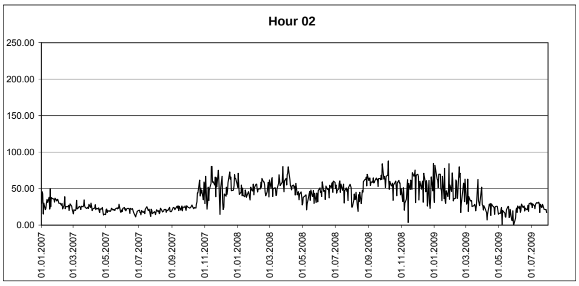

Hour 22

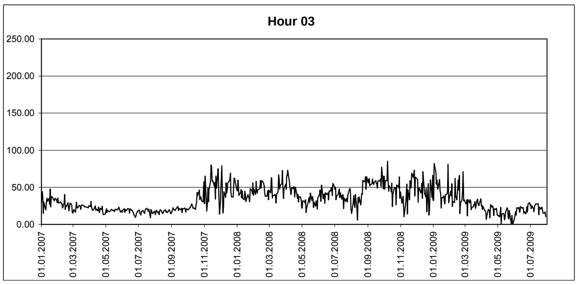

Hour 23

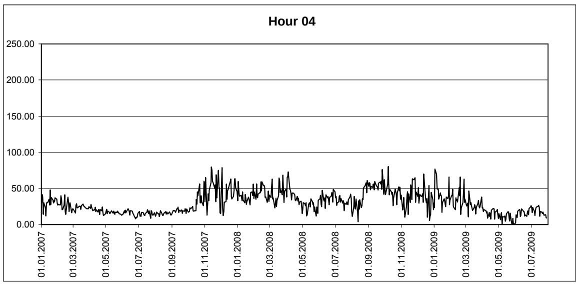

Hour 24

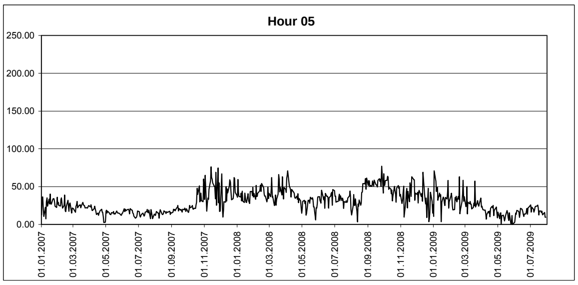
Hourly Spot Prices – *SWISSIX* (Hours 1-12)

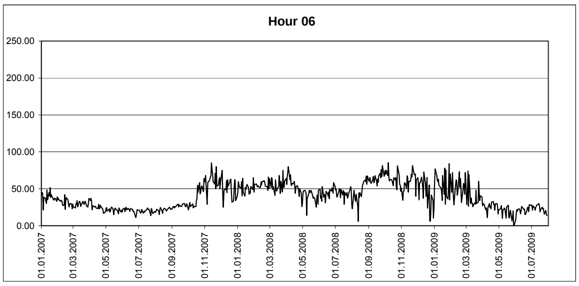


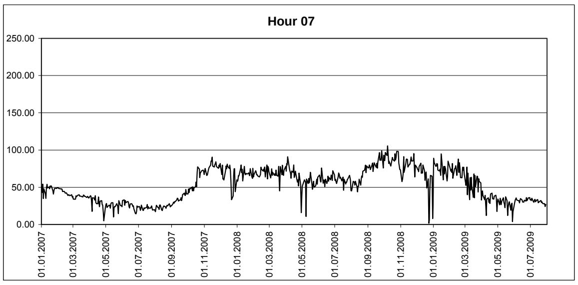


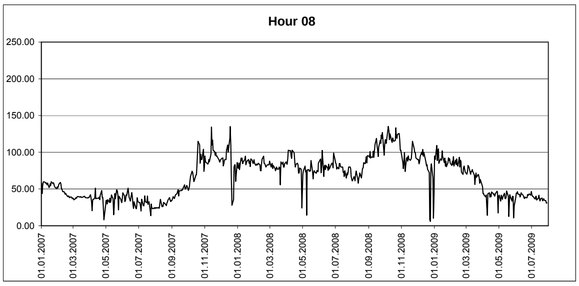


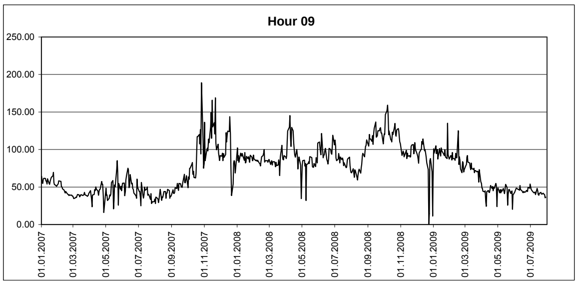


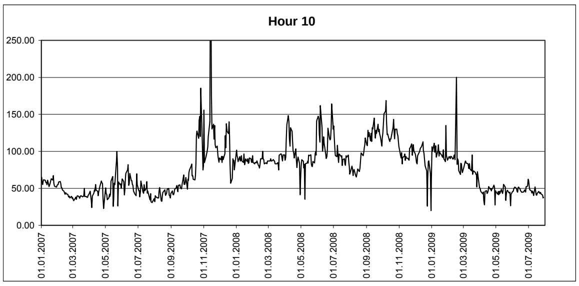


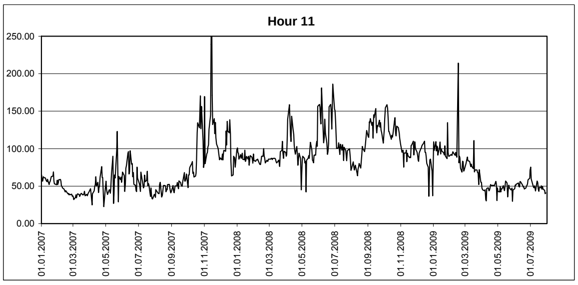


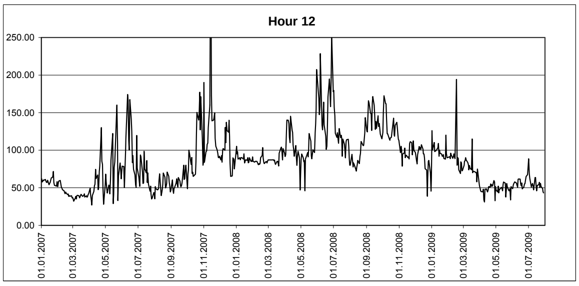




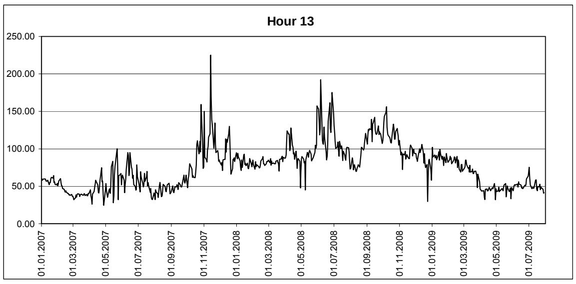


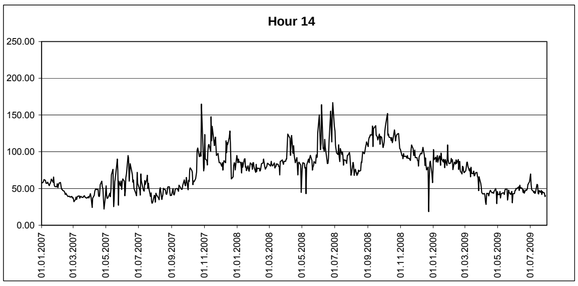


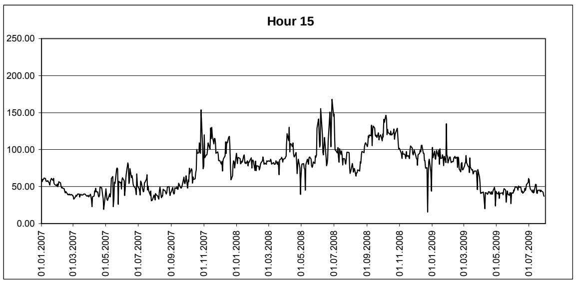


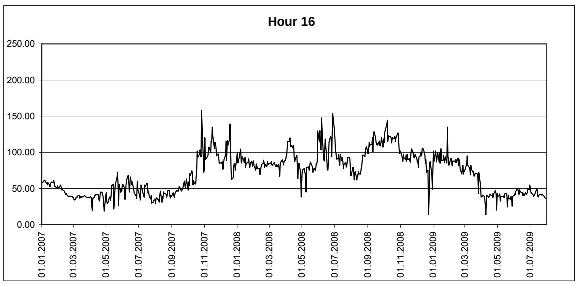


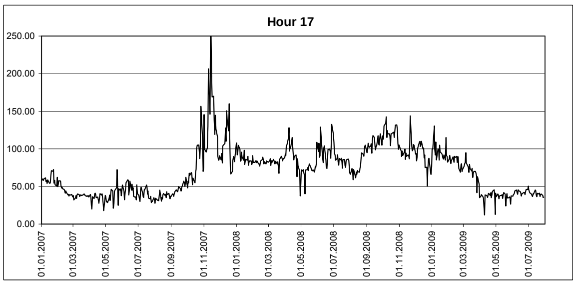
Hourly Spot Prices – *SWISSIX* (Hours 13-24)

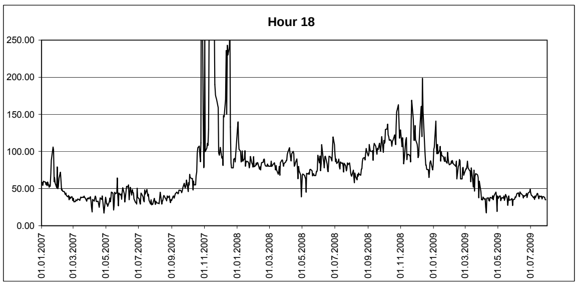


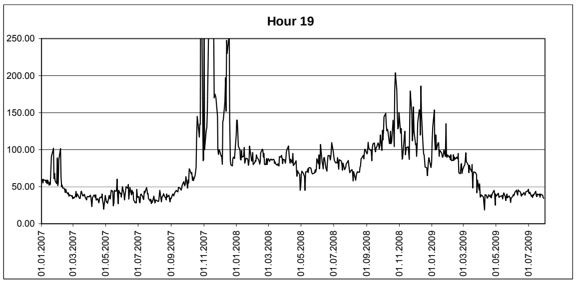


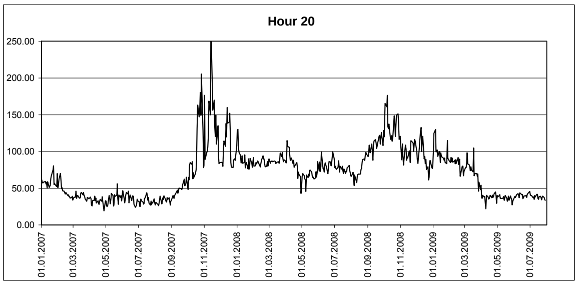


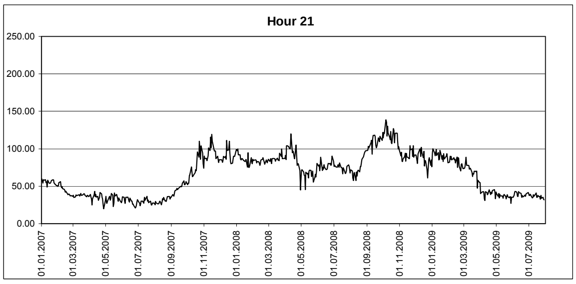


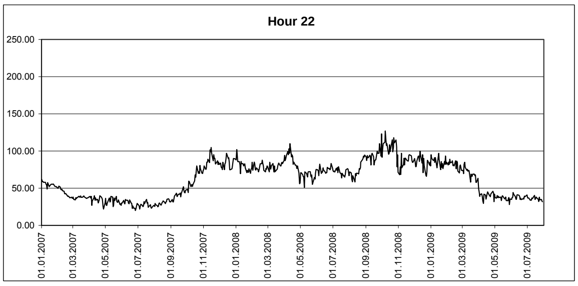


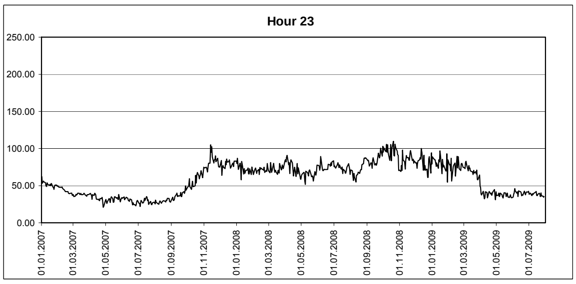


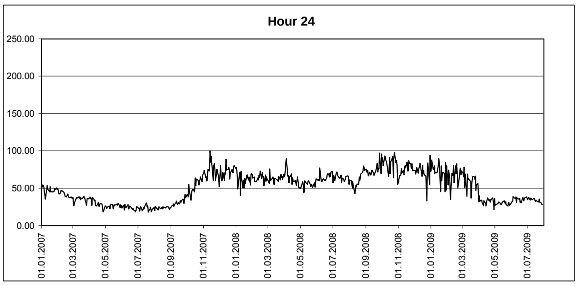












Descriptive Statistics of Hourly Spot Prices

SWISSIX

	Hour 1	Hour 2	Hour 3	Hour 4	Hour 5	Hour 6	Hour 7	Hour 8	Hour 9	Hour 10	Hour 11	Hour 12
Mean	45.12	37.84	33.23	30.29	29.74	39.86	52.65	65.75	73.18	76.88	79.54	85.65
Median	44.43	33.89	30.05	27.49	27.07	37.41	54.41	70.11	75.10	79.16	80.06	84.41
Maximum	87.56	87.94	85.02	80.33	77.02	85.30	105.51	135.22	188.88	317.80	313.52	314.76
Minimum	4.07	0.56	0.15	0.06	0.10	0.33	1.88	1.10	0.51	5.03	8.25	24.90
Std. Dev.	18.55	17.53	16.15	15.45	15.07	17.55	21.89	27.52	29.72	33.53	33.73	37.47
Skewness	0.16	0.44	0.64	0.73	0.61	0.31	-0.02	0.10	0.39	1.37	1.18	1.35
Kurtosis	1.79	2.20	2.72	3.05	2.81	2.12	1.88	2.08	2.70	8.96	6.71	6.88

	Hour 13	Hour 14	Hour 15	Hour 16	Hour 17	Hour 18	Hour 19	Hour 20	Hour 21	Hour 22	Hour 23	Hour 24
Mean	75.71	73.71	72.64	70.85	70.91	74.74	76.87	70.94	65.89	62.34	59.46	51.91
Median	75.94	75.06	74.79	72.92	71.97	70.59	71.59	70.16	70.07	69.02	65.06	54.99
Maximum	225.02	166.84	167.81	158.29	258.37	522.58	553.88	299.49	138.51	126.95	109.89	100.03
Minimum	24.52	18.57	15.64	13.84	12.18	17.10	18.59	18.98	19.97	20.10	20.83	17.80
Std. Dev.	28.98	27.81	28.31	28.16	32.03	49.49	52.04	34.87	27.02	24.17	21.61	19.92
Skewness	0.77	0.46	0.41	0.29	1.04	3.94	3.88	1.20	0.13	0.03	-0.01	0.05
Kurtosis	3.96	2.70	2.50	2.20	5.97	29.24	28.37	6.24	1.88	1.78	1.72	1.84

PHELIX

	Hour 1	Hour 2	Hour 3	Hour 4	Hour 5	Hour 6	Hour 7	Hour 8	Hour 9	Hour 10	Hour 11	Hour 12
Mean	36.68	31.64	28.43	25.79	26.74	34.43	43.75	62.16	66.34	69.43	72.78	80.19
Median	32.81	28.36	26.73	24.06	24.98	30.55	40.02	58.07	60.06	62.16	64.75	72.05
Maximum	75.01	69.63	64.09	60.20	61.93	70.51	104.93	301.01	437.26	249.92	240.71	387.11
Minimum	-16.67	-151.67	-101.52	-101.52	-101.50	-9.98	-50.88	-0.61	0.00	0.00	0.00	5.56
Std. Dev.	15.31	16.14	14.70	14.32	15.00	14.44	19.97	29.88	32.87	31.95	33.53	40.89
Skewness	0.39	-1.92	-0.80	-0.95	-1.52	0.37	0.13	1.13	2.72	1.23	1.29	2.08
Kurtosis	2.55	26.68	11.34	12.30	17.03	2.57	3.28	8.39	26.78	5.67	5.53	11.04

	Hour 13	Hour 14	Hour 15	Hour 16	Hour 17	Hour 18	Hour 19	Hour 20	Hour 21	Hour 22	Hour 23	Hour 24
Mean	70.69	67.50	64.00	59.69	58.51	66.06	68.80	62.97	58.22	50.41	47.77	39.58
Median	66.12	61.16	56.92	53.40	53.10	57.59	62.97	59.80	55.19	45.85	42.85	35.55
Maximum	216.01	250.22	188.48	195.00	250.04	821.90	701.01	299.09	194.62	118.93	94.82	80.98
Minimum	6.96	2.65	0.07	0.12	10.57	11.58	15.95	17.97	15.07	13.48	15.95	9.15
Std. Dev.	29.60	29.19	28.92	26.66	27.45	53.63	46.92	31.72	24.72	19.47	17.37	15.21
Skewness	0.97	1.03	0.96	0.83	1.25	7.38	5.16	1.90	0.83	0.62	0.46	0.49
Kurtosis	4.26	5.17	3.89	3.53	6.86	87.63	56.21	11.11	3.89	2.69	2.16	2.25

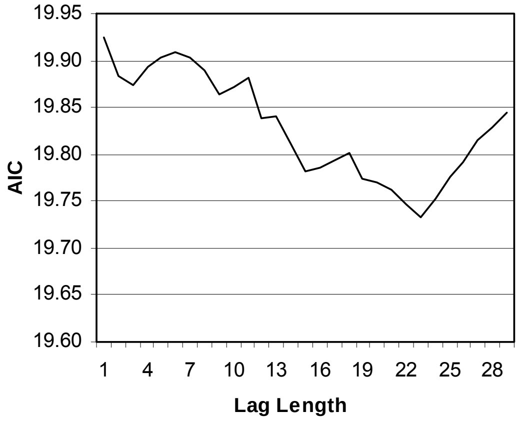
EXAA

	Hour 1	Hour 2	Hour 3	Hour 4	Hour 5	Hour 6	Hour 7	Hour 8	Hour 9	Hour 10	Hour 11	Hour 12
Mean	36.41	31.49	28.14	25.92	26.85	33.51	43.14	61.51	66.50	70.21	73.36	79.69
Median	32.01	28.50	25.45	23.03	24.14	29.60	39.06	55.47	62.50	64.12	67.50	71.92
Maximum	74.04	66.90	62.94	61.03	62.95	71.48	97.37	150.00	192.01	200.51	200.36	248.27
Minimum	2.14	0.61	0.10	0.01	0.01	0.01	0.01	0.01	3.43	10.00	11.67	0.07
Std. Dev.	14.47	13.49	12.94	12.48	12.83	14.14	18.75	27.97	28.53	30.23	31.74	36.17
Skewness	0.46	0.46	0.40	0.48	0.45	0.34	0.33	0.49	0.70	0.86	0.96	1.16
Kurtosis	2.25	2.44	2.56	2.72	2.67	2.48	2.42	2.58	3.19	3.38	3.52	4.40

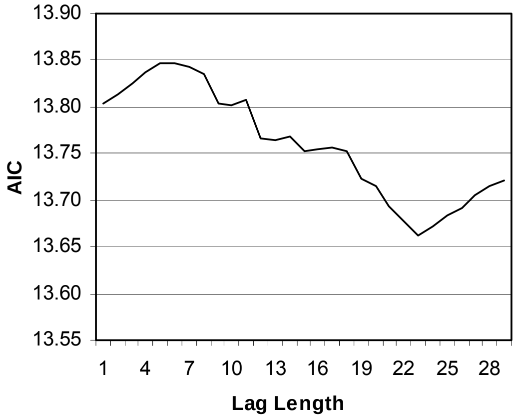
	Hour 13	Hour 14	Hour 15	Hour 16	Hour 17	Hour 18	Hour 19	Hour 20	Hour 21	Hour 22	Hour 23	Hour 24
Mean	71.50	67.90	64.26	60.75	60.80	69.28	72.29	65.53	58.45	50.76	47.95	39.79
Median	66.42	63.00	59.00	55.25	53.89	59.91	65.43	63.30	54.85	45.00	43.21	35.29
Maximum	183.33	170.00	153.60	156.27	180.02	517.55	519.93	302.37	137.15	112.59	94.94	81.21
Minimum	20.88	20.57	16.90	16.48	11.70	15.00	19.63	20.00	22.90	20.73	20.41	12.42
Std. Dev.	29.44	28.13	27.36	26.16	28.45	50.29	49.51	32.82	24.47	19.41	17.50	15.17
Skewness	0.90	0.82	0.80	0.77	1.03	4.02	3.67	1.55	0.71	0.62	0.48	0.57
Kurtosis	3.40	3.17	3.05	2.92	4.02	28.23	25.00	8.03	2.81	2.47	2.13	2.37

Sensitivity Analysis for AIC of Johansen Cointegration Tests

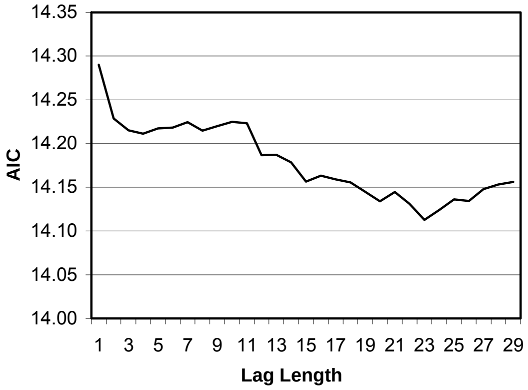
Multivariate framework



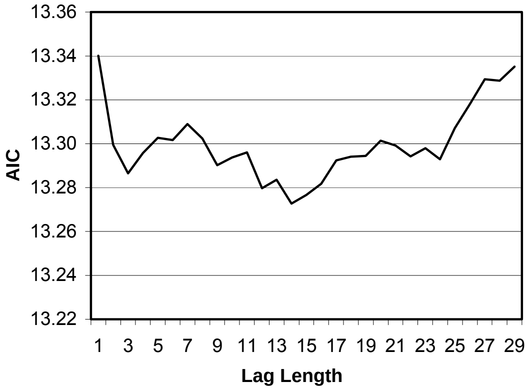
Price pair: PHELIX/EXAA



Price pair: PHELIX/SWISSIX

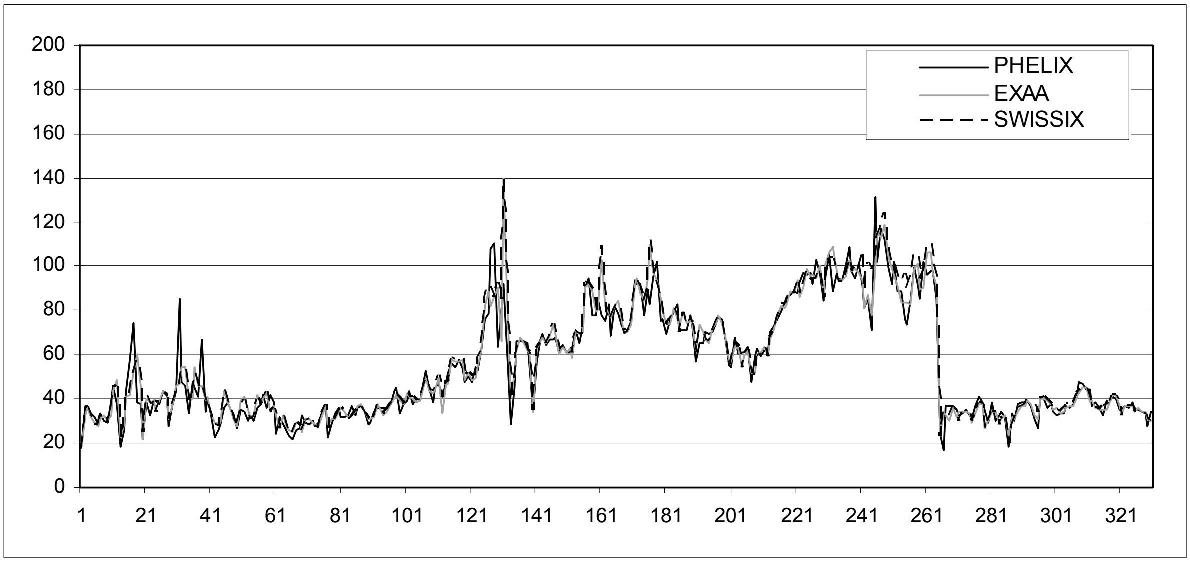


Price pair: SWISSIX/EXAA

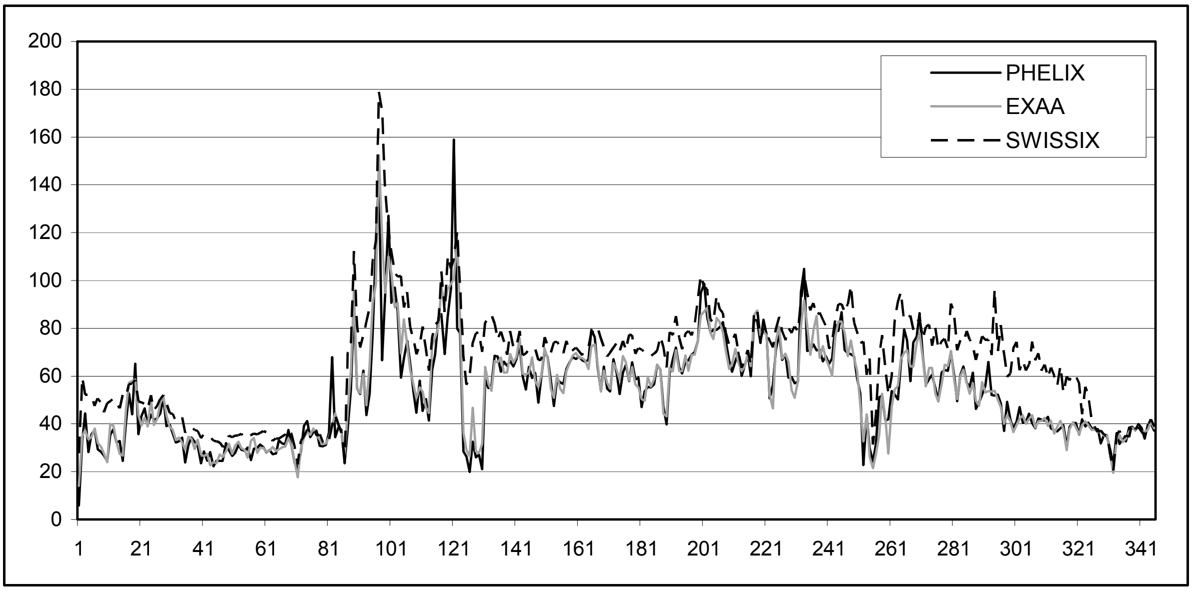


Graphs and Descriptive Statistics of Winter and Summer Daily Average Price Series

Summer Price Series:



Winter Price Series:

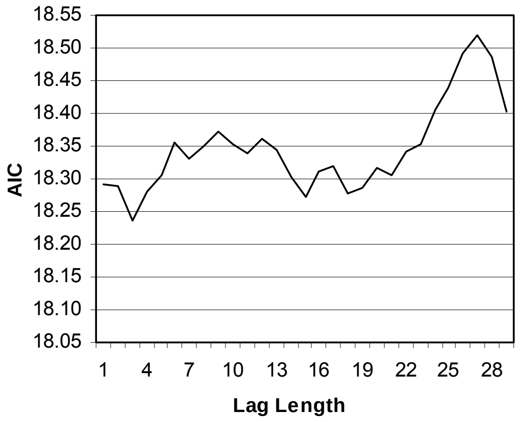


Descriptive Statistics:

	Summer series (May, 1 - Oct, 31)			*Winter series (Nov, 1 - Apr, 30)*		
	PHELIX	EXAA	SWISSIX	PHELIX	EXAA	SWISSIX
Mean	54.96	55.62	56.23	52.80	53.27	65.96
Median	44.55	45.05	44.63	52.51	52.91	70.54
Maximum	131.40	140.00	139.95	158.97	152.38	178.80
Minimum	17.06	18.75	17.59	5.80	14.00	20.46
Standard Deviation	24.54	24.95	25.80	20.61	20.33	22.68
Observations	330	330	330	345	345	345

Sensitivity Analysis for AIC of Johansen Cointegration Tests (Summer/Winter Series)

Multivariate framework, summer series



Multivariate framework, winter series